

# The Correctness of Launchbury’s Natural Semantics for Lazy Evaluation

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In his seminal paper “Natural Semantics for Lazy Evaluation” [Lau93], John Launchbury proves his semantics correct with respect to a denotational semantics, and outlines an adequacy proof. We have formalized both semantics and machine-checked the correctness proof, clarifying some details. Furthermore, we provide a new and more direct adequacy proof that does not require intermediate operational semantics.

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# 1 Introduction

The Natural Semantics for Lazy Evaluation [Lau93] created by John Launchbury in 1992 is often taken as the base for formal treatments of call-by-need evaluation, either to prove properties of lazy evaluation or as a base to describe extensions of the language or the implementation of the language. Therefore, assurance about the correctness and adequacy of the semantics is important in this field of research. Launchbury himself supports his semantics by defining a standard denotational semantics to prove both correctness and adequacy.

Although his proofs are already on the more rigorous side for pen-and-paper proofs, they have not yet been verified by transforming them to machine-checked proofs. The present work fills this gap by formalizing both semantics in the proof assistant Isabelle and proving both correctness and adequacy.

Our correctness formal proof is very close to the original proof. This is possible if the operator  $\sqcup$  is understood as a right-sided update. If we were to understand  $\sqcup$  as the least upper bound, then Theorem 2 in [Lau93], which is the generalization of the correctness statement used for Launchbury’s inductive proof, is wrong. The main correctness result still holds, but needs a different proof; this is discussed in greater detail in [Bre13].

Launchbury outlines an adequacy proof via an intermediate operational semantics and resourced denotational semantics. The alternative operational semantics uses indirection instead of substitution for applications, does not update variable results and does not perform blackholing during evaluation of a variable. The equivalence of these two operational semantics is hard and tricky to prove. We found a direct proof for the adequacy of the original operational semantics and the (slightly modified) resourced denotational semantics. This is, as far as we know, the first complete and rigorous proof of adequacy of Launchbury’s semantics.

In this development we extend Launchbury’s syntax and semantics with boolean values and an if-then-else construct, in order to base a subsequent work [?] on this. This extension does not affect the validity of the proven theorems, and the extra cases can simply be ignored if one is interested in the plain semantics. The next introductory section does exactly that. Unfortunately, such meta-level arguments are not easily implemented inside a theorem prover.

Our contributions are:

- We define the natural and denotational semantics given by Launchbury in the theorem prover Isabelle.
- We demonstrate how to use both the Nominal package (to handle name binding) [UK12] and the HOLCF [Huf12] package (for the domain-theoretic aspects) in the same development.
- We verify Launchbury’s proof of correctness.

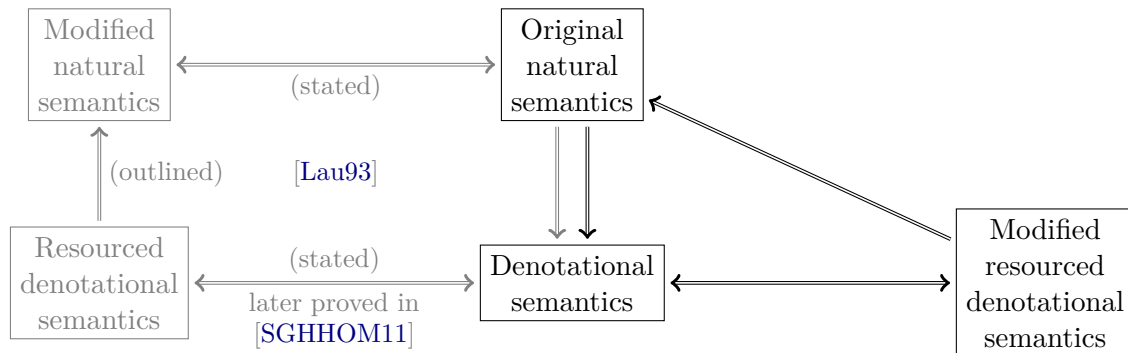
- We provide a new and more direct proof of adequacy.
- In order to do so, we formalize parts of [SGHHOM11], fixing a mistake in the proof.

## 1.1 Main definitions and theorems

For your convenience, the main definitions and theorems of the present work are assembled in this section. The following formulas are mechanically pretty-printed versions of the statements as defined resp. proven in Isabelle. Free variables are all-quantified. Some type conversion functions (like *set*) are omitted. The relations  $\sharp$  and  $\sharp^*$  come from the Nominal package and express freshness of the variables on the left with regard to the expressions on the right.

### 1.1.1 The big picture

The following picture gives an overview of the different semantics. Elements printed in black are formally defined and proved in the present work, while the gray square on the left shows the proofs and propositions in Launchbury's original work [Lau93].



### 1.1.2 Expressions

The type *var* of variables is abstract and provided by the Nominal package. All we know about it is that it is countably infinite. Expressions of type *exp* are given by the following grammar:

$e ::= \lambda x. e$	lambda abstraction
$e x$	application
$x$	variable
$let\ as\ in\ e$	recursive let

In the introduction we pretty-print expressions to resemble the notation in [Lau93] and omit the constructor names *Var*, *App*, *Lam* and *Let*. In the actual theories, these are visible. These expressions are, due to the machinery of the Nominal package, actually alpha-equivalency classes, so  $\lambda x. x = \lambda y. y$  holds provably. This differs from Launchbury's original definition, which expects distinctly-named expressions and performs explicit alpha-renaming in the semantics.

The type *heap* is an abbreviation for  $(var \times exp)$  *list*. These are *not* alpha-equivalency classes, i.e. we manage the bindings in heaps explicitly.

### 1.1.3 The natural semantics

Launchbury's original semantics, extended with some technical overhead related to name binding (following [Ses97]), is defined as follows:

$$\begin{array}{c}
\frac{}{\Gamma : \lambda x. e \Downarrow_L \Gamma : \lambda x. e} \quad \text{LAMBDA} \\
\\
\frac{y \# (\Gamma, e, x, L, \Delta, \Theta, z) \quad \Gamma : e \Downarrow_L \quad \Delta : \lambda y. e' \quad \Delta : e'[y := x] \Downarrow_L \quad \Theta : z}{\Gamma : e x \Downarrow_L \quad \Theta : z} \quad \text{APPLICATION} \\
\\
\frac{(x, e) \in \Gamma \quad \Gamma \setminus x : e \Downarrow_x . L \quad \Delta : z}{\Gamma : x \Downarrow_L (x, z) \cdot \Delta : z} \quad \text{VARIABLE} \\
\\
\frac{dom \Delta \#* (\Gamma, L) \quad \Delta @ \Gamma : body \Downarrow_L \quad \Theta : z}{\Gamma : let \Delta in body \Downarrow_L \quad \Theta : z} \quad \text{LET}
\end{array}$$

### 1.1.4 The denotational semantics

The value domain of the denotational semantics is the initial solution to

$$D = [D \rightarrow D]_{\perp}$$

as introduced in [Abr90]. The type *Value*, together with the bottom value  $\perp$ , the injection *Fn* and the projection  $\_ \Downarrow Fn \_ :: Value \rightarrow Value \rightarrow Value$ , is constructed as a pointed chain-complete partial order from this equation by the HOLCF package. The type of semantic environments is  $var \Rightarrow Value$ .

The semantics of an expression  $e :: exp$  in an environment  $\rho :: var \Rightarrow Value$  is written  $\llbracket e \rrbracket_{\rho} :: Value$  and defined by the following equations:

$$\begin{aligned}
\llbracket \lambda x. e \rrbracket_{\rho} &= Fn \cdot (\Lambda v. \llbracket e \rrbracket_{\rho(x := v)}) \\
\llbracket e x \rrbracket_{\rho} &= \llbracket e \rrbracket_{\rho} \Downarrow Fn \rho x \\
\llbracket x \rrbracket_{\rho} &= \rho x \\
\llbracket let \Gamma in body \rrbracket_{\rho} &= \llbracket body \rrbracket_{\llbracket \Gamma \rrbracket_{\rho}}
\end{aligned}$$

The expression  $\llbracket \Gamma \rrbracket_{\varrho}$  maps the evaluation function over a heap, returning an environment:

$$\begin{aligned} (\llbracket \Gamma \rrbracket_{\varrho}) v &= \llbracket e \rrbracket_{\varrho} && \text{if } (v, e) \in \Gamma \\ (\llbracket \Gamma \rrbracket_{\varrho}) v &= \perp && \text{if } v \notin \text{dom } \Gamma \end{aligned}$$

The semantics  $\{\Gamma\}_{\varrho} :: \text{var} \Rightarrow \text{Value}$  of a heap  $\Gamma :: \text{heap}$  in an environment  $\varrho :: \text{var} \Rightarrow \text{Value}$  is defined by the recursive equation

$$\{\Gamma\}_{\varrho} = \varrho \text{ ++}_{\text{dom } \Gamma} \llbracket \Gamma \rrbracket_{\{\Gamma\}_{\varrho}}$$

where

$$\begin{aligned} (f \text{ ++}_A g) a &= f a && \text{if } a \notin A \\ (f \text{ ++}_A g) a &= g a && \text{if } a \in A. \end{aligned}$$

The semantics of the heap in the empty environment  $\perp$  is abbreviated as  $\{\Gamma\}$ .

### 1.1.5 Correctness and Adequacy

The statement of correctness reads: If  $\Gamma : e \Downarrow_L \Delta : v$  and, as a side condition,  $fv(\Gamma, e) \subseteq L \cup \text{dom } \Gamma$  holds, then

$$\llbracket e \rrbracket_{\{\Gamma\}_{\varrho}} = \llbracket v \rrbracket_{\{\Delta\}_{\varrho}}.$$

The statement of adequacy reads:

$$\text{If } \llbracket e \rrbracket_{\{\Gamma\}} \neq \perp \text{ then } \exists \Delta v. \Gamma : e \Downarrow_S \Delta : v.$$

## 1.2 Differences to our previous work

We have previously published [Bre13] of which the present work is a continuation. They differ in scope and focus:

### 1.2.1 The treatment of $\sqcup$

In [Bre13], the question of the precise meaning of  $\sqcup$  is discussed in detail. The original paper is not clear about whether this operator denotes the least upper bound, or the right-sided override operator. A lemma stated in [Lau93] only holds if  $\sqcup$  is the least upper bound, but with that definition, Launchbury's Theorem 2 – the generalized correctness theorem – is false; a counter-example is given in [Bre13].

We came up with an alternative operational semantics that keeps more of the evaluation context in the judgments and allows the correctness theorem to be proved inductively without the problematic generalization. We proved the two operational semantics equivalent and thus obtained the (non-generalized) correctness of Launchbury’s semantics.

We also showed that if one takes  $\sqcup$  to be the update operator, Theorem 2 holds and the proof goes through as it is. Furthermore, we showed that the resulting denotational semantics are identical for expressions, and can differ only for heaps. Therefore, the question of the precise meaning of  $\sqcup$  can be considered of little importance and for the present work we solely work with right sided updates. We also avoid the ambiguous syntax  $\sqcup$  and write  $\_ ++ \_ \_$  instead (the index indicates on what set the function on the right overrides the function on the left). The alternative operational semantics is not included in this work.

### 1.2.2 The types of environments

Another difference is the choice of the type for environments, which map variables to semantics values. A naive choice is  $var \Rightarrow Value$ , but this causes problems when defining the value semantics, for which

$$\llbracket \lambda x. e \rrbracket_{\rho} = Fn \cdot (\Lambda v. \llbracket e \rrbracket_{\rho(x := v)})$$

is a defining equation. The argument on the left hand side is the representative of an equivalence class (defined using the Nominal package), so this is only allowed if the right hand side is indeed independent of the actual choice of  $x$ . This is shown most commonly and easily if  $x$  is fresh in all the other arguments ( $x \# \rho$ ), and indeed the Nominal package allows us to specify this as a side condition to the defining equation, which is what we did in [Bre13].

But this convenience comes as a price: Such side-conditions are only allowed if the argument has finite support (otherwise there might no variable fulfilling  $x \# \rho$ ). More precisely: The type of the argument must be a member of the *fs* typeclass provided by the Nominal package. The type  $var \Rightarrow Value$  cannot be made a member of this class, as there obviously are elements that have infinite support. The fix here was to introduce a new type constructor, *fmap*, for partial functions with finite domain. This is fine: Only functions with finite domain matter in our formalisation.

The introduction of *fmap* had further consequences. The main type class of the HOLCF package, which we use to define domains and continuous functions on them, is the class *cpo*, of chain-complete partial orders. With the usual ordering on partial functions,  $(var, Value)$  *fmap* cannot be a member of this class. The fix here is to use a different ordering and only let elements be comparable that have the same domain. In our formalisation, the domain is always known (e.g. all variables bound on some heap), so this worked out.

But not without causing yet another issue: With this ordering,  $(var, Value)$  *fmap* is a *cpo*, but lacks a bottom element, i.e. now it is no *pcpo*, and HOLCF’s built-in operator

$\mu x. f x$  for expressing least fixed-points, as they occur in the semantics of heaps, is not available. Furthermore,  $\sqcup$  is not a total function, i.e. defined only on a subset of all possible arguments. The solution was a rather convoluted set of theories that formalize functions that are continuous on a specific set, fixed-points on such sets etc.

In the present work, this problems is solved in a much more elegant way. Using a small trick we defined the semantics functions so that

$$\llbracket \lambda x. e \rrbracket_{\varrho} = Fn \cdot (\Lambda v. \llbracket e \rrbracket_{\varrho(x := v)})$$

holds unconditionally. The actual, technical definition is

$$\llbracket \lambda x. e \rrbracket_{\varrho} = Fn \cdot (\Lambda v. \llbracket e \rrbracket_{\varrho|_{fv}(\lambda x. e)}(x := v))$$

where the right-hand-side can be shown to be invariant of the choice of  $x$ , as  $x \notin fv(\lambda x. e)$ . Once the function is defined, the equality  $\llbracket e \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho|_{fv} e}$  can be proved.

With that, the desired equation for  $\llbracket \lambda x. e \rrbracket_{\varrho}$  follows. The same trick is applied to the equation for  $\llbracket \text{let } \Gamma \text{ in body} \rrbracket_{\varrho}$ .

This allows us to use the type  $var \Rightarrow Value$  for the semantic environments and considerably simplifies the formalization compared to [Bre13].

### 1.2.3 No type *assn*

The nominal package provides means to define types that are alpha-equivalence classes, and we use that to define our type *exp*, which contains a constructor *let binds in expr*. The desired type of the parameter for the binding is  $(var \times exp)$  *list*, but the Nominal package does not support such nested recursion, and requires a mutual recursive definition with a custom type (*assn*) with constructors *ANil* and *ACons* that is isomorphic to  $(var \times exp)$  *list*. In [Bre13], this type and conversion functions from and to  $(var \times exp)$  *list* cluttered the whole development. In the present work we improved this by defining the type with a “temporary” constructor *LetA*. Afterwards we define conversions functions and the desired constructor *Let*, and re-state all lemmas produced by the Nominal package (such as type exhaustiveness, distinctiveness of constructors and the induction rules) with that constructor. From that point on, the development is free of the crutch *assn*.

In short, the notable changes in this work over [Bre13] are:

- We consider  $\sqcup$  to be a right-sided update and do discuss neither the problem with  $\sqcup$  denoting the least upper bound, nor possible solutions.
- This, a simpler choice for the type of semantic environments and a better definition of the type for terms, considerably simplifies the work.
- Most importantly, this work contains a complete and formal proof of the adequacy of Launchbury’s semantics.

### 1.3 Related work

Lidia Sánchez-Gil, Mercedes Hidalgo-Herrero and Yolanda Ortega-Mallén have worked on formal aspects of Launchbury’s semantics as well.

They identified a step in his adequacy proof relating the standard and the resourced denotational semantics that is not as trivial as it seems at first and worked out a detailed pen-and-paper proof [SGHHOM11], where they first construct a similarity relation  $\_ \triangleleft \_$  between the standard semantic domain (*Value*) and the resourced domain (*CValue*) and show that the denotation semantics yield similar results ( $\varrho \triangleleft^* \sigma \implies \llbracket e \rrbracket_\varrho \triangleleft (\mathcal{N} \llbracket e \rrbracket_\sigma) \cdot C^\infty$ ), which is one step in the adequacy proof. We formalized this (Sections 8.1 and 8.2), identifying and fixing a mistake in the paper (Lemma 2.3(3) does not hold; the problem can be fixed by applying an extra round of take-induction in the proof of Proposition 9).

Currently, they are working on completing the adequacy proof as outlined by Launchbury, i.e. by going via the alternative natural semantics given in [Lau93], which differs from the semantics above in that the application rule works with an indirection on the heap instead of a substitution and that the variable rule has no blackholing and no update. In [SGHHOM14], they relate the original semantics with one where indirections have been introduced. The next step, modifying the variable rule, is under development. Once that is done they can close the loop and have completed Launchbury’s work.

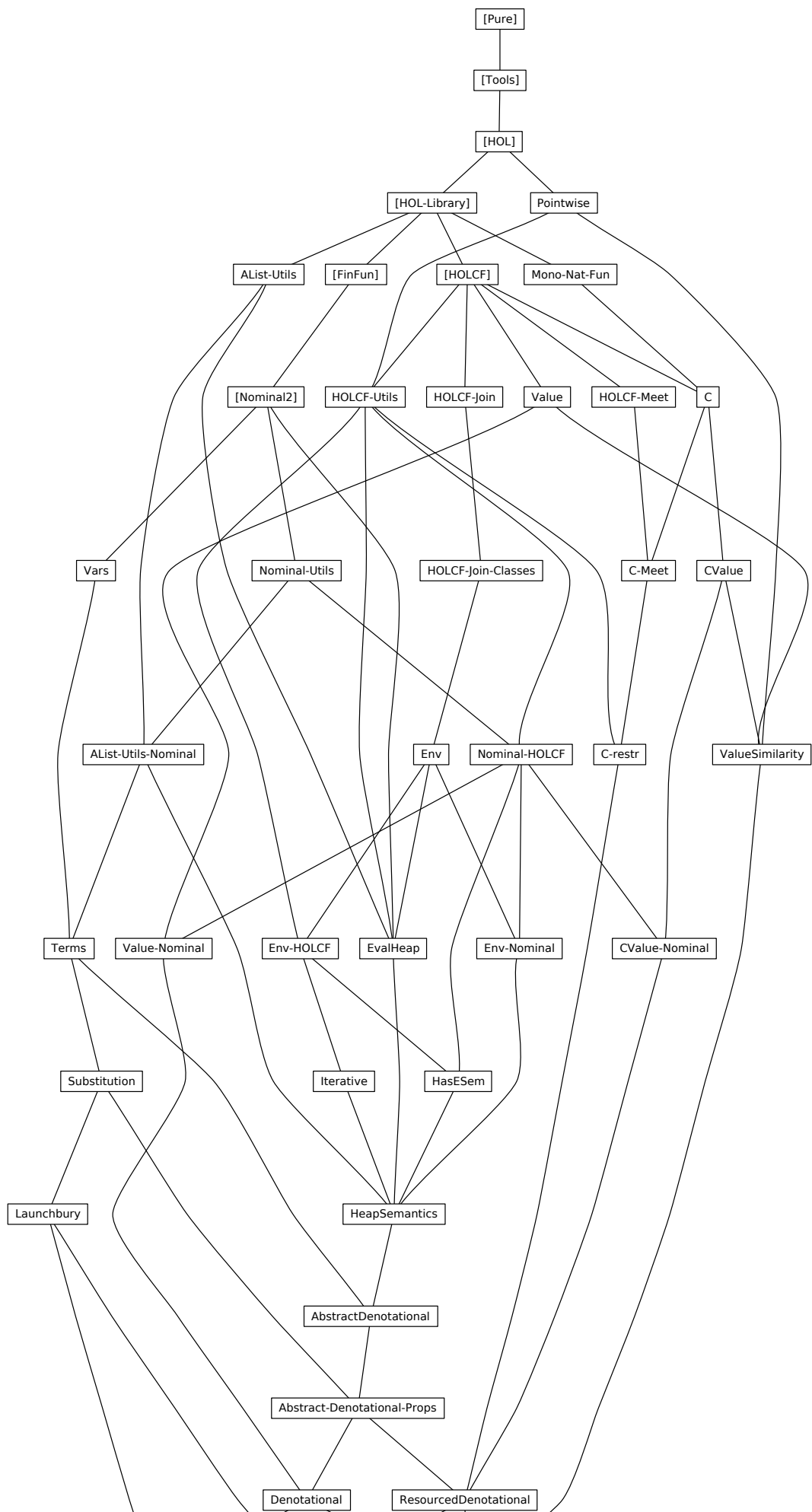
This work proves the adequacy as stated by Launchbury as well, but in contrast to his proof outline no alternative operational semantics is introduced. The problems of indirection vs. substitution and of blackholing is solved on the denotational side instead, which turned out to be much easier than proving the various operational semantics to be equivalent.

### 1.4 Theory overview

The following chapters contain the complete Isabelle theories, with one section per theory. Their interdependencies are visualized in Figure 1.

Chapter 2 contains auxiliary theories, not necessarily tied to Launchbury’s semantics. The base theories are kept independent of Nominal and HOLCF where possible, the lemmas combining them are in theories of their own, creatively named by appending *-Nominal* resp. *-HOLCF*. You will find these theories:

- A definition for lifting a relation point-wise (*Pointwise*).
- A collection of definition related to associative lists (*AList-Utils*, *AList-Utils-Nominal*).
- A characterization of monotonous functions  $\mathbb{N} \rightarrow \mathbb{N}$  (*Mono-Nat-Fun*).
- General utility functions extending Nominal (*Nominal-Utils*).



- General utility functions extending HOLCF (*HOLCF-Utils*).
- Binary meets in the context of HOLCF (*HOLCF-Meet*).
- A theory combining notions from HOLCF and Nominal, e.g. continuity of permutation (*Nominal-HOLCF*).
- A theory for working with pcpo-valued functions as semantic environments (*Env*, *Env-Nominal*, *Env-HOLCF*).
- A function *evalHeap* that converts between associative lists and functions. (*Eval-Heap*)

Chapter 3 defines the syntax and Launchbury’s natural semantics.

Chapter 4 sets the stage for the denotational semantics by defining a locale *semantic-domain* for denotational domains, and an instantiation for the standard domain.

Chapter 5 defines the denotational semantics. It also introduces the locale *has-ESem* which abstracts over the value semantics when defining the semantics of heaps.

Chapter 6 defines the resourced denotational semantics.

Chapter 7 proves the correctness of Launchbury’s semantics with regard to both denotational semantics. We need the correctness with regard to the resourced semantics in the adequacy proof.

Chapter 8 proves the two denotational semantics related, which is used in

Chapter 9, where finally the adequacy is proved.

## 1.5 Acknowledgements

I’d like to thank Lidia Sánchez-Gil, Mercedes Hidalgo-Herrero and Yolanda Ortega-Mallén for inviting me to Madrid to discuss our respective approaches.

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## 2 Auxiliary theories

### 2.1 Pointwise

**theory** *Pointwise* **imports** *Main* **begin**

Lifting a relation to a function.

**definition** *pointwise* **where** *pointwise*  $P\ m\ m' = (\forall\ x.\ P\ (m\ x)\ (m'\ x))$

**lemma** *pointwiseI[intro]*:  $(\bigwedge\ x.\ P\ (m\ x)\ (m'\ x)) \implies\ \textit{pointwise}\ P\ m\ m'$  *<proof>*

**end**

### 2.2 AList-Utills

**theory** *AList-Utills*

**imports** *Main* *HOL-Library.AList*

**begin**

**declare** *implies-True-equals* [*simp*] *False-implies-equals*[*simp*]

We want to have *delete* and *update* back in the namespace.

**abbreviation** *delete* **where** *delete*  $\equiv\ \textit{AList.delete}$

**abbreviation** *update* **where** *update*  $\equiv\ \textit{AList.update}$

**abbreviation** *restrictA* **where** *restrictA*  $\equiv\ \textit{AList.restrict}$

**abbreviation** *clearjunk* **where** *clearjunk*  $\equiv\ \textit{AList.clearjunk}$

**lemmas** *restrict-eq* = *AList.restrict-eq*

**and** *delete-eq* = *AList.delete-eq*

**lemma** *restrictA-append*:  $\textit{restrictA}\ S\ (a@b) = \textit{restrictA}\ S\ a\ @\ \textit{restrictA}\ S\ b$   
*<proof>*

**lemma** *length-restrictA-le*:  $\textit{length}\ (\textit{restrictA}\ S\ a) \leq \textit{length}\ a$   
*<proof>*

#### 2.2.1 The domain of an associative list

**definition** *domA*

**where** *domA*  $h = \textit{fst}\ 'set\ h$

**lemma** *domA-append[simp]*:  $\textit{domA}\ (a\ @\ b) = \textit{domA}\ a\ \cup\ \textit{domA}\ b$

**and** [*simp*]:  $\textit{domA}\ ((v,e)\ \#\ h) = \textit{insert}\ v\ (\textit{domA}\ h)$

**and** [*simp*]:  $\textit{domA}\ (p\ \#\ h) = \textit{insert}\ (\textit{fst}\ p)\ (\textit{domA}\ h)$

**and** [*simp*]:  $\textit{domA}\ [] = \{\}$

*<proof>*

**lemma** *domA-from-set*:

$(x, e) \in \text{set } h \implies x \in \text{dom}A \ h$   
 $\langle \text{proof} \rangle$

**lemma** *finite-domA[simp]*:  
 $\text{finite } (\text{dom}A \ \Gamma)$   
 $\langle \text{proof} \rangle$

**lemma** *domA-delete[simp]*:  
 $\text{dom}A \ (\text{delete } x \ \Gamma) = \text{dom}A \ \Gamma - \{x\}$   
 $\langle \text{proof} \rangle$

**lemma** *domA-restrictA[simp]*:  
 $\text{dom}A \ (\text{restrict}A \ S \ \Gamma) = \text{dom}A \ \Gamma \cap S$   
 $\langle \text{proof} \rangle$

**lemma** *delete-not-domA[simp]*:  
 $x \notin \text{dom}A \ \Gamma \implies \text{delete } x \ \Gamma = \Gamma$   
 $\langle \text{proof} \rangle$

**lemma** *deleted-not-domA*:  $x \notin \text{dom}A \ (\text{delete } x \ \Gamma)$   
 $\langle \text{proof} \rangle$

**lemma** *dom-map-of-conv-domA*:  
 $\text{dom} \ (\text{map-of } \Gamma) = \text{dom}A \ \Gamma$   
 $\langle \text{proof} \rangle$

**lemma** *domA-map-of-Some-the*:  
 $x \in \text{dom}A \ \Gamma \implies \text{map-of } \Gamma \ x = \text{Some } (\text{the } (\text{map-of } \Gamma \ x))$   
 $\langle \text{proof} \rangle$

**lemma** *domA-clearjunk[simp]*:  $\text{dom}A \ (\text{clearjunk } \Gamma) = \text{dom}A \ \Gamma$   
 $\langle \text{proof} \rangle$

**lemma** *the-map-option-domA[simp]*:  $x \in \text{dom}A \ \Gamma \implies \text{the } (\text{map-option } f \ (\text{map-of } \Gamma \ x)) = f$   
 $(\text{the } (\text{map-of } \Gamma \ x))$   
 $\langle \text{proof} \rangle$

**lemma** *map-of-domAD*:  $\text{map-of } \Gamma \ x = \text{Some } e \implies x \in \text{dom}A \ \Gamma$   
 $\langle \text{proof} \rangle$

**lemma** *restrictA-noop*:  $\text{dom}A \ \Gamma \subseteq S \implies \text{restrict}A \ S \ \Gamma = \Gamma$   
 $\langle \text{proof} \rangle$

**lemma** *restrictA-cong*:  
 $(\bigwedge x. x \in \text{dom}A \ m1 \implies x \in V \longleftrightarrow x \in V') \implies m1 = m2 \implies \text{restrict}A \ V \ m1 = \text{restrict}A$   
 $V' \ m2$   
 $\langle \text{proof} \rangle$

## 2.2.2 Other lemmas about associative lists

**lemma** *delete-set-none*:  $(\text{map-of } l)(x := \text{None}) = \text{map-of } (\text{delete } x \ l)$   
 ⟨proof⟩

**lemma** *list-size-delete[simp]*:  $\text{size-list } \text{size } (\text{delete } x \ l) < \text{Suc } (\text{size-list } \text{size } l)$   
 ⟨proof⟩

**lemma** *delete-append[simp]*:  $\text{delete } x \ (l1 \ @ \ l2) = \text{delete } x \ l1 \ @ \ \text{delete } x \ l2$   
 ⟨proof⟩

**lemma** *map-of-delete-insert*:  
**assumes**  $\text{map-of } \Gamma \ x = \text{Some } e$   
**shows**  $\text{map-of } ((x,e) \ # \ \text{delete } x \ \Gamma) = \text{map-of } \Gamma$   
 ⟨proof⟩

**lemma** *map-of-delete-iff[simp]*:  $\text{map-of } (\text{delete } x \ \Gamma) \ xa = \text{Some } e \iff (\text{map-of } \Gamma \ xa = \text{Some } e) \wedge xa \neq x$   
 ⟨proof⟩

**lemma** *map-add-domA[simp]*:  
 $x \in \text{domA } \Gamma \implies (\text{map-of } \Delta \ ++ \ \text{map-of } \Gamma) \ x = \text{map-of } \Gamma \ x$   
 $x \notin \text{domA } \Gamma \implies (\text{map-of } \Delta \ ++ \ \text{map-of } \Gamma) \ x = \text{map-of } \Delta \ x$   
 ⟨proof⟩

**lemma** *set-delete-subset*:  $\text{set } (\text{delete } k \ al) \subseteq \text{set } al$   
 ⟨proof⟩

**lemma** *dom-delete-subset*:  $\text{snd } \text{' set } (\text{delete } k \ al) \subseteq \text{snd } \text{' set } al$   
 ⟨proof⟩

**lemma** *map-ran-cong[fundef-cong]*:  
 $\llbracket \bigwedge x . x \in \text{set } m1 \implies f1 \ (fst \ x) \ (snd \ x) = f2 \ (fst \ x) \ (snd \ x) ; m1 = m2 \rrbracket$   
 $\implies \text{map-ran } f1 \ m1 = \text{map-ran } f2 \ m2$   
 ⟨proof⟩

**lemma** *domA-map-ran[simp]*:  $\text{domA } (\text{map-ran } f \ m) = \text{domA } m$   
 ⟨proof⟩

**lemma** *map-ran-delete*:  
 $\text{map-ran } f \ (\text{delete } x \ \Gamma) = \text{delete } x \ (\text{map-ran } f \ \Gamma)$   
 ⟨proof⟩

**lemma** *map-ran-restrictA*:  
 $\text{map-ran } f \ (\text{restrictA } V \ \Gamma) = \text{restrictA } V \ (\text{map-ran } f \ \Gamma)$   
 ⟨proof⟩

**lemma** *map-ran-append*:  
 $\text{map-ran } f \ (\Gamma @ \Delta) = \text{map-ran } f \ \Gamma \ @ \ \text{map-ran } f \ \Delta$

*<proof>*

### 2.2.3 Syntax for map comprehensions

**definition**  $mapCollect :: ('a \Rightarrow 'b \Rightarrow 'c) \Rightarrow ('a \rightarrow 'b) \Rightarrow 'c \text{ set}$   
where  $mapCollect f m = \{f k v \mid k v . m k = Some v\}$

**syntax**

- $MapCollect :: 'c \Rightarrow ptttrn \Rightarrow ptttrn \Rightarrow 'a \rightarrow 'b \Rightarrow 'c \text{ set}$  ( $\langle (1\{- \mid /- / \mapsto /- / \in /- / \}) \rangle$ )

**syntax-consts**

- $MapCollect == mapCollect$

**translations**

$\{e \mid k \mapsto v \in m\} == CONST mapCollect (\lambda k v . e) m$

**lemma**  $mapCollect\text{-}empty[simp]: \{f k v \mid k \mapsto v \in Map.empty\} = \{\}$

*<proof>*

**lemma**  $mapCollect\text{-}const[simp]:$

$m \neq Map.empty \Longrightarrow \{e \mid k \mapsto v \in m\} = \{e\}$

*<proof>*

**lemma**  $mapCollect\text{-}cong[fundef\text{-}cong]:$

$(\bigwedge k v . m1 k = Some v \Longrightarrow f1 k v = f2 k v) \Longrightarrow m1 = m2 \Longrightarrow mapCollect f1 m1 = mapCollect f2 m2$

*<proof>*

**lemma**  $mapCollectE[elim!]:$

**assumes**  $x \in \{f k v \mid k \mapsto v \in m\}$

**obtains**  $k v$  **where**  $m k = Some v$  **and**  $x = f k v$

*<proof>*

**lemma**  $mapCollectI[intro]:$

**assumes**  $m k = Some v$

**shows**  $f k v \in \{f k v \mid k \mapsto v \in m\}$

*<proof>*

**lemma**  $ball\text{-}mapCollect[simp]:$

$(\forall x \in \{f k v \mid k \mapsto v \in m\} . P x) \longleftrightarrow (\forall k v . m k = Some v \longrightarrow P (f k v))$

*<proof>*

**lemma**  $image\text{-}mapCollect[simp]:$

$g \ ` \ \{f k v \mid k \mapsto v \in m\} = \{g (f k v) \mid k \mapsto v \in m\}$

*<proof>*

**lemma**  $mapCollect\text{-}map\text{-}upd[simp]:$

$mapCollect f (m(k \mapsto v)) = insert (f k v) (mapCollect f (m(k := None)))$

*<proof>*

**definition** *mapCollectFilter* :: ('a ⇒ 'b ⇒ (bool × 'c)) ⇒ ('a → 'b) ⇒ 'c set  
**where** *mapCollectFilter* f m = {snd (f k v) | k v . m k = Some v ∧ fst (f k v)}

**syntax**

-*MapCollectFilter* :: 'c ⇒ pptrn ⇒ pptrn ⇒ ('a → 'b) ⇒ bool ⇒ 'c set (⟨(1{- |/-/↦/-/∈/-/. /-})⟩)

**syntax-consts**

-*MapCollectFilter* == *mapCollectFilter*

**translations**

{e | k↦v ∈ m . P } == *CONST* *mapCollectFilter* (λk v. (P,e)) m

**lemma** *mapCollectFilter-const-False[simp]*:

{e | k↦v ∈ m . False } = {}

⟨*proof*⟩

**lemma** *mapCollectFilter-const-True[simp]*:

{e | k↦v ∈ m . True } = {e | k↦v ∈ m}

⟨*proof*⟩

**end**

## 2.3 Mono-Nat-Fun

**theory** *Mono-Nat-Fun*

**imports** *HOL-Library.Infinite-Set*

**begin**

The following lemma proves that a monotonous function from and to the natural numbers is either eventually constant or unbounded.

**lemma** *nat-mono-characterization*:

**fixes** f :: nat ⇒ nat

**assumes** *mono* f

**obtains** n **where**  $\bigwedge m . n \leq m \implies f n = f m \mid \bigwedge m . \exists n . m \leq f n$

⟨*proof*⟩

**end**

## 2.4 Nominal-Utills

**theory** *Nominal-Utills*

**imports** *Nominal2.Nominal2* *HOL-Library.AList*

**begin**

## 2.4.1 Lemmas helping with equivariance proofs

**lemma** *perm-rel-lemma*:

**assumes**  $\bigwedge \pi x y. r (\pi \cdot x) (\pi \cdot y) \implies r x y$   
**shows**  $r (\pi \cdot x) (\pi \cdot y) \longleftrightarrow r x y$  (**is** ?l  $\longleftrightarrow$  ?r)  
 <proof>

**lemma** *perm-rel-lemma2*:

**assumes**  $\bigwedge \pi x y. r x y \implies r (\pi \cdot x) (\pi \cdot y)$   
**shows**  $r x y \longleftrightarrow r (\pi \cdot x) (\pi \cdot y)$  (**is** ?l  $\longleftrightarrow$  ?r)  
 <proof>

**lemma** *fun-eqvI*:

**assumes** *f-eqv*[*eqvt*]:  $(\bigwedge p x. p \cdot (f x) = f (p \cdot x))$   
**shows**  $p \cdot f = f$  <proof>

**lemma** *eqvt-at-apply*:

**assumes** *eqvt-at*  $f x$   
**shows**  $(p \cdot f) x = f x$   
 <proof>

**lemma** *eqvt-at-apply'*:

**assumes** *eqvt-at*  $f x$   
**shows**  $p \cdot f x = f (p \cdot x)$   
 <proof>

**lemma** *eqvt-at-apply''*:

**assumes** *eqvt-at*  $f x$   
**shows**  $(p \cdot f) (p \cdot x) = f (p \cdot x)$   
 <proof>

**lemma** *size-list-eqv*[*eqvt*]:  $p \cdot \text{size-list } f x = \text{size-list } (p \cdot f) (p \cdot x)$

<proof>

## 2.4.2 Freshness via equivariance

**lemma** *eqvt-fresh-cong1*:  $(\bigwedge p x. p \cdot (f x) = f (p \cdot x)) \implies a \# x \implies a \# f x$

<proof>

**lemma** *eqvt-fresh-cong2*:

**assumes** *eqvt*:  $(\bigwedge p x y. p \cdot (f x y) = f (p \cdot x) (p \cdot y))$   
**and** *fresh1*:  $a \# x$  **and** *fresh2*:  $a \# y$   
**shows**  $a \# f x y$

<proof>

**lemma** *eqvt-fresh-star-cong1*:

**assumes** *eqvt*:  $(\bigwedge p x. p \cdot (f x) = f (p \cdot x))$   
**and** *fresh1*:  $a \#* x$   
**shows**  $a \#* f x$

*<proof>*

**lemma** *eqvt-fresh-star-cong2*:

**assumes** *eqvt*:  $(\bigwedge p x y. p \cdot (f x y) = f (p \cdot x) (p \cdot y))$

**and** *fresh1*:  $a \#^* x$  **and** *fresh2*:  $a \#^* y$

**shows**  $a \#^* f x y$

*<proof>*

**lemma** *eqvt-fresh-cong3*:

**assumes** *eqvt*:  $(\bigwedge p x y z. p \cdot (f x y z) = f (p \cdot x) (p \cdot y) (p \cdot z))$

**and** *fresh1*:  $a \# x$  **and** *fresh2*:  $a \# y$  **and** *fresh3*:  $a \# z$

**shows**  $a \# f x y z$

*<proof>*

**lemma** *eqvt-fresh-star-cong3*:

**assumes** *eqvt*:  $(\bigwedge p x y z. p \cdot (f x y z) = f (p \cdot x) (p \cdot y) (p \cdot z))$

**and** *fresh1*:  $a \#^* x$  **and** *fresh2*:  $a \#^* y$  **and** *fresh3*:  $a \#^* z$

**shows**  $a \#^* f x y z$

*<proof>*

### 2.4.3 Additional simplification rules

**lemma** *not-self-fresh[simp]*:  $\text{atom } x \# x \longleftrightarrow \text{False}$

*<proof>*

**lemma** *fresh-star-singleton*:  $\{x\} \#^* e \longleftrightarrow x \# e$

*<proof>*

### 2.4.4 Additional equivariance lemmas

**lemma** *eqvt-cases*:

**fixes**  $f x \pi$

**assumes** *eqvt*:  $\bigwedge x. \pi \cdot f x = f (\pi \cdot x)$

**obtains**  $f x f (\pi \cdot x) \mid \neg f x \quad \neg f (\pi \cdot x)$

*<proof>*

**lemma** *range-eqvt*:  $\pi \cdot \text{range } Y = \text{range } (\pi \cdot Y)$

*<proof>*

**lemma** *case-option-eqvt[eqvt]*:

$\pi \cdot \text{case-option } d f x = \text{case-option } (\pi \cdot d) (\pi \cdot f) (\pi \cdot x)$

*<proof>*

**lemma** *supp-option-eqvt*:

$\text{supp } (\text{case-option } d f x) \subseteq \text{supp } d \cup \text{supp } f \cup \text{supp } x$

*<proof>*

**lemma** *funpow-eqvt[simp,eqvt]*:

$\pi \cdot ((f :: 'a \Rightarrow 'a::pt) \overset{\sim}{\sim} n) = (\pi \cdot f) \overset{\sim}{\sim} (\pi \cdot n)$

*<proof>*

**lemma** *delete-eqvt*[eqvt]:

$$\pi \cdot AList.delete\ x\ \Gamma = AList.delete\ (\pi \cdot x)\ (\pi \cdot \Gamma)$$

*<proof>*

**lemma** *restrict-eqvt*[eqvt]:

$$\pi \cdot AList.restrict\ S\ \Gamma = AList.restrict\ (\pi \cdot S)\ (\pi \cdot \Gamma)$$

*<proof>*

**lemma** *supp-restrict*:

$$supp\ (AList.restrict\ S\ \Gamma) \subseteq supp\ \Gamma$$

*<proof>*

**lemma** *clearjunk-eqvt*[eqvt]:

$$\pi \cdot AList.clearjunk\ \Gamma = AList.clearjunk\ (\pi \cdot \Gamma)$$

*<proof>*

**lemma** *map-ran-eqvt*[eqvt]:

$$\pi \cdot map-ran\ f\ \Gamma = map-ran\ (\pi \cdot f)\ (\pi \cdot \Gamma)$$

*<proof>*

**lemma** *dom-perm*:

$$dom\ (\pi \cdot f) = \pi \cdot (dom\ f)$$

*<proof>*

**lemmas** *dom-perm-rev*[simp,eqvt] = *dom-perm*[symmetric]

**lemma** *ran-perm*[simp]:

$$\pi \cdot (ran\ f) = ran\ (\pi \cdot f)$$

*<proof>*

**lemma** *map-add-eqvt*[eqvt]:

$$\pi \cdot (m1\ ++\ m2) = (\pi \cdot m1)\ ++\ (\pi \cdot m2)$$

*<proof>*

**lemma** *map-of-eqvt*[eqvt]:

$$\pi \cdot map-of\ l = map-of\ (\pi \cdot l)$$

*<proof>*

**lemma** *concat-eqvt*[eqvt]:  $\pi \cdot concat\ l = concat\ (\pi \cdot l)$

*<proof>*

**lemma** *tranclp-eqvt*[eqvt]:  $\pi \cdot tranclp\ P\ v_1\ v_2 = tranclp\ (\pi \cdot P)\ (\pi \cdot v_1)\ (\pi \cdot v_2)$

*<proof>*

**lemma** *rtranclp-eqvt*[eqvt]:  $\pi \cdot rtranclp\ P\ v_1\ v_2 = rtranclp\ (\pi \cdot P)\ (\pi \cdot v_1)\ (\pi \cdot v_2)$

*<proof>*

**lemma** *Set-filter-eqvt*[eqvt]:  $\pi \cdot Set.filter\ P\ S = Set.filter\ (\pi \cdot P)\ (\pi \cdot S)$

*<proof>*

**lemma** *Sigma-eqvt'*[*eqvt*]:  $\pi \cdot \text{Sigma} = \text{Sigma}$

*<proof>*

**lemma** *override-on-eqvt*[*eqvt*]:

$\pi \cdot (\text{override-on } m1 \ m2 \ S) = \text{override-on } (\pi \cdot m1) \ (\pi \cdot m2) \ (\pi \cdot S)$

*<proof>*

**lemma** *card-eqvt*[*eqvt*]:

$\pi \cdot (\text{card } S) = \text{card } (\pi \cdot S)$

*<proof>*

**lemma** *Projl-permute*:

**assumes**  $a: \exists y. f = \text{Inl } y$

**shows**  $(p \cdot (\text{Sum-Type.proj1 } f)) = \text{Sum-Type.proj1 } (p \cdot f)$

*<proof>*

**lemma** *Projr-permute*:

**assumes**  $a: \exists y. f = \text{Inr } y$

**shows**  $(p \cdot (\text{Sum-Type.proj2 } f)) = \text{Sum-Type.proj2 } (p \cdot f)$

*<proof>*

## 2.4.5 Freshness lemmas

**lemma** *fresh-list-elem*:

**assumes**  $a \# \Gamma$

**and**  $e \in \text{set } \Gamma$

**shows**  $a \# e$

*<proof>*

**lemma** *set-not-fresh*:

$x \in \text{set } L \implies \neg(\text{atom } x \# L)$

*<proof>*

**lemma** *pure-fresh-star*[*simp*]:  $a \#* (x :: 'a :: \text{pure})$

*<proof>*

**lemma** *supp-set-mem*:  $x \in \text{set } L \implies \text{supp } x \subseteq \text{supp } L$

*<proof>*

**lemma** *set-supp-mono*:  $\text{set } L \subseteq \text{set } L2 \implies \text{supp } L \subseteq \text{supp } L2$

*<proof>*

**lemma** *fresh-star-at-base*:

**fixes**  $x :: 'a :: \text{at-base}$

**shows**  $S \#* x \iff \text{atom } x \notin S$

*<proof>*

#### 2.4.6 Freshness and support for subsets of variables

**lemma** *supp-mono*:  $finite (B :: 'a::fs\ set) \implies A \subseteq B \implies supp\ A \subseteq supp\ B$   
*<proof>*

**lemma** *fresh-subset*:  
 $finite\ B \implies x \# (B :: 'a::at-base\ set) \implies A \subseteq B \implies x \# A$   
*<proof>*

**lemma** *fresh-star-subset*:  
 $finite\ B \implies x \#* (B :: 'a::at-base\ set) \implies A \subseteq B \implies x \#* A$   
*<proof>*

**lemma** *fresh-star-set-subset*:  
 $x \#* (B :: 'a::at-base\ list) \implies set\ A \subseteq set\ B \implies x \#* A$   
*<proof>*

#### 2.4.7 The set of free variables of an expression

**definition** *fv* ::  $'a::pt \Rightarrow 'b::at-base\ set$   
**where**  $fv\ e = \{v.\ atom\ v \in supp\ e\}$

**lemma** *fv-eqt[simp,eqt]*:  $\pi \cdot (fv\ e) = fv\ (\pi \cdot e)$   
*<proof>*

**lemma** *fv-Nil[simp]*:  $fv\ [] = \{\}$   
*<proof>*

**lemma** *fv-Cons[simp]*:  $fv\ (x \# xs) = fv\ x \cup fv\ xs$   
*<proof>*

**lemma** *fv-Pair[simp]*:  $fv\ (x, y) = fv\ x \cup fv\ y$   
*<proof>*

**lemma** *fv-append[simp]*:  $fv\ (x @ y) = fv\ x \cup fv\ y$   
*<proof>*

**lemma** *fv-at-base[simp]*:  $fv\ a = \{a::'a::at-base\}$   
*<proof>*

**lemma** *fv-pure[simp]*:  $fv\ (a::'a::pure) = \{\}$   
*<proof>*

**lemma** *fv-set-at-base[simp]*:  $fv\ (l :: ('a :: at-base)\ list) = set\ l$   
*<proof>*

**lemma** *flip-not-fv*:  $a \notin fv\ x \implies b \notin fv\ x \implies (a \leftrightarrow b) \cdot x = x$   
*<proof>*

**lemma** *fv-not-fresh*:  $atom\ x \# e \longleftrightarrow x \notin fv\ e$   
*<proof>*

**lemma** *fresh-fv*:  $\text{finite } (fv\ e :: 'a\ \text{set}) \implies \text{atom } (x :: ('a::\text{at-base})) \# (fv\ e :: 'a\ \text{set}) \longleftrightarrow \text{atom } x \# e$   
 <proof>

**lemma** *finite-fv[simp]*:  $\text{finite } (fv\ (e::'a::fs) :: ('b::\text{at-base})\ \text{set})$   
 <proof>

**definition** *fv-list* ::  $'a::fs \Rightarrow 'b::\text{at-base}\ \text{list}$   
 where *fv-list*  $e = (\text{SOME } l.\ \text{set } l = fv\ e)$

**lemma** *set-fv-list[simp]*:  $\text{set } (fv\text{-list } e) = (fv\ e :: ('b::\text{at-base})\ \text{set})$   
 <proof>

**lemma** *fresh-fv-list[simp]*:  
 $a \# (fv\text{-list } e :: 'b::\text{at-base}\ \text{list}) \longleftrightarrow a \# (fv\ e :: 'b::\text{at-base}\ \text{set})$   
 <proof>

### 2.4.8 Other useful lemmas

**lemma** *pure-permute-id*:  $\text{permute } p = (\lambda\ x.\ (x::'a::\text{pure}))$   
 <proof>

**lemma** *supp-set-elem-finite*:  
 assumes *finite*  $S$   
 and  $(m::'a::fs) \in S$   
 and  $y \in \text{supp } m$   
 shows  $y \in \text{supp } S$   
 <proof>

**lemmas** *fresh-star-Cons* = *fresh-star-list*(2)

**lemma** *mem-permute-set*:  
 shows  $x \in p \cdot S \longleftrightarrow (-\ p \cdot x) \in S$   
 <proof>

**lemma** *flip-set-both-not-in*:  
 assumes  $x \notin S$  and  $x' \notin S$   
 shows  $((x' \leftrightarrow x) \cdot S) = S$   
 <proof>

**lemma** *inj-atom*: *inj atom* <proof>

**lemmas** *image-Int*[*OF inj-atom, simp*]

**lemma** *eqvt-uncurry*:  $\text{eqvt } f \implies \text{eqvt } (\text{case-prod } f)$   
 <proof>

**lemma** *supp-fun-app-eqvt2*:  
 assumes  $a: \text{eqvt } f$

**shows**  $\text{supp } (f x y) \subseteq \text{supp } x \cup \text{supp } y$   
*<proof>*

**lemma** *supp-fun-app-eqv3*:  
**assumes**  $a: \text{eqvt } f$   
**shows**  $\text{supp } (f x y z) \subseteq \text{supp } x \cup \text{supp } y \cup \text{supp } z$   
*<proof>*

**lemma** *permute-0[simp]*:  $\text{permute } 0 = (\lambda x. x)$   
*<proof>*

**lemma** *permute-comp[simp]*:  $\text{permute } x \circ \text{permute } y = \text{permute } (x + y)$  *<proof>*

**lemma** *map-permute*:  $\text{map } (\text{permute } p) = \text{permute } p$   
*<proof>*

**lemma** *fresh-star-restrictA[intro]*:  $a \# \Gamma \implies a \# \text{AList.restrict } V \Gamma$   
*<proof>*

**lemma** *Abs-lst-Nil-eq[simp]*:  $[\ ] \text{lst. } (x::'a::fs) = [xs] \text{lst. } x' \longleftrightarrow (([\ ], x) = (xs, x'))$   
*<proof>*

**lemma** *Abs-lst-Nil-eq2[simp]*:  $[xs] \text{lst. } (x::'a::fs) = [\ ] \text{lst. } x' \longleftrightarrow ((xs, x) = ([\ ], x'))$   
*<proof>*

**end**

## 2.5 AList-Utills-Nominal

**theory** *AList-Utills-Nominal*  
**imports** *AList-Utills Nominal-Utills*  
**begin**

### 2.5.1 Freshness lemmas related to associative lists

**lemma** *domA-not-fresh*:  
 $x \in \text{domA } \Gamma \implies \neg(\text{atom } x \# \Gamma)$   
*<proof>*

**lemma** *fresh-delete*:  
**assumes**  $a \# \Gamma$   
**shows**  $a \# \text{delete } v \Gamma$   
*<proof>*

**lemma** *fresh-star-delete*:

**assumes**  $S \#* \Gamma$

**shows**  $S \#* \text{delete } v \Gamma$

*<proof>*

**lemma** *fv-delete-subset*:

$fv (\text{delete } v \Gamma) \subseteq fv \Gamma$

*<proof>*

**lemma** *fresh-heap-expr*:

**assumes**  $a \# \Gamma$

**and**  $(x,e) \in \text{set } \Gamma$

**shows**  $a \# e$

*<proof>*

**lemma** *fresh-heap-expr'*:

**assumes**  $a \# \Gamma$

**and**  $e \in \text{snd } \Gamma \text{ set } \Gamma$

**shows**  $a \# e$

*<proof>*

**lemma** *fresh-star-heap-expr'*:

**assumes**  $S \#* \Gamma$

**and**  $e \in \text{snd } \Gamma \text{ set } \Gamma$

**shows**  $S \#* e$

*<proof>*

**lemma** *fresh-map-of*:

**assumes**  $x \in \text{dom } A \Gamma$

**assumes**  $a \# \Gamma$

**shows**  $a \# \text{the } (\text{map-of } \Gamma x)$

*<proof>*

**lemma** *fresh-star-map-of*:

**assumes**  $x \in \text{dom } A \Gamma$

**assumes**  $a \#* \Gamma$

**shows**  $a \#* \text{the } (\text{map-of } \Gamma x)$

*<proof>*

**lemma** *domA-fv-subset*:  $\text{dom } A \Gamma \subseteq fv \Gamma$

*<proof>*

**lemma** *map-of-fv-subset*:  $x \in \text{dom } A \Gamma \implies fv (\text{the } (\text{map-of } \Gamma x)) \subseteq fv \Gamma$

*<proof>*

**lemma** *map-of-Some-fv-subset*:  $\text{map-of } \Gamma x = \text{Some } e \implies fv e \subseteq fv \Gamma$

*<proof>*

## 2.5.2 Equivariance lemmas

**lemma** *domA[eqvt]*:  
  $\pi \cdot \text{domA } \Gamma = \text{domA } (\pi \cdot \Gamma)$   
 *<proof>*

**lemma** *mapCollect[eqvt]*:  
  $\pi \cdot \text{mapCollect } f \ m = \text{mapCollect } (\pi \cdot f) (\pi \cdot m)$   
 *<proof>*

## 2.5.3 Freshness and distinctness

**lemma** *fresh-distinct*:  
 **assumes** *atom* '  $S \#* \Gamma$   
 **shows**  $S \cap \text{domA } \Gamma = \{\}$   
 *<proof>*

**lemma** *fresh-distinct-list*:  
 **assumes** *atom* '  $S \#* l$   
 **shows**  $S \cap \text{set } l = \{\}$   
 *<proof>*

**lemma** *fresh-distinct-fv*:  
 **assumes** *atom* '  $S \#* l$   
 **shows**  $S \cap \text{fv } l = \{\}$   
 *<proof>*

## 2.5.4 Pure codomains

**lemma** *domA-fv-pure*:  
 **fixes**  $\Gamma :: ('a::\text{at-base} \times 'b::\text{pure}) \text{ list}$   
 **shows**  $\text{fv } \Gamma = \text{domA } \Gamma$   
 *<proof>*

**lemma** *domA-fresh-pure*:  
 **fixes**  $\Gamma :: ('a::\text{at-base} \times 'b::\text{pure}) \text{ list}$   
 **shows**  $x \in \text{domA } \Gamma \longleftrightarrow \neg(\text{atom } x \# \Gamma)$   
 *<proof>*

**end**

## 2.6 HOLCF-Utills

**theory** *HOLCF-Utills*  
 **imports** *HOLCF Pointwise*  
 **begin**

**default-sort** *type*

**lemmas** *cont-fun[simp]*

**lemmas** *cont2cont-fun*[*simp*]

**lemma** *cont-compose2*:

**assumes**  $\bigwedge y. \text{cont } (\lambda x. c \ x \ y)$   
**assumes**  $\bigwedge x. \text{cont } (\lambda y. c \ x \ y)$   
**assumes** *cont f*  
**assumes** *cont g*  
**shows** *cont*  $(\lambda x. c \ (f \ x) \ (g \ x))$   
*<proof>*

**lemma** *pointwise-adm*:

**fixes**  $P :: 'a::\text{pcpo} \Rightarrow 'b::\text{pcpo} \Rightarrow \text{bool}$   
**assumes** *adm*  $(\lambda x. P \ (fst \ x) \ (snd \ x))$   
**shows** *adm*  $(\lambda m. \text{pointwise } P \ (fst \ m) \ (snd \ m))$   
*<proof>*

**lemma** *cfun-beta-Pair*:

**assumes** *cont*  $(\lambda p. f \ (fst \ p) \ (snd \ p))$   
**shows** *csplit*. $(\Lambda a \ b. f \ a \ b) \cdot (x, y) = f \ x \ y$   
*<proof>*

**lemma** *fun-upd-mono*:

$\varrho1 \sqsubseteq \varrho2 \implies v1 \sqsubseteq v2 \implies \varrho1(x := v1) \sqsubseteq \varrho2(x := v2)$   
*<proof>*

**lemma** *fun-upd-cont*[*simp, cont2cont*]:

**assumes** *cont f* **and** *cont h*  
**shows** *cont*  $(\lambda x. (f \ x)(v := h \ x)) :: 'a \Rightarrow 'b::\text{pcpo}$   
*<proof>*

**lemma** *fun-upd-belowI*:

**assumes**  $\bigwedge z. z \neq x \implies \varrho \ z \sqsubseteq \varrho' \ z$   
**assumes**  $y \sqsubseteq \varrho' \ x$   
**shows**  $\varrho(x := y) \sqsubseteq \varrho'$   
*<proof>*

**lemma** *cont-if-else-above*:

**assumes** *cont f*  
**assumes** *cont g*  
**assumes**  $\bigwedge x. f \ x \sqsubseteq g \ x$   
**assumes**  $\bigwedge x \ y. x \sqsubseteq y \implies P \ y \implies P \ x$   
**assumes** *adm P*  
**shows** *cont*  $(\lambda x. \text{if } P \ x \ \text{then } f \ x \ \text{else } g \ x)$  (**is cont ?I**)  
*<proof>*

**fun** *up2option* ::  $'a::\text{cpo}_\perp \Rightarrow 'a \ \text{option}$

**where** *up2option* *Ibottom* = *None*

|  $up2option (Iup a) = Some a$

**lemma** *up2option-simps*[simp]:  
 $up2option \perp = None$   
 $up2option (up \cdot x) = Some x$   
 $\langle proof \rangle$

**fun** *option2up* :: 'a option  $\Rightarrow$  'a::cpo $\perp$   
**where** *option2up* None =  $\perp$   
|  $option2up (Some a) = up \cdot a$

**lemma** *option2up-up2option*[simp]:  
 $option2up (up2option x) = x$   
 $\langle proof \rangle$

**lemma** *up2option-option2up*[simp]:  
 $up2option (option2up x) = x$   
 $\langle proof \rangle$

**lemma** *adm-subst2*:  $cont f \Longrightarrow cont g \Longrightarrow adm (\lambda x. f (fst x) = g (snd x))$   
 $\langle proof \rangle$

### 2.6.1 Composition of fun and cfun

**lemma** *cont2cont-comp* [simp, cont2cont]:  
**assumes** *cont f*  
**assumes**  $\bigwedge x. cont (f x)$   
**assumes** *cont g*  
**shows**  $cont (\lambda x. (f x) \circ (g x))$   
 $\langle proof \rangle$

**definition** *cfun-comp* :: ('a::pcpo  $\rightarrow$  'b::pcpo)  $\rightarrow$  ('c::type  $\Rightarrow$  'a)  $\rightarrow$  ('c::type  $\Rightarrow$  'b)  
**where** *cfun-comp* =  $(\Lambda f \varrho. (\lambda x. f \cdot x) \circ \varrho)$

**lemma** [simp]:  $cfun-comp \cdot f \cdot (\varrho(x := v)) = (cfun-comp \cdot f \cdot \varrho)(x := f \cdot v)$   
 $\langle proof \rangle$

**lemma** *cfun-comp-app*[simp]:  $(cfun-comp \cdot f \cdot \varrho) x = f \cdot (\varrho x)$   
 $\langle proof \rangle$

**lemma** *fix-eq-fix*:  
 $f \cdot (fix \cdot g) \sqsubseteq fix \cdot g \Longrightarrow g \cdot (fix \cdot f) \sqsubseteq fix \cdot f \Longrightarrow fix \cdot f = fix \cdot g$   
 $\langle proof \rangle$

### 2.6.2 Additional transitivity rules

These collect side-conditions of the form *cont f*, so the usual way to discharge them is to write *by this (intro cont2cont)+* at the end.

**lemma** *below-trans-cong*[trans]:

$a \sqsubseteq f x \implies x \sqsubseteq y \implies \text{cont } f \implies a \sqsubseteq f y$   
 $\langle \text{proof} \rangle$

**lemma** *not-bot-below-trans*[*trans*]:

$a \neq \perp \implies a \sqsubseteq b \implies b \neq \perp$   
 $\langle \text{proof} \rangle$

**lemma** *not-bot-below-trans-cong*[*trans*]:

$f a \neq \perp \implies a \sqsubseteq b \implies \text{cont } f \implies f b \neq \perp$   
 $\langle \text{proof} \rangle$

**end**

## 2.7 HOLCF-Meet

**theory** *HOLCF-Meet*

**imports** *HOLCF*

**begin**

This theory defines the  $\sqcap$  operator on HOLCF domains, and introduces a type class for domains where all finite meets exist.

### 2.7.1 Towards meets: Lower bounds

**context** *po*

**begin**

**definition** *is-lb* :: 'a set  $\Rightarrow$  'a  $\Rightarrow$  bool (**infix**  $\langle \rangle \rangle$  55) **where**

$S \rangle | x \longleftrightarrow (\forall y \in S. x \sqsubseteq y)$

**lemma** *is-lbI*:  $(\forall x. x \in S \implies l \sqsubseteq x) \implies S \rangle | l$

$\langle \text{proof} \rangle$

**lemma** *is-lbD*:  $[S \rangle | l; x \in S] \implies l \sqsubseteq x$

$\langle \text{proof} \rangle$

**lemma** *is-lb-empty* [*simp*]:  $\{\} \rangle | l$

$\langle \text{proof} \rangle$

**lemma** *is-lb-insert* [*simp*]:  $(\text{insert } x A) \rangle | y = (y \sqsubseteq x \wedge A \rangle | y)$

$\langle \text{proof} \rangle$

**lemma** *is-lb-downward*:  $[S \rangle | l; y \sqsubseteq l] \implies S \rangle | y$

$\langle \text{proof} \rangle$

### 2.7.2 Greatest lower bounds

**definition** *is-glb* :: 'a set  $\Rightarrow$  'a  $\Rightarrow$  bool (**infix**  $\langle \rangle \rangle$  55) **where**

$S \rangle \rangle | x \longleftrightarrow S \rangle | x \wedge (\forall u. S \rangle | u \longrightarrow u \sqsubseteq x)$

**definition**  $glb :: 'a \text{ set} \Rightarrow 'a$  ( $\langle \sqcap \rangle \rightarrow [60]60$ ) **where**  
 $glb S = (THE x. S \gg| x)$

Access to the definition as inference rule

**lemma** *is-glbD1*:  $S \gg| x \implies S \gg| x$   
 $\langle proof \rangle$

**lemma** *is-glbD2*:  $[|S \gg| x; S \gg| u|] \implies u \sqsubseteq x$   
 $\langle proof \rangle$

**lemma** (*in po*) *is-glbI*:  $[|S \gg| x; \forall u. S \gg| u \implies u \sqsubseteq x|] \implies S \gg| x$   
 $\langle proof \rangle$

**lemma** *is-glb-above-iff*:  $S \gg| x \implies u \sqsubseteq x \longleftrightarrow S \gg| u$   
 $\langle proof \rangle$

glbs are unique

**lemma** *is-glb-unique*:  $[|S \gg| x; S \gg| y|] \implies x = y$   
 $\langle proof \rangle$

technical lemmas about *glb* and ( $\gg|$ )

**lemma** *is-glb-glb*:  $M \gg| x \implies M \gg| glb M$   
 $\langle proof \rangle$

**lemma** *glb-eqI*:  $M \gg| l \implies glb M = l$   
 $\langle proof \rangle$

**lemma** *is-glb-singleton*:  $\{x\} \gg| x$   
 $\langle proof \rangle$

**lemma** *glb-singleton [simp]*:  $glb \{x\} = x$   
 $\langle proof \rangle$

**lemma** *is-glb-bin*:  $x \sqsubseteq y \implies \{x, y\} \gg| x$   
 $\langle proof \rangle$

**lemma** *glb-bin*:  $x \sqsubseteq y \implies glb \{x, y\} = x$   
 $\langle proof \rangle$

**lemma** *is-glb-maximal*:  $[|S \gg| x; x \in S|] \implies S \gg| x$   
 $\langle proof \rangle$

**lemma** *glb-maximal*:  $[|S \gg| x; x \in S|] \implies glb S = x$   
 $\langle proof \rangle$

**lemma** *glb-above*:  $S \gg| z \implies x \sqsubseteq glb S \longleftrightarrow S \gg| x$   
 $\langle proof \rangle$

**end**

**lemma** (in *cpo*) *Meet-insert*:  $S \gg| l \implies \{x, l\} \gg| l2 \implies \text{insert } x S \gg| l2$   
*<proof>*

Binary, hence finite meets.

**class** *Finite-Meet-cpo* = *cpo* +  
**assumes** *binary-meet-exists*:  $\exists l. l \sqsubseteq x \wedge l \sqsubseteq y \wedge (\forall z. z \sqsubseteq x \longrightarrow z \sqsubseteq y \longrightarrow z \sqsubseteq l)$   
**begin**

**lemma** *binary-meet-exists'*:  $\exists l. \{x, y\} \gg| l$   
*<proof>*

**lemma** *finite-meet-exists*:

**assumes**  $S \neq \{\}$

**and** *finite*  $S$

**shows**  $\exists x. S \gg| x$

*<proof>*

**end**

**definition** *meet* ::  $'a::cpo \Rightarrow 'a \Rightarrow 'a$  (**infix**  $\langle \sqcap \rangle$  80) **where**  
 $x \sqcap y = (\text{if } \exists z. \{x, y\} \gg| z \text{ then } \text{glb } \{x, y\} \text{ else } x)$

**lemma** *meet-def'*:  $(x::'a::\text{Finite-Meet-cpo}) \sqcap y = \text{glb } \{x, y\}$   
*<proof>*

**lemma** *meet-comm*:  $(x::'a::\text{Finite-Meet-cpo}) \sqcap y = y \sqcap x$  *<proof>*

**lemma** *meet-bot1* [*simp*]:

**fixes**  $y :: 'a :: \{\text{Finite-Meet-cpo}, \text{pcpo}\}$

**shows**  $(\perp \sqcap y) = \perp$  *<proof>*

**lemma** *meet-bot2* [*simp*]:

**fixes**  $x :: 'a :: \{\text{Finite-Meet-cpo}, \text{pcpo}\}$

**shows**  $(x \sqcap \perp) = \perp$  *<proof>*

**lemma** *meet-below1* [*intro*]:

**fixes**  $x y :: 'a :: \text{Finite-Meet-cpo}$

**assumes**  $x \sqsubseteq z$

**shows**  $(x \sqcap y) \sqsubseteq z$  *<proof>*

**lemma** *meet-below2* [*intro*]:

**fixes**  $x y :: 'a :: \text{Finite-Meet-cpo}$

**assumes**  $y \sqsubseteq z$

**shows**  $(x \sqcap y) \sqsubseteq z$  *<proof>*

**lemma** *meet-above-iff*:

**fixes**  $x y z :: 'a :: \text{Finite-Meet-cpo}$

**shows**  $z \sqsubseteq x \sqcap y \longleftrightarrow z \sqsubseteq x \wedge z \sqsubseteq y$

*<proof>*

**lemma** *below-meet*[simp]:

**fixes**  $x y :: 'a :: \text{Finite-Meet-cpo}$

**assumes**  $x \sqsubseteq z$

**shows**  $(x \sqcap z) = x$  *<proof>*

**lemma** *below-meet2*[simp]:

**fixes**  $x y :: 'a :: \text{Finite-Meet-cpo}$

**assumes**  $z \sqsubseteq x$

**shows**  $(x \sqcap z) = z$  *<proof>*

**lemma** *meet-aboveI*:

**fixes**  $x y z :: 'a :: \text{Finite-Meet-cpo}$

**shows**  $z \sqsubseteq x \implies z \sqsubseteq y \implies z \sqsubseteq x \sqcap y$  *<proof>*

**lemma** *is-meetI*:

**fixes**  $x y z :: 'a :: \text{Finite-Meet-cpo}$

**assumes**  $z \sqsubseteq x$

**assumes**  $z \sqsubseteq y$

**assumes**  $\bigwedge a. [a \sqsubseteq x ; a \sqsubseteq y] \implies a \sqsubseteq z$

**shows**  $x \sqcap y = z$

*<proof>*

**lemma** *meet-assoc*[simp]:  $((x :: 'a :: \text{Finite-Meet-cpo}) \sqcap y) \sqcap z = x \sqcap (y \sqcap z)$

*<proof>*

**lemma** *meet-self*[simp]:  $r \sqcap r = (r :: 'a :: \text{Finite-Meet-cpo})$

*<proof>*

**lemma** [simp]:  $(r :: 'a :: \text{Finite-Meet-cpo}) \sqcap (r \sqcap x) = r \sqcap x$

*<proof>*

**lemma** *meet-monofun1*:

**fixes**  $y :: 'a :: \text{Finite-Meet-cpo}$

**shows** *monofun*  $(\lambda x. (x \sqcap y))$

*<proof>*

**lemma** *chain-meet1*:

**fixes**  $y :: 'a :: \text{Finite-Meet-cpo}$

**assumes** *chain*  $Y$

**shows** *chain*  $(\lambda i. Y i \sqcap y)$

*<proof>*

**class** *cont-binary-meet* = *Finite-Meet-cpo* +

**assumes** *meet-cont'*: *chain*  $Y \implies (\bigsqcap i. Y i) \sqcap y = (\bigsqcap i. Y i \sqcap y)$

**lemma** *meet-cont1*:

**fixes**  $y :: 'a :: \text{cont-binary-meet}$

**shows** *cont*  $(\lambda x. (x \sqcap y))$

*<proof>*

```

lemma meet-cont2:
  fixes  $x :: 'a :: \text{cont-binary-meet}$ 
  shows  $\text{cont } (\lambda y. (x \sqcap y)) \langle \text{proof} \rangle$ 

lemma meet-cont[cont2cont,simp]:  $\text{cont } f \implies \text{cont } g \implies \text{cont } (\lambda x. (f x \sqcap (g x :: 'a :: \text{cont-binary-meet})))$ 
   $\langle \text{proof} \rangle$ 

end

```

## 2.8 Nominal-HOLCF

```

theory Nominal-HOLCF
imports
  Nominal-Utils HOLCF-Utils
begin

```

### 2.8.1 Type class of continuous permutations and variations thereof

```

class cont-pt =
  cpo +
  pt +
  assumes perm-cont:  $\bigwedge p. \text{cont } ((\text{permute } p) :: 'a :: \{cpo, pt\} \Rightarrow 'a)$ 

class discr-pt =
  discrete-cpo +
  pt

class pcpo-pt =
  cont-pt +
  pcpo

instance pcpo-pt  $\subseteq$  cont-pt
   $\langle \text{proof} \rangle$ 

instance discr-pt  $\subseteq$  cont-pt
   $\langle \text{proof} \rangle$ 

lemma (in cont-pt) perm-cont-simp[simp]:  $\pi \cdot x \sqsubseteq \pi \cdot y \longleftrightarrow x \sqsubseteq y$ 
   $\langle \text{proof} \rangle$ 

lemma (in cont-pt) perm-below-to-right:  $\pi \cdot x \sqsubseteq y \longleftrightarrow x \sqsubseteq - \pi \cdot y$ 
   $\langle \text{proof} \rangle$ 

lemma perm-is-ub-simp[simp]:  $\pi \cdot S <| \pi \cdot (x :: 'a :: \text{cont-pt}) \longleftrightarrow S <| x$ 
   $\langle \text{proof} \rangle$ 

lemma perm-is-ub-eqvt[simp,eqvt]:  $S <| (x :: 'a :: \text{cont-pt}) \implies \pi \cdot S <| \pi \cdot x$ 
   $\langle \text{proof} \rangle$ 

```

**lemma** *perm-is-lub-simp*[simp]:  $\pi \cdot S \ll\mid \pi \cdot (x :: 'a :: cont-pt) \longleftrightarrow S \ll\mid x$   
 ⟨proof⟩

**lemma** *perm-is-lub-eqt*[simp,eqvt]:  $S \ll\mid (x :: 'a :: cont-pt) \implies \pi \cdot S \ll\mid \pi \cdot x$   
 ⟨proof⟩

**lemmas** *perm-cont2cont*[simp,cont2cont] = *cont-compose*[OF *perm-cont*]

**lemma** *perm-still-cont*:  $cont (\pi \cdot f) = cont (f :: ('a :: cont-pt) \Rightarrow ('b :: cont-pt))$   
 ⟨proof⟩

**lemma** *perm-bottom*[simp,eqvt]:  $\pi \cdot \perp = (\perp :: 'a :: \{cont-pt,pcpo\})$   
 ⟨proof⟩

**lemma** *bot-supp*[simp]:  $supp (\perp :: 'a :: pcpo-pt) = \{\}$   
 ⟨proof⟩

**lemma** *bot-fresh*[simp]:  $a \# (\perp :: 'a :: pcpo-pt)$   
 ⟨proof⟩

**lemma** *bot-fresh-star*[simp]:  $a \#* (\perp :: 'a :: pcpo-pt)$   
 ⟨proof⟩

**lemma** *below-eqt* [eqvt]:  
 $\pi \cdot (x \sqsubseteq y) = (\pi \cdot x \sqsubseteq \pi \cdot (y :: 'a :: cont-pt))$  ⟨proof⟩

**lemma** *lub-eqt*[simp]:  
 $(\exists z. S \ll\mid (z :: 'a :: \{cont-pt\})) \implies \pi \cdot lub S = lub (\pi \cdot S)$   
 ⟨proof⟩

**lemma** *chain-eqt*[eqvt]:  
**fixes**  $F :: nat \Rightarrow 'a :: cont-pt$   
**shows**  $chain F \implies chain (\pi \cdot F)$   
 ⟨proof⟩

## 2.8.2 Instance for *cfun*

**instantiation** *cfun* ::  $(cont-pt, cont-pt) pt$

**begin**

**definition**  $p \cdot (f :: 'a \rightarrow 'b) = (\Lambda x. p \cdot (f \cdot (- p \cdot x)))$

**instance**

⟨proof⟩

**end**

**lemma** *permute-cfun-eq*:  $permute p = (\lambda f. (Abs-cfun (permute p)) oo f oo (Abs-cfun (permute (-p))))$   
 ⟨proof⟩

**lemma** *Cfun-app-eqv*[*eqvt*]:  
 $\pi \cdot (f \cdot x) = (\pi \cdot f) \cdot (\pi \cdot x)$   
 ⟨*proof*⟩

**lemma** *permute-Lam*:  $\text{cont } f \implies p \cdot (\Lambda x. f x) = (\Lambda x. (p \cdot f) x)$   
 ⟨*proof*⟩

**lemma** *Abs-cfun-eqv*:  $\text{cont } f \implies (p \cdot \text{Abs-cfun}) f = \text{Abs-cfun } f$   
 ⟨*proof*⟩

**lemma** *cfun-eqvI*:  $(\Lambda x. p \cdot (f \cdot x) = f' \cdot (p \cdot x)) \implies p \cdot f = f'$   
 ⟨*proof*⟩

**lemma** *ID-eqv*[*eqvt*]:  $\pi \cdot \text{ID} = \text{ID}$   
 ⟨*proof*⟩

**instance** *cfun* :: (*cont-pt*, *cont-pt*) *cont-pt*  
 ⟨*proof*⟩

**instance** *cfun* :: ({*pure,cont-pt*}, {*pure,cont-pt*}) *pure*  
 ⟨*proof*⟩

**instance** *cfun* :: (*cont-pt*, *pcpo-pt*) *pcpo-pt*  
 ⟨*proof*⟩

### 2.8.3 Instance for *fun*

**lemma** *permute-fun-eq*:  $\text{permute } p = (\lambda f. (\text{permute } p) \circ f \circ (\text{permute } (-p)))$   
 ⟨*proof*⟩

**instance** *fun* :: (*pt*, *cont-pt*) *cont-pt*  
 ⟨*proof*⟩

**lemma** *fix-eqv*[*eqvt*]:  
 $\pi \cdot \text{fix} = (\text{fix} :: ('a \rightarrow 'a) \rightarrow 'a :: \{\text{cont-pt}, \text{pcpo}\})$   
 ⟨*proof*⟩

### 2.8.4 Instance for *u*

**instantiation** *u* :: (*cont-pt*) *pt*

**begin**

**definition**  $p \cdot (x :: 'a \ u) = \text{fup} \cdot (\Lambda x. \text{up} \cdot (p \cdot x)) \cdot x$

**instance**

⟨*proof*⟩

**end**

**instance** *u* :: (*cont-pt*) *cont-pt*  
 ⟨*proof*⟩

**instance**  $u :: (cont-pt) \text{ pcpo-pt} \langle proof \rangle$

**class**  $pure\text{-}cont\text{-}pt = pure + cont\text{-}pt$

**instance**  $u :: (pure\text{-}cont\text{-}pt) \text{ pure} \langle proof \rangle$

**lemma**  $up\text{-}eqvt[eqvt]: \pi \cdot up = up \langle proof \rangle$

**lemma**  $fup\text{-}eqvt[eqvt]: \pi \cdot fup = fup \langle proof \rangle$

### 2.8.5 Instance for *lift*

**instantiation**  $lift :: (pt) \text{ pt}$

**begin**

**definition**  $p \cdot (x :: 'a \text{ lift}) = case\text{-}lift \perp (\lambda x. Def (p \cdot x)) x$

**instance**

$\langle proof \rangle$

**end**

**instance**  $lift :: (pt) \text{ cont-pt} \langle proof \rangle$

**instance**  $lift :: (pt) \text{ pcpo-pt} \langle proof \rangle$

**instance**  $lift :: (pure) \text{ pure} \langle proof \rangle$

**lemma**  $Def\text{-}eqvt[eqvt]: \pi \cdot (Def x) = Def (\pi \cdot x) \langle proof \rangle$

**lemma**  $case\text{-}lift\text{-}eqvt[eqvt]: \pi \cdot case\text{-}lift d f x = case\text{-}lift (\pi \cdot d) (\pi \cdot f) (\pi \cdot x) \langle proof \rangle$

### 2.8.6 Instance for *prod*

**instance**  $prod :: (cont-pt, cont-pt) \text{ cont-pt} \langle proof \rangle$

**end**

## 2.9 Env

**theory** *Env*

**imports** *Main HOLCF-Join-Classes*

**begin**

**default-sort** *type*

Our type for environments is a function with a pcpo as the co-domain; this theory collects related definitions.

### 2.9.1 The domain of a pcpo-valued function

**definition** *edom* :: ('key  $\Rightarrow$  'value::pcpo)  $\Rightarrow$  'key set  
**where** *edom* *m* = {*x*. *m* *x*  $\neq$   $\perp$ }

**lemma** *bot-edom*[*simp*]: *edom*  $\perp$  = {} *<proof>*

**lemma** *bot-edom2*[*simp*]: *edom* ( $\lambda$ .  $\perp$ ) = {} *<proof>*

**lemma** *edomIff*: (*a*  $\in$  *edom* *m*) = (*m* *a*  $\neq$   $\perp$ ) *<proof>*

**lemma** *edom-iff2*: (*m* *a* =  $\perp$ )  $\longleftrightarrow$  (*a*  $\notin$  *edom* *m*) *<proof>*

**lemma** *edom-empty-iff-bot*: *edom* *m* = {}  $\longleftrightarrow$  *m* =  $\perp$   
*<proof>*

**lemma** *lookup-not-edom*: *x*  $\notin$  *edom* *m*  $\implies$  *m* *x* =  $\perp$  *<proof>*

**lemma** *lookup-edom*[*simp*]: *m* *x*  $\neq$   $\perp$   $\implies$  *x*  $\in$  *edom* *m* *<proof>*

**lemma** *edom-mono*: *x*  $\sqsubseteq$  *y*  $\implies$  *edom* *x*  $\subseteq$  *edom* *y*  
*<proof>*

**lemma** *edom-subset-adm*[*simp*]:  
*adm* ( $\lambda$  *ae*'. *edom* *ae*'  $\subseteq$  *S*)  
*<proof>*

### 2.9.2 Updates

**lemma** *edom-fun-upd-subset*: *edom* (*h* (*x* := *v*))  $\subseteq$  *insert* *x* (*edom* *h*)  
*<proof>*

**declare** *fun-upd-same*[*simp*] *fun-upd-other*[*simp*]

### 2.9.3 Restriction

**definition** *env-restr* :: 'a set  $\Rightarrow$  ('a  $\Rightarrow$  'b::pcpo)  $\Rightarrow$  ('a  $\Rightarrow$  'b)  
**where** *env-restr* *S* *m* = ( $\lambda$  *x*. if *x*  $\in$  *S* then *m* *x* else  $\perp$ )

**abbreviation** *env-restr-rev* (**infixl** <f|' 110)  
**where** *env-restr-rev* *m* *S*  $\equiv$  *env-restr* *S* *m*

**notation** (*latex output*) *env-restr-rev* ( $\langle \cdot | \cdot \rangle$ )

**lemma** *env-restr-empty-iff[simp]*:  $m f|' S = \perp \longleftrightarrow \text{edom } m \cap S = \{\}$   
*<proof>*

**lemmas** *env-restr-empty* = *iffD2[OF env-restr-empty-iff, simp]*

**lemma** *lookup-env-restr[simp]*:  $x \in S \Longrightarrow (m f|' S) x = m x$   
*<proof>*

**lemma** *lookup-env-restr-not-there[simp]*:  $x \notin S \Longrightarrow (\text{env-restr } S m) x = \perp$   
*<proof>*

**lemma** *lookup-env-restr-eq*:  $(m f|' S) x = (\text{if } x \in S \text{ then } m x \text{ else } \perp)$   
*<proof>*

**lemma** *env-restr-eqI*:  $(\bigwedge x. x \in S \Longrightarrow m_1 x = m_2 x) \Longrightarrow m_1 f|' S = m_2 f|' S$   
*<proof>*

**lemma** *env-restr-eqD*:  $m_1 f|' S = m_2 f|' S \Longrightarrow x \in S \Longrightarrow m_1 x = m_2 x$   
*<proof>*

**lemma** *env-restr-belowI*:  $(\bigwedge x. x \in S \Longrightarrow m_1 x \sqsubseteq m_2 x) \Longrightarrow m_1 f|' S \sqsubseteq m_2 f|' S$   
*<proof>*

**lemma** *env-restr-belowD*:  $m_1 f|' S \sqsubseteq m_2 f|' S \Longrightarrow x \in S \Longrightarrow m_1 x \sqsubseteq m_2 x$   
*<proof>*

**lemma** *env-restr-env-restr[simp]*:  
 $x f|' d2 f|' d1 = x f|' (d1 \cap d2)$   
*<proof>*

**lemma** *env-restr-env-restr-subset*:  
 $d1 \subseteq d2 \Longrightarrow x f|' d2 f|' d1 = x f|' d1$   
*<proof>*

**lemma** *env-restr-useless*:  $\text{edom } m \subseteq S \Longrightarrow m f|' S = m$   
*<proof>*

**lemma** *env-restr-UNIV[simp]*:  $m f|' \text{UNIV} = m$   
*<proof>*

**lemma** *env-restr-fun-upd[simp]*:  $x \in S \Longrightarrow m1(x := v) f|' S = (m1 f|' S)(x := v)$   
*<proof>*

**lemma** *env-restr-fun-upd-other[simp]*:  $x \notin S \Longrightarrow m1(x := v) f|' S = m1 f|' S$   
*<proof>*

**lemma** *env-restr-eq-subset*:  
**assumes**  $S \subseteq S'$

**and**  $m1 f|' S' = m2 f|' S'$   
**shows**  $m1 f|' S = m2 f|' S$   
 ⟨proof⟩

**lemma** *env-restr-below-subset*:  
**assumes**  $S \subseteq S'$   
**and**  $m1 f|' S' \sqsubseteq m2 f|' S'$   
**shows**  $m1 f|' S \sqsubseteq m2 f|' S$   
 ⟨proof⟩

**lemma** *edom-env[simp]*:  
 $edom (m f|' S) = edom m \cap S$   
 ⟨proof⟩

**lemma** *env-restr-below-self*:  $f f|' S \sqsubseteq f$   
 ⟨proof⟩

**lemma** *env-restr-below-trans*:  
 $m1 f|' S1 \sqsubseteq m2 f|' S1 \implies m2 f|' S2 \sqsubseteq m3 f|' S2 \implies m1 f|' (S1 \cap S2) \sqsubseteq m3 f|' (S1 \cap S2)$   
 ⟨proof⟩

**lemma** *env-restr-cont*:  $cont (env-restr S)$   
 ⟨proof⟩

**lemma** *env-restr-mono*:  $m1 \sqsubseteq m2 \implies m1 f|' S \sqsubseteq m2 f|' S$   
 ⟨proof⟩

**lemma** *env-restr-mono2*:  $S2 \subseteq S1 \implies m f|' S2 \sqsubseteq m f|' S1$   
 ⟨proof⟩

**lemmas** *cont-compose*[*OF env-restr-cont, cont2cont, simp*]

**lemma** *env-restr-cong*:  $(\bigwedge x. edom m \subseteq S \cap S' \cup -S \cap -S') \implies m f|' S = m f|' S'$   
 ⟨proof⟩

## 2.9.4 Deleting

**definition** *env-delete* ::  $'a \Rightarrow ('a \Rightarrow 'b) \Rightarrow ('a \Rightarrow 'b::pcpo)$   
**where**  $env-delete x m = m(x := \perp)$

**lemma** *lookup-env-delete[simp]*:  
 $x' \neq x \implies env-delete x m x' = m x'$   
 ⟨proof⟩

**lemma** *lookup-env-delete-None[simp]*:  
 $env-delete x m x = \perp$   
 ⟨proof⟩

**lemma** *edom-env-delete[simp]*:

$\text{edom } (\text{env-delete } x \ m) = \text{edom } m - \{x\}$   
*<proof>*

**lemma** *edom-env-delete-subset*:

$\text{edom } (\text{env-delete } x \ m) \subseteq \text{edom } m$  *<proof>*

**lemma** *env-delete-fun-upd[simp]*:

$\text{env-delete } x \ (m(x := v)) = \text{env-delete } x \ m$   
*<proof>*

**lemma** *env-delete-fun-upd2[simp]*:

$(\text{env-delete } x \ m)(x := v) = m(x := v)$   
*<proof>*

**lemma** *env-delete-fun-upd3[simp]*:

$x \neq y \implies \text{env-delete } x \ (m(y := v)) = (\text{env-delete } x \ m)(y := v)$   
*<proof>*

**lemma** *env-delete-noop[simp]*:

$x \notin \text{edom } m \implies \text{env-delete } x \ m = m$   
*<proof>*

**lemma** *fun-upd-env-delete[simp]*:  $x \in \text{edom } \Gamma \implies (\text{env-delete } x \ \Gamma)(x := \Gamma \ x) = \Gamma$

*<proof>*

**lemma** *env-restr-env-delete-other[simp]*:  $x \notin S \implies \text{env-delete } x \ m \upharpoonright S = m \upharpoonright S$

*<proof>*

**lemma** *env-delete-restr*:  $\text{env-delete } x \ m = m \upharpoonright (-\{x\})$

*<proof>*

**lemma** *below-env-deleteI*:  $f \ x = \perp \implies f \sqsubseteq g \implies f \sqsubseteq \text{env-delete } x \ g$

*<proof>*

**lemma** *env-delete-below-cong[intro]*:

**assumes**  $x \neq v \implies e1 \ x \sqsubseteq e2 \ x$

**shows**  $\text{env-delete } v \ e1 \ x \sqsubseteq \text{env-delete } v \ e2 \ x$

*<proof>*

**lemma** *env-delete-env-restr-swap*:

$\text{env-delete } x \ (\text{env-restr } S \ e) = \text{env-restr } S \ (\text{env-delete } x \ e)$

*<proof>*

**lemma** *env-delete-mono*:

$m \sqsubseteq m' \implies \text{env-delete } x \ m \sqsubseteq \text{env-delete } x \ m'$

*<proof>*

**lemma** *env-delete-below-arg*:

*env-delete*  $x m \sqsubseteq m$   
 ⟨proof⟩

### 2.9.5 Merging of two functions

We'd like to have some nice syntax for *override-on*.

**abbreviation** *override-on-syn*  $(\langle - \ ++ \ - \ \rightarrow [100, 0, 100] \ 100)$  **where**  $f1 \ ++_S f2 \equiv \text{override-on } f1 \ f2 \ S$

**lemma** *override-on-bot*[simp]:

$\perp \ ++_S m = m \ f|' S$   
 $m \ ++_S \perp = m \ f|' (-S)$   
 ⟨proof⟩

**lemma** *edom-override-on*[simp]:  $\text{edom } (m1 \ ++_S m2) = (\text{edom } m1 - S) \cup (\text{edom } m2 \cap S)$   
 ⟨proof⟩

**lemma** *lookup-override-on-eq*:  $(m1 \ ++_S m2) \ x = (\text{if } x \in S \ \text{then } m2 \ x \ \text{else } m1 \ x)$   
 ⟨proof⟩

**lemma** *override-on-upd-swap*:

$x \notin S \implies \varrho(x := z) \ ++_S \varrho' = (\varrho \ ++_S \varrho')(x := z)$   
 ⟨proof⟩

**lemma** *override-on-upd*:

$x \in S \implies \varrho \ ++_S (\varrho'(x := z)) = (\varrho \ ++_S - \{x\} \ \varrho')(x := z)$   
 ⟨proof⟩

**lemma** *env-restr-add*:  $(m1 \ ++_{S2} m2) \ f|' S = m1 \ f|' S \ ++_{S2} m2 \ f|' S$   
 ⟨proof⟩

**lemma** *env-delete-add*:  $\text{env-delete } x \ (m1 \ ++_S m2) = \text{env-delete } x \ m1 \ ++_S - \{x\} \ \text{env-delete } x \ m2$   
 ⟨proof⟩

### 2.9.6 Environments with binary joins

**lemma** *edom-join*[simp]:  $\text{edom } (f \sqcup (g :: ('a :: \text{type} \Rightarrow 'b :: \{\text{Finite-Join-cpo}, \text{pcpo}\}))) = \text{edom } f \cup \text{edom } g$   
 ⟨proof⟩

**lemma** *env-delete-join*[simp]:  $\text{env-delete } x \ (f \sqcup (g :: ('a :: \text{type} \Rightarrow 'b :: \{\text{Finite-Join-cpo}, \text{pcpo}\}))) = \text{env-delete } x \ f \sqcup \text{env-delete } x \ g$   
 ⟨proof⟩

**lemma** *env-restr-join*:

**fixes**  $m1 \ m2 :: 'a :: \text{type} \Rightarrow 'b :: \{\text{Finite-Join-cpo}, \text{pcpo}\}$   
**shows**  $(m1 \sqcup m2) \ f|' S = (m1 \ f|' S) \sqcup (m2 \ f|' S)$

*<proof>*

**lemma** *env-restr-join2*:

**fixes**  $m :: 'a::type \Rightarrow 'b::\{Finite-Join-cpo,pcpo\}$

**shows**  $m f|' S \sqcup m f|' S' = m f|' (S \cup S')$

*<proof>*

**lemma** *join-env-restr-UNIV*:

**fixes**  $m :: 'a::type \Rightarrow 'b::\{Finite-Join-cpo,pcpo\}$

**shows**  $S1 \cup S2 = UNIV \Longrightarrow (m f|' S1) \sqcup (m f|' S2) = m$

*<proof>*

**lemma** *env-restr-split*:

**fixes**  $m :: 'a::type \Rightarrow 'b::\{Finite-Join-cpo,pcpo\}$

**shows**  $m = m f|' S \sqcup m f|' (- S)$

*<proof>*

**lemma** *env-restr-below-split*:

$m f|' S \sqsubseteq m' \Longrightarrow m f|' (- S) \sqsubseteq m' \Longrightarrow m \sqsubseteq m'$

*<proof>*

## 2.9.7 Singleton environments

**definition** *esing*  $:: 'a \Rightarrow 'b::\{pcpo\} \rightarrow ('a \Rightarrow 'b)$

**where**  $esing\ x = (\Lambda a. (\lambda y. (if\ x = y\ then\ a\ else\ \perp)))$

**lemma** *esing-bot[simp]*:  $esing\ x \cdot \perp = \perp$

*<proof>*

**lemma** *esing-simps[simp]*:

$(esing\ x \cdot n)\ x = n$

$x' \neq x \Longrightarrow (esing\ x \cdot n)\ x' = \perp$

*<proof>*

**lemma** *esing-eq-up-iff[simp]*:  $(esing\ x \cdot (up \cdot a))\ y = up \cdot a' \longleftrightarrow (x = y \wedge a = a')$

*<proof>*

**lemma** *esing-below-iff[simp]*:  $esing\ x \cdot a \sqsubseteq ae \longleftrightarrow a \sqsubseteq ae\ x$

*<proof>*

**lemma** *edom-esing-subset*:  $edom\ (esing\ x \cdot n) \subseteq \{x\}$

*<proof>*

**lemma** *edom-esing-up[simp]*:  $edom\ (esing\ x \cdot (up \cdot n)) = \{x\}$

*<proof>*

**lemma** *env-delete-esing[simp]*:  $env-delete\ x\ (esing\ x \cdot n) = \perp$

*<proof>*

**lemma** *env-restr-esing*[simp]:  
 $x \in S \implies \text{esing } x.v \text{ f} \upharpoonright S = \text{esing } x.v$   
 ⟨proof⟩

**lemma** *env-restr-esing2*[simp]:  
 $x \notin S \implies \text{esing } x.v \text{ f} \upharpoonright S = \perp$   
 ⟨proof⟩

**lemma** *esing-eq-iff*[simp]:  
 $\text{esing } x.v = \text{esing } x.v' \iff v = v'$   
 ⟨proof⟩

end

## 2.10 Env-Nominal

**theory** *Env-Nominal*  
 imports *Env Nominal-Utils Nominal-HOLCF*  
 begin

### 2.10.1 Equivariance lemmas

**lemma** *edom-perm*:  
 fixes  $f :: 'a::pt \Rightarrow 'b::\{pcpo-pt\}$   
 shows  $\text{edom } (\pi \cdot f) = \pi \cdot (\text{edom } f)$   
 ⟨proof⟩

**lemmas** *edom-perm-rev*[simp,eqvt] = *edom-perm*[symmetric]

**lemma** *mem-edom-perm*[simp]:  
 fixes  $\varrho :: 'a::at-base \Rightarrow 'b::\{pcpo-pt\}$   
 shows  $xa \in \text{edom } (p \cdot \varrho) \iff \neg p \cdot xa \in \text{edom } \varrho$   
 ⟨proof⟩

**lemma** *env-restr-eqvt*[eqvt]:  
 fixes  $m :: 'a::pt \Rightarrow 'b::\{cont-pt,pcpo\}$   
 shows  $\pi \cdot m \text{ f} \upharpoonright d = (\pi \cdot m) \text{ f} \upharpoonright (\pi \cdot d)$   
 ⟨proof⟩

**lemma** *env-delete-eqvt*[eqvt]:  
 fixes  $m :: 'a::pt \Rightarrow 'b::\{cont-pt,pcpo\}$   
 shows  $\pi \cdot \text{env-delete } x \ m = \text{env-delete } (\pi \cdot x) \ (\pi \cdot m)$   
 ⟨proof⟩

**lemma** *esing-eqvt*[eqvt]:  $\pi \cdot (\text{esing } x) = \text{esing } (\pi \cdot x)$   
 ⟨proof⟩

## 2.10.2 Permutation and restriction

**lemma** *env-restr-perm*:  
fixes  $\varrho :: 'a::at-base \Rightarrow 'b::\{pcpo-pt,pure\}$   
assumes  $supp\ p \#* S$  and  $[simp]: finite\ S$   
shows  $(p \cdot \varrho) f|' S = \varrho f|' S$   
*<proof>*

**lemma** *env-restr-perm'*:  
fixes  $\varrho :: 'a::at-base \Rightarrow 'b::\{pcpo-pt,pure\}$   
assumes  $supp\ p \#* S$  and  $[simp]: finite\ S$   
shows  $p \cdot (\varrho f|' S) = \varrho f|' S$   
*<proof>*

**lemma** *env-restr-flip*:  
fixes  $\varrho :: 'a::at-base \Rightarrow 'b::\{pcpo-pt,pure\}$   
assumes  $x \notin S$  and  $x' \notin S$   
shows  $((x' \leftrightarrow x) \cdot \varrho) f|' S = \varrho f|' S$   
*<proof>*

**lemma** *env-restr-flip'*:  
fixes  $\varrho :: 'a::at-base \Rightarrow 'b::\{pcpo-pt,pure\}$   
assumes  $x \notin S$  and  $x' \notin S$   
shows  $(x' \leftrightarrow x) \cdot (\varrho f|' S) = \varrho f|' S$   
*<proof>*

## 2.10.3 Pure codomains

**lemma** *edom-fv-pure*:  
fixes  $f :: ('a::at-base \Rightarrow 'b::\{pcpo,pure\})$   
assumes  $finite\ (edom\ f)$   
shows  $fv\ f \subseteq edom\ f$   
*<proof>*

end

## 2.11 Env-HOLCF

**theory** *Env-HOLCF*  
imports *Env HOLCF-Utills*  
begin

### 2.11.1 Continuity and pcpo-valued functions

**lemma** *override-on-belowI*:  
assumes  $\bigwedge a. a \in S \Longrightarrow y\ a \sqsubseteq z\ a$   
and  $\bigwedge a. a \notin S \Longrightarrow x\ a \sqsubseteq z\ a$   
shows  $x\ ++_S\ y \sqsubseteq z$

*<proof>*

**lemma** *override-on-cont1*:  $\text{cont } (\lambda x. x \text{ ++}_S m)$   
*<proof>*

**lemma** *override-on-cont2*:  $\text{cont } (\lambda x. m \text{ ++}_S x)$   
*<proof>*

**lemma** *override-on-cont2cont*[*simp*, *cont2cont*]:  
**assumes**  $\text{cont } f$   
**assumes**  $\text{cont } g$   
**shows**  $\text{cont } (\lambda x. f x \text{ ++}_S g x)$   
*<proof>*

**lemma** *override-on-mono*:  
**assumes**  $x1 \sqsubseteq (x2 :: 'a::\text{type} \Rightarrow 'b::\text{cpo})$   
**assumes**  $y1 \sqsubseteq y2$   
**shows**  $x1 \text{ ++}_S y1 \sqsubseteq x2 \text{ ++}_S y2$   
*<proof>*

**lemma** *fun-upd-below-env-deleteI*:  
**assumes**  $\text{env-delete } x \ \varrho \sqsubseteq \text{env-delete } x \ \varrho'$   
**assumes**  $y \sqsubseteq \varrho' x$   
**shows**  $\varrho(x := y) \sqsubseteq \varrho'$   
*<proof>*

**lemma** *fun-upd-belowI2*:  
**assumes**  $\bigwedge z. z \neq x \implies \varrho z \sqsubseteq \varrho' z$   
**assumes**  $\varrho x \sqsubseteq y$   
**shows**  $\varrho \sqsubseteq \varrho'(x := y)$   
*<proof>*

**lemma** *env-restr-belowI*:  
**assumes**  $\bigwedge x. x \in S \implies (m1 f|' S) x \sqsubseteq (m2 f|' S) x$   
**shows**  $m1 f|' S \sqsubseteq m2 f|' S$   
*<proof>*

**lemma** *env-restr-belowI2*:  
**assumes**  $\bigwedge x. x \in S \implies m1 x \sqsubseteq m2 x$   
**shows**  $m1 f|' S \sqsubseteq m2$   
*<proof>*

**lemma** *env-restr-below-itself*:  
**shows**  $m f|' S \sqsubseteq m$   
*<proof>*

**lemma** *env-restr-cont*:  $\text{cont } (\text{env-restr } S)$   
*<proof>*

**lemma** *env-restr-belowD*:  
**assumes**  $m1\ f|\ 'S \sqsubseteq m2\ f|\ 'S$   
**assumes**  $x \in S$   
**shows**  $m1\ x \sqsubseteq m2\ x$   
 $\langle proof \rangle$

**lemma** *env-restr-eqD*:  
**assumes**  $m1\ f|\ 'S = m2\ f|\ 'S$   
**assumes**  $x \in S$   
**shows**  $m1\ x = m2\ x$   
 $\langle proof \rangle$

**lemma** *env-restr-below-subset*:  
**assumes**  $S \subseteq S'$   
**and**  $m1\ f|\ 'S' \sqsubseteq m2\ f|\ 'S'$   
**shows**  $m1\ f|\ 'S \sqsubseteq m2\ f|\ 'S$   
 $\langle proof \rangle$

**lemma** *override-on-below-restrI*:  
**assumes**  $x\ f|\ '(-S) \sqsubseteq z\ f|\ '(-S)$   
**and**  $y\ f|\ 'S \sqsubseteq z\ f|\ 'S$   
**shows**  $x\ ++_S\ y \sqsubseteq z$   
 $\langle proof \rangle$

**lemma** *fmap-below-add-restrI*:  
**assumes**  $x\ f|\ '(-S) \sqsubseteq y\ f|\ '(-S)$   
**and**  $x\ f|\ 'S \sqsubseteq z\ f|\ 'S$   
**shows**  $x \sqsubseteq y\ ++_S\ z$   
 $\langle proof \rangle$

**lemmas** *env-restr-cont2cont*[*simp,cont2cont*] = *cont-compose*[*OF env-restr-cont*]

**lemma** *env-delete-cont*: *cont (env-delete x)*  
 $\langle proof \rangle$

**lemmas** *env-delete-cont2cont*[*simp,cont2cont*] = *cont-compose*[*OF env-delete-cont*]

**end**

## 2.12 EvalHeap

**theory** *EvalHeap*

**imports** *AList-Utils Env Nominal2.Nominal2 HOLCF-Utils*

**begin**

### 2.12.1 Conversion from heaps to environments

**fun**

$evalHeap :: ('var \times 'exp) list \Rightarrow ('exp \Rightarrow 'value::\{pure,pcpo\}) \Rightarrow 'var \Rightarrow 'value$

**where**

$evalHeap [] - = \perp$

$| evalHeap ((x,e)\#h) eval = (evalHeap h eval) (x := eval e)$

**lemma** *cont2cont-evalHeap[simp, cont2cont]*:

$(\bigwedge e . e \in snd \text{ ' set } h \implies cont (\lambda \varrho . eval \varrho e)) \implies cont (\lambda \varrho . evalHeap h (eval \varrho))$   
 $\langle proof \rangle$

**lemma** *evalHeap-eqvt[eqvt]*:

$\pi \cdot evalHeap h eval = evalHeap (\pi \cdot h) (\pi \cdot eval)$   
 $\langle proof \rangle$

**lemma** *edom-evalHeap-subset:edom (evalHeap h eval) \subseteq domA h*

$\langle proof \rangle$

**lemma** *evalHeap-cong[fundef-cong]*:

$\llbracket heap1 = heap2 ; (\bigwedge e . e \in snd \text{ ' set } heap2 \implies eval1 e = eval2 e) \rrbracket$   
 $\implies evalHeap heap1 eval1 = evalHeap heap2 eval2$   
 $\langle proof \rangle$

**lemma** *lookupEvalHeap*:

**assumes**  $v \in domA h$

**shows**  $(evalHeap h f) v = f (the (map-of h v))$

$\langle proof \rangle$

**lemma** *lookupEvalHeap'*:

**assumes**  $map-of \Gamma v = Some e$

**shows**  $(evalHeap \Gamma f) v = f e$

$\langle proof \rangle$

**lemma** *lookupEvalHeap-other[simp]*:

**assumes**  $v \notin domA \Gamma$

**shows**  $(evalHeap \Gamma f) v = \perp$

$\langle proof \rangle$

**lemma** *env-restr-evalHeap-noop*:

$domA h \subseteq S \implies env-restr S (evalHeap h eval) = evalHeap h eval$

$\langle proof \rangle$

**lemma** *env-restr-evalHeap-same[simp]*:

$env-restr (domA h) (evalHeap h eval) = evalHeap h eval$

$\langle proof \rangle$

**lemma** *evalHeap-cong'*:

$\llbracket (\bigwedge x . x \in domA heap \implies eval1 (the (map-of heap x)) = eval2 (the (map-of heap x))) \rrbracket$   
 $\implies evalHeap heap eval1 = evalHeap heap eval2$

$\langle \text{proof} \rangle$

**lemma** *lookupEvalHeapNotAppend[simp]*:

**assumes**  $x \notin \text{dom}A \ \Gamma$

**shows**  $(\text{evalHeap} (\Gamma @ h) f) x = \text{evalHeap} h f x$

$\langle \text{proof} \rangle$

**lemma** *evalHeap-delete[simp]*:  $\text{evalHeap} (\text{delete } x \ \Gamma) \text{ eval} = \text{env-delete } x (\text{evalHeap } \Gamma \text{ eval})$

$\langle \text{proof} \rangle$

**lemma** *evalHeap-mono*:

$x \notin \text{dom}A \ \Gamma \implies$

$\text{evalHeap} \ \Gamma \ \text{eval} \sqsubseteq \text{evalHeap} ((x, e) \# \Gamma) \ \text{eval}$

$\langle \text{proof} \rangle$

### 2.12.2 Reordering lemmas

**lemma** *evalHeap-reorder*:

**assumes**  $\text{map-of } \Gamma = \text{map-of } \Delta$

**shows**  $\text{evalHeap} \ \Gamma \ h = \text{evalHeap} \ \Delta \ h$

$\langle \text{proof} \rangle$

**lemma** *evalHeap-reorder-head*:

**assumes**  $x \neq y$

**shows**  $\text{evalHeap} ((x, e1) \# (y, e2) \# \Gamma) \ \text{eval} = \text{evalHeap} ((y, e2) \# (x, e1) \# \Gamma) \ \text{eval}$

$\langle \text{proof} \rangle$

**lemma** *evalHeap-reorder-head-append*:

**assumes**  $x \notin \text{dom}A \ \Gamma$

**shows**  $\text{evalHeap} ((x, e) \# \Gamma @ \Delta) \ \text{eval} = \text{evalHeap} (\Gamma @ ((x, e) \# \Delta)) \ \text{eval}$

$\langle \text{proof} \rangle$

**lemma** *evalHeap-subst-exp*:

**assumes**  $\text{eval } e = \text{eval } e'$

**shows**  $\text{evalHeap} ((x, e) \# \Gamma) \ \text{eval} = \text{evalHeap} ((x, e') \# \Gamma) \ \text{eval}$

$\langle \text{proof} \rangle$

**end**

## 3 Launchbury’s natural semantics

### 3.1 Vars

```
theory Vars
imports Nominal2.Nominal2
begin
```

The type of variables is abstract and provided by the `Nominal` package. All we know is that it is countable.

```
atom-decl var

end
```

### 3.2 Terms

```
theory Terms
imports Nominal-Utils Vars AList-Utils-Nominal
begin
```

#### 3.2.1 Expressions

This is the main data type of the development; our minimal lambda calculus with recursive let-bindings. It is created using the `nominal_datatype` command, which creates alpha-equivalence classes.

The package does not support nested recursion, so the bindings of the let cannot simply be of type  $(var, exp)$  list. Instead, the definition of lists have to be inlined here, as the custom type `assn`. Later we create conversion functions between these two types, define a properly typed `let` and redo the various lemmas in terms of that, so that afterwards, the type `assn` is no longer referenced.

```
nominal-datatype exp =
  Var var
| App exp var
| LetA as::assn body::exp binds bn as in body as
| Lam x::var body::exp binds x in body (⟨Lam [-]. -⟩ [100, 100] 100)
| Bool bool
| IfThenElse exp exp exp (⟨((-) / ? (-) / : (-)⟩ [0, 0, 10] 10)
and assn =
  ANil | ACons var exp assn
binder
  bn :: assn ⇒ atom list
where bn ANil = [] | bn (ACons x t as) = (atom x) # (bn as)

notation (latex output) Terms.Var (⟨-⟩)
notation (latex output) Terms.App (⟨- -⟩)
```

**notation** (*latex output*) *Terms.Lam* ( $\langle \lambda \cdot \cdot \rightarrow [100, 100] 100 \rangle$ )

**type-synonym** *heap* = (*var* × *exp*) *list*

**lemma** *exp-assn-size-eqvt*[*eqvt*]:  $p \cdot (\text{size} :: \text{exp} \Rightarrow \text{nat}) = \text{size}$   
*<proof>*

### 3.2.2 Rewriting in terms of heaps

We now work towards using *heap* instead of *assn*. All this could be skipped if Nominal supported nested recursion.

Conversion from *assn* to *heap*.

**nominal-function** *asToHeap* :: *assn* ⇒ *heap*  
**where** *ANilToHeap*: *asToHeap* *ANil* = []  
| *AConsToHeap*: *asToHeap* (*ACons* *v e as*) = (*v*, *e*) # *asToHeap as*  
*<proof>*  
**nominal-termination**(*eqvt*) *<proof>*

**lemma** *asToHeap-eqvt*: *eqvt asToHeap*  
*<proof>*

The other direction.

**fun** *heapToAssn* :: *heap* ⇒ *assn*  
**where** *heapToAssn* [] = *ANil*  
| *heapToAssn* ((*v,e*)# $\Gamma$ ) = *ACons v e (heapToAssn  $\Gamma$ )*

**declare** *heapToAssn.simps*[*simp del*]

**lemma** *heapToAssn-eqvt*[*simp,eqvt*]:  $p \cdot \text{heapToAssn } \Gamma = \text{heapToAssn } (p \cdot \Gamma)$   
*<proof>*

**lemma** *bn-heapToAssn*:  $\text{bn } (\text{heapToAssn } \Gamma) = \text{map } (\lambda x. \text{atom } (\text{fst } x)) \Gamma$   
*<proof>*

**lemma** *set-bn-to-atom-domA*:  
 $\text{set } (\text{bn } as) = \text{atom } \text{' domA } (\text{asToHeap } as)$   
*<proof>*

They are inverse to each other.

**lemma** *heapToAssn-asToHeap*[*simp*]:  
 $\text{heapToAssn } (\text{asToHeap } as) = as$   
*<proof>*

**lemma** *asToHeap-heapToAssn*[*simp*]:  
 $\text{asToHeap } (\text{heapToAssn } as) = as$   
*<proof>*

**lemma** *heapToAssn-inject*[simp]:  
 $heapToAssn\ x = heapToAssn\ y \longleftrightarrow x = y$   
 ⟨proof⟩

They are transparent to various notions from the Nominal package.

**lemma** *supp-heapToAssn*:  $supp\ (heapToAssn\ \Gamma) = supp\ \Gamma$   
 ⟨proof⟩

**lemma** *supp-asToHeap*:  $supp\ (asToHeap\ as) = supp\ as$   
 ⟨proof⟩

**lemma** *fv-asToHeap*:  $fv\ (asToHeap\ \Gamma) = fv\ \Gamma$   
 ⟨proof⟩

**lemma** *fv-heapToAssn*:  $fv\ (heapToAssn\ \Gamma) = fv\ \Gamma$   
 ⟨proof⟩

**lemma** [simp]:  $size\ (heapToAssn\ \Gamma) = size-list\ (\lambda\ (v,e) . size\ e)\ \Gamma$   
 ⟨proof⟩

**lemma** *Lam-eq-same-var*[simp]:  $Lam\ [y].\ e = Lam\ [y].\ e' \longleftrightarrow e = e'$   
 ⟨proof⟩

Now we define the Let constructor in the form that we actually want.

**hide-const** *HOL.Let*

**definition** *Let* ::  $heap \Rightarrow exp \Rightarrow exp$   
**where**  $Let\ \Gamma\ e = LetA\ (heapToAssn\ \Gamma)\ e$

**notation** (*latex output*)  $Let\ (\langle let - in \rangle)$

**abbreviation**

$LetBe :: var \Rightarrow exp \Rightarrow exp \Rightarrow exp\ (\langle let - be - in \rangle [100,100,100]\ 100)$   
**where**  
 $let\ x\ be\ t1\ in\ t2 \equiv Let\ [(x,t1)]\ t2$

We rewrite all (relevant) lemmas about *LetA* in terms of *Let*.

**lemma** *size-Let*[simp]:  $size\ (Let\ \Gamma\ e) = size-list\ (\lambda p. size\ (snd\ p))\ \Gamma + size\ e + Suc\ 0$   
 ⟨proof⟩

**lemma** *Let-distinct*[simp]:

$Var\ v \neq Let\ \Gamma\ e$   
 $Let\ \Gamma\ e \neq Var\ v$   
 $App\ e\ v \neq Let\ \Gamma\ e'$   
 $Lam\ [v].\ e' \neq Let\ \Gamma\ e$   
 $Let\ \Gamma\ e \neq Lam\ [v].\ e'$   
 $Let\ \Gamma\ e' \neq App\ e\ v$   
 $Bool\ b \neq Let\ \Gamma\ e$

$Let \Gamma e \neq Bool b$   
 $(scrut ? e1 : e2) \neq Let \Gamma e$   
 $Let \Gamma e \neq (scrut ? e1 : e2)$   
 $\langle proof \rangle$

**lemma** *Let-perm-simps*[simp,eqvt]:  
 $p \cdot Let \Gamma e = Let (p \cdot \Gamma) (p \cdot e)$   
 $\langle proof \rangle$

**lemma** *Let-supp*:  
 $supp (Let \Gamma e) = (supp e \cup supp \Gamma) - atom \text{ ' } (domA \Gamma)$   
 $\langle proof \rangle$

**lemma** *Let-fresh*[simp]:  
 $a \# Let \Gamma e = (a \# e \wedge a \# \Gamma \vee a \in atom \text{ ' } domA \Gamma)$   
 $\langle proof \rangle$

**lemma** *Abs-eq-cong*:  
**assumes**  $\bigwedge p. (p \cdot x = x') \longleftrightarrow (p \cdot y = y')$   
**assumes**  $supp y = supp x$   
**assumes**  $supp y' = supp x'$   
**shows**  $([a]lst. x = [a]lst. x') \longleftrightarrow ([a]lst. y = [a]lst. y')$   
 $\langle proof \rangle$

**lemma** *Let-eq-iff*[simp]:  
 $(Let \Gamma e = Let \Gamma' e') = ([map (\lambda x. atom (fst x)) \Gamma ]lst. (e, \Gamma) = [map (\lambda x. atom (fst x)) \Gamma']lst. (e', \Gamma'))$   
 $\langle proof \rangle$

**lemma** *exp-strong-exhaust*:  
**fixes**  $c :: 'a :: fs$   
**assumes**  $\bigwedge var. y = Var var \implies P$   
**assumes**  $\bigwedge exp var. y = App exp var \implies P$   
**assumes**  $\bigwedge \Gamma exp. atom \text{ ' } domA \Gamma \#* c \implies y = Let \Gamma exp \implies P$   
**assumes**  $\bigwedge var exp. \{atom var\} \#* c \implies y = Lam [var]. exp \implies P$   
**assumes**  $\bigwedge b. (y = Bool b) \implies P$   
**assumes**  $\bigwedge scrut e1 e2. y = (scrut ? e1 : e2) \implies P$   
**shows**  $P$   
 $\langle proof \rangle$

And finally the induction rules with *Let*.

**lemma** *exp-heap-induct*[case-names Var App Let Lam Bool IfThenElse Nil Cons]:  
**assumes**  $\bigwedge b var. P1 (Var var)$   
**assumes**  $\bigwedge exp var. P1 exp \implies P1 (App exp var)$   
**assumes**  $\bigwedge \Gamma exp. P2 \Gamma \implies P1 exp \implies P1 (Let \Gamma exp)$   
**assumes**  $\bigwedge var exp. P1 exp \implies P1 (Lam [var]. exp)$   
**assumes**  $\bigwedge b. P1 (Bool b)$   
**assumes**  $\bigwedge scrut e1 e2. P1 scrut \implies P1 e1 \implies P1 e2 \implies P1 (scrut ? e1 : e2)$   
**assumes**  $P2 \square$

**assumes**  $\bigwedge var\ exp\ \Gamma. P1\ exp \implies P2\ \Gamma \implies P2\ ((var, exp)\#\Gamma)$   
**shows**  $P1\ e$  **and**  $P2\ \Gamma$   
 $\langle proof \rangle$

**lemma** *exp-heap-strong-induct*[*case-names Var App Let Lam Bool IfThenElse Nil Cons*]:  
**assumes**  $\bigwedge var\ c. P1\ c\ (Var\ var)$   
**assumes**  $\bigwedge exp\ var\ c. (\bigwedge c. P1\ c\ exp) \implies P1\ c\ (App\ exp\ var)$   
**assumes**  $\bigwedge \Gamma\ exp\ c. atom\ 'domA\ \Gamma\ \#\#* c \implies (\bigwedge c. P2\ c\ \Gamma) \implies (\bigwedge c. P1\ c\ exp) \implies P1\ c\ (Let\ \Gamma\ exp)$   
**assumes**  $\bigwedge var\ exp\ c. \{atom\ var\}\ \#\#* c \implies (\bigwedge c. P1\ c\ exp) \implies P1\ c\ (Lam\ [var].\ exp)$   
**assumes**  $\bigwedge b\ c. P1\ c\ (Bool\ b)$   
**assumes**  $\bigwedge scrut\ e1\ e2\ c. (\bigwedge c. P1\ c\ scrut) \implies (\bigwedge c. P1\ c\ e1) \implies (\bigwedge c. P1\ c\ e2) \implies P1\ c\ (scrut\ ?\ e1 : e2)$   
**assumes**  $\bigwedge c. P2\ c\ []$   
**assumes**  $\bigwedge var\ exp\ \Gamma\ c. (\bigwedge c. P1\ c\ exp) \implies (\bigwedge c. P2\ c\ \Gamma) \implies P2\ c\ ((var,exp)\#\Gamma)$   
**fixes**  $c :: 'a :: fs$   
**shows**  $P1\ c\ e$  **and**  $P2\ c\ \Gamma$   
 $\langle proof \rangle$

### 3.2.3 Nice induction rules

These rules can be used instead of the original induction rules, which require a separate goal for *assn*.

**lemma** *exp-induct*[*case-names Var App Let Lam Bool IfThenElse*]:  
**assumes**  $\bigwedge var. P\ (Var\ var)$   
**assumes**  $\bigwedge exp\ var. P\ exp \implies P\ (App\ exp\ var)$   
**assumes**  $\bigwedge \Gamma\ exp. (\bigwedge x. x \in domA\ \Gamma \implies P\ (the\ (map-of\ \Gamma\ x))) \implies P\ exp \implies P\ (Let\ \Gamma\ exp)$   
**assumes**  $\bigwedge var\ exp. P\ exp \implies P\ (Lam\ [var].\ exp)$   
**assumes**  $\bigwedge b. P\ (Bool\ b)$   
**assumes**  $\bigwedge scrut\ e1\ e2. P\ scrut \implies P\ e1 \implies P\ e2 \implies P\ (scrut\ ?\ e1 : e2)$   
**shows**  $P\ exp$   
 $\langle proof \rangle$

**lemma** *exp-strong-induct-set*[*case-names Var App Let Lam Bool IfThenElse*]:  
**assumes**  $\bigwedge var\ c. P\ c\ (Var\ var)$   
**assumes**  $\bigwedge exp\ var\ c. (\bigwedge c. P\ c\ exp) \implies P\ c\ (App\ exp\ var)$   
**assumes**  $\bigwedge \Gamma\ exp\ c.$   
 $atom\ 'domA\ \Gamma\ \#\#* c \implies (\bigwedge c\ x\ e. (x,e) \in set\ \Gamma \implies P\ c\ e) \implies (\bigwedge c. P\ c\ exp) \implies P\ c\ (Let\ \Gamma\ exp)$   
**assumes**  $\bigwedge var\ exp\ c. \{atom\ var\}\ \#\#* c \implies (\bigwedge c. P\ c\ exp) \implies P\ c\ (Lam\ [var].\ exp)$   
**assumes**  $\bigwedge b\ c. P\ c\ (Bool\ b)$   
**assumes**  $\bigwedge scrut\ e1\ e2\ c. (\bigwedge c. P\ c\ scrut) \implies (\bigwedge c. P\ c\ e1) \implies (\bigwedge c. P\ c\ e2) \implies P\ c\ (scrut\ ?\ e1 : e2)$   
**shows**  $P\ (c::'a::fs)\ exp$   
 $\langle proof \rangle$

**lemma** *exp-strong-induct*[*case-names Var App Let Lam Bool IfThenElse*]:  
**assumes**  $\bigwedge var\ c.\ P\ c\ (Var\ var)$   
**assumes**  $\bigwedge exp\ var\ c.\ (\bigwedge c.\ P\ c\ exp) \implies P\ c\ (App\ exp\ var)$   
**assumes**  $\bigwedge \Gamma\ exp\ c.$   
 $atom\ 'domA\ \Gamma\ \#\#*\ c \implies (\bigwedge c\ x.\ x \in domA\ \Gamma \implies P\ c\ (the\ (map-of\ \Gamma\ x))) \implies (\bigwedge c.\ P\ c\ exp) \implies P\ c\ (Let\ \Gamma\ exp)$   
**assumes**  $\bigwedge var\ exp\ c.\ \{atom\ var\}\ \#\#*\ c \implies (\bigwedge c.\ P\ c\ exp) \implies P\ c\ (Lam\ [var].\ exp)$   
**assumes**  $\bigwedge b\ c.\ P\ c\ (Bool\ b)$   
**assumes**  $\bigwedge scrut\ e1\ e2\ c.\ (\bigwedge c.\ P\ c\ scrut) \implies (\bigwedge c.\ P\ c\ e1) \implies (\bigwedge c.\ P\ c\ e2) \implies P\ c\ (scrut\ ?\ e1\ : e2)$   
**shows**  $P\ (c::'a::fs)\ exp$   
 $\langle proof \rangle$

### 3.2.4 Testing alpha equivalence

**lemma** *alpha-test*:  
**shows**  $Lam\ [x].\ (Var\ x) = Lam\ [y].\ (Var\ y)$   
 $\langle proof \rangle$

**lemma** *alpha-test2*:  
**shows**  $let\ x\ be\ (Var\ x)\ in\ (Var\ x) = let\ y\ be\ (Var\ y)\ in\ (Var\ y)$   
 $\langle proof \rangle$

**lemma** *alpha-test3*:  
**shows**  
 $Let\ [(x,\ Var\ y),\ (y,\ Var\ x)]\ (Var\ x)$   
 $=$   
 $Let\ [(y,\ Var\ x),\ (x,\ Var\ y)]\ (Var\ y)$  (**is**  $Let\ ?la\ ?lb = -$ )  
 $\langle proof \rangle$

### 3.2.5 Free variables

**lemma** *fv-supp-exp*:  $supp\ e = atom\ '(fv\ (e::exp)\ ::\ var\ set)$  **and** *fv-supp-as*:  $supp\ as = atom\ '(fv\ (as::assn)\ ::\ var\ set)$   
 $\langle proof \rangle$

**lemma** *fv-supp-heap*:  $supp\ (\Gamma::heap) = atom\ '(fv\ \Gamma\ ::\ var\ set)$   
 $\langle proof \rangle$

**lemma** *fv-Lam[simp]*:  $fv\ (Lam\ [x].\ e) = fv\ e - \{x\}$   
 $\langle proof \rangle$

**lemma** *fv-Var[simp]*:  $fv\ (Var\ x) = \{x\}$   
 $\langle proof \rangle$

**lemma** *fv-App[simp]*:  $fv\ (App\ e\ x) = insert\ x\ (fv\ e)$   
 $\langle proof \rangle$

**lemma** *fv-Let[simp]*:  $fv\ (Let\ \Gamma\ e) = (fv\ \Gamma \cup fv\ e) - domA\ \Gamma$   
 $\langle proof \rangle$

**lemma** *fv-Bool[simp]*:  $fv\ (Bool\ b) = \{\}$   
 $\langle proof \rangle$

**lemma** *fv-IfThenElse[simp]*:  $fv\ (scrut\ ?\ e1\ : e2) = fv\ scrut \cup fv\ e1 \cup fv\ e2$

*<proof>*

**lemma** *fv-delete-heap*:

**assumes** *map-of*  $\Gamma x = \text{Some } e$

**shows**  $\text{fv} (\text{delete } x \ \Gamma, e) \cup \{x\} \subseteq (\text{fv} (\Gamma, \text{Var } x) :: \text{var set})$

*<proof>*

### 3.2.6 Lemmas helping with nominal definitions

**lemma** *eqvt-lam-case*:

**assumes**  $\text{Lam } [x]. e = \text{Lam } [x']. e'$

**assumes**  $\bigwedge \pi . \text{supp } (-\pi) \#^* (\text{fv} (\text{Lam } [x]. e) :: \text{var set}) \implies$

$\text{supp } \pi \#^* (\text{Lam } [x]. e) \implies$

$F (\pi \cdot e) (\pi \cdot x) (\text{Lam } [x]. e) = F e x (\text{Lam } [x]. e)$

**shows**  $F e x (\text{Lam } [x]. e) = F e' x' (\text{Lam } [x']. e')$

*<proof>*

**lemma** *eqvt-let-case*:

**assumes**  $\text{Let } as \ \text{body} = \text{Let } as' \ \text{body}'$

**assumes**  $\bigwedge \pi .$

$\text{supp } (-\pi) \#^* (\text{fv} (\text{Let } as \ \text{body}) :: \text{var set}) \implies$

$\text{supp } \pi \#^* \text{Let } as \ \text{body} \implies$

$F (\pi \cdot as) (\pi \cdot \text{body}) (\text{Let } as \ \text{body}) = F as \ \text{body} (\text{Let } as \ \text{body})$

**shows**  $F as \ \text{body} (\text{Let } as \ \text{body}) = F as' \ \text{body}' (\text{Let } as' \ \text{body}')$

*<proof>*

### 3.2.7 A smart constructor for lets

Certain program transformations might change the bound variables, possibly making it an empty list. This smart constructor avoids the empty let in the resulting expression. Semantically, it should not make a difference.

**definition** *SmartLet* ::  $\text{heap} \Rightarrow \text{exp} \Rightarrow \text{exp}$

**where**  $\text{SmartLet } \Gamma \ e = (\text{if } \Gamma = [] \ \text{then } e \ \text{else } \text{Let } \Gamma \ e)$

**lemma** *SmartLet-eqvt[eqvt]*:  $\pi \cdot (\text{SmartLet } \Gamma \ e) = \text{SmartLet } (\pi \cdot \Gamma) (\pi \cdot e)$

*<proof>*

**lemma** *SmartLet-supp*:

$\text{supp } (\text{SmartLet } \Gamma \ e) = (\text{supp } e \cup \text{supp } \Gamma) - \text{atom } ' (\text{domA } \Gamma)$

*<proof>*

**lemma** *fv-SmartLet[simp]*:  $\text{fv} (\text{SmartLet } \Gamma \ e) = (\text{fv } \Gamma \cup \text{fv } e) - \text{domA } \Gamma$

*<proof>*

### 3.2.8 A predicate for value expressions

**nominal-function**  $isLam :: exp \Rightarrow bool$  **where**

$isLam (Var x) = False$  |  
 $isLam (Lam [x]. e) = True$  |  
 $isLam (App e x) = False$  |  
 $isLam (Let as e) = False$  |  
 $isLam (Bool b) = False$  |  
 $isLam (scrut ? e1 : e2) = False$   
 $\langle proof \rangle$

**nominal-termination** ( $eqvt$ )  $\langle proof \rangle$

**lemma**  $isLam-Lam$ :  $isLam (Lam [x]. e) \langle proof \rangle$

**lemma**  $isLam-obtain-fresh$ :

**assumes**  $isLam z$   
**obtains**  $y e'$   
**where**  $z = (Lam [y]. e')$  **and**  $atom y \# (c::'a::fs)$   
 $\langle proof \rangle$

**nominal-function**  $isVal :: exp \Rightarrow bool$  **where**

$isVal (Var x) = False$  |  
 $isVal (Lam [x]. e) = True$  |  
 $isVal (App e x) = False$  |  
 $isVal (Let as e) = False$  |  
 $isVal (Bool b) = True$  |  
 $isVal (scrut ? e1 : e2) = False$   
 $\langle proof \rangle$

**nominal-termination** ( $eqvt$ )  $\langle proof \rangle$

**lemma**  $isVal-Lam$ :  $isVal (Lam [x]. e) \langle proof \rangle$

**lemma**  $isVal-Bool$ :  $isVal (Bool b) \langle proof \rangle$

### 3.2.9 The notion of thunks

**definition**  $thunks :: heap \Rightarrow var\ set$  **where**

$thunks \Gamma = \{x . case\ map-of\ \Gamma\ x\ of\ Some\ e \Rightarrow \neg isVal\ e \mid None \Rightarrow False\}$

**lemma**  $thunks-Nil[simp]$ :  $thunks [] = \{\}$   $\langle proof \rangle$

**lemma**  $thunks-domA$ :  $thunks \Gamma \subseteq domA \Gamma$

$\langle proof \rangle$

**lemma**  $thunks-Cons$ :  $thunks ((x,e)\#\Gamma) = (if\ isVal\ e\ then\ thunks\ \Gamma - \{x\}\ else\ insert\ x\ (thunks\ \Gamma))$

$\langle proof \rangle$

**lemma**  $thunks-append[simp]$ :  $thunks (\Delta @ \Gamma) = thunks \Delta \cup (thunks \Gamma - domA \Delta)$

$\langle proof \rangle$

**lemma** *thunks-delete[simp]*:  $\text{thunks } (\text{delete } x \ \Gamma) = \text{thunks } \Gamma - \{x\}$   
 ⟨proof⟩

**lemma** *thunksI[intro]*:  $\text{map-of } \Gamma \ x = \text{Some } e \implies \neg \text{isVal } e \implies x \in \text{thunks } \Gamma$   
 ⟨proof⟩

**lemma** *thunksE[intro]*:  $x \in \text{thunks } \Gamma \implies \text{map-of } \Gamma \ x = \text{Some } e \implies \neg \text{isVal } e$   
 ⟨proof⟩

**lemma** *thunks-cong*:  $\text{map-of } \Gamma = \text{map-of } \Delta \implies \text{thunks } \Gamma = \text{thunks } \Delta$   
 ⟨proof⟩

**lemma** *thunks-eqvt[eqvt]*:  
 $\pi \cdot \text{thunks } \Gamma = \text{thunks } (\pi \cdot \Gamma)$   
 ⟨proof⟩

### 3.2.10 Non-recursive Let bindings

**definition** *nonrec* ::  $\text{heap} \Rightarrow \text{bool}$  **where**  
 $\text{nonrec } \Gamma = (\exists \ x \ e. \ \Gamma = [(x,e)] \wedge x \notin \text{fv } e)$

**lemma** *nonrecE*:  
**assumes**  $\text{nonrec } \Gamma$   
**obtains**  $x \ e$  **where**  $\Gamma = [(x,e)]$  **and**  $x \notin \text{fv } e$   
 ⟨proof⟩

**lemma** *nonrec-eqvt[eqvt]*:  
 $\text{nonrec } \Gamma \implies \text{nonrec } (\pi \cdot \Gamma)$   
 ⟨proof⟩

**lemma** *exp-induct-rec[case-names Var App Let Let-nonrec Lam Bool IfThenElse]*:  
**assumes**  $\bigwedge \text{var}. P \ (\text{Var } \text{var})$   
**assumes**  $\bigwedge \text{exp } \text{var}. P \ \text{exp} \implies P \ (\text{App } \text{exp } \text{var})$   
**assumes**  $\bigwedge \Gamma \ \text{exp}. \neg \text{nonrec } \Gamma \implies (\bigwedge \ x. \ x \in \text{domA } \Gamma \implies P \ (\text{the } (\text{map-of } \Gamma \ x))) \implies P \ \text{exp}$   
 $\implies P \ (\text{Let } \Gamma \ \text{exp})$   
**assumes**  $\bigwedge \ x \ e \ \text{exp}. \ x \notin \text{fv } e \implies P \ e \implies P \ \text{exp} \implies P \ (\text{let } x \ \text{be } e \ \text{in } \ \text{exp})$   
**assumes**  $\bigwedge \text{var } \ \text{exp}. P \ \text{exp} \implies P \ (\text{Lam } [\text{var}]. \ \text{exp})$   
**assumes**  $\bigwedge b. P \ (\text{Bool } b)$   
**assumes**  $\bigwedge \ \text{scrut } \ e1 \ e2. P \ \text{scrut} \implies P \ e1 \implies P \ e2 \implies P \ (\text{scrut } ? \ e1 : \ e2)$   
**shows**  $P \ \text{exp}$   
 ⟨proof⟩

**lemma** *exp-strong-induct-rec[case-names Var App Let Let-nonrec Lam Bool IfThenElse]*:  
**assumes**  $\bigwedge \text{var } \ c. P \ c \ (\text{Var } \text{var})$   
**assumes**  $\bigwedge \text{exp } \text{var } \ c. (\bigwedge c. P \ c \ \text{exp}) \implies P \ c \ (\text{App } \text{exp } \text{var})$   
**assumes**  $\bigwedge \Gamma \ \text{exp } \ c.$   
 $\text{atom } \text{'domA } \Gamma \ \#* \ c \implies \neg \text{nonrec } \Gamma \implies (\bigwedge c \ x. \ x \in \text{domA } \Gamma \implies P \ c \ (\text{the } (\text{map-of } \Gamma \ x)))$   
 $\implies (\bigwedge c. P \ c \ \text{exp}) \implies P \ c \ (\text{Let } \Gamma \ \text{exp})$

**assumes**  $\bigwedge x e \exp c. \{atom\ x\} \#* c \implies x \notin fv\ e \implies (\bigwedge c. P\ c\ e) \implies (\bigwedge c. P\ c\ \exp) \implies P\ c$   
*(let x be e in exp)*  
**assumes**  $\bigwedge var \exp c. \{atom\ var\} \#* c \implies (\bigwedge c. P\ c\ \exp) \implies P\ c$  (*Lam [var]. exp*)  
**assumes**  $\bigwedge b c. P\ c$  (*Bool b*)  
**assumes**  $\bigwedge scrut\ e1\ e2\ c. (\bigwedge c. P\ c\ scrut) \implies (\bigwedge c. P\ c\ e1) \implies (\bigwedge c. P\ c\ e2) \implies P\ c$   
*(scrut ? e1 : e2)*  
**shows**  $P\ (c::'a::fs)\ \exp$   
*<proof>*

**lemma** *exp-strong-induct-rec-set*[*case-names Var App Let Let-nonrec Lam Bool IfThenElse*]:

**assumes**  $\bigwedge var c. P\ c$  (*Var var*)  
**assumes**  $\bigwedge exp\ var\ c. (\bigwedge c. P\ c\ \exp) \implies P\ c$  (*App exp var*)  
**assumes**  $\bigwedge \Gamma\ exp\ c.$   
 $atom\ 'domA\ \Gamma\ \#* c \implies \neg nonrec\ \Gamma \implies (\bigwedge c\ x\ e. (x,e) \in set\ \Gamma \implies P\ c\ e) \implies (\bigwedge c. P\ c\ \exp) \implies P\ c$   
*(Let  $\Gamma$  exp)*  
**assumes**  $\bigwedge x e \exp c. \{atom\ x\} \#* c \implies x \notin fv\ e \implies (\bigwedge c. P\ c\ e) \implies (\bigwedge c. P\ c\ \exp) \implies P\ c$   
*(let x be e in exp)*  
**assumes**  $\bigwedge var \exp c. \{atom\ var\} \#* c \implies (\bigwedge c. P\ c\ \exp) \implies P\ c$  (*Lam [var]. exp*)  
**assumes**  $\bigwedge b c. P\ c$  (*Bool b*)  
**assumes**  $\bigwedge scrut\ e1\ e2\ c. (\bigwedge c. P\ c\ scrut) \implies (\bigwedge c. P\ c\ e1) \implies (\bigwedge c. P\ c\ e2) \implies P\ c$   
*(scrut ? e1 : e2)*  
**shows**  $P\ (c::'a::fs)\ \exp$   
*<proof>*

### 3.2.11 Renaming a lambda-bound variable

**lemma** *change-Lam-Variable*:

**assumes**  $y' \neq y \implies atom\ y' \# (e, y)$   
**shows**  $Lam\ [y].\ e = Lam\ [y'].\ ((y \leftrightarrow y') \cdot e)$   
*<proof>*

end

## 3.3 Substitution

**theory** *Substitution*

**imports** *Terms*

**begin**

Defining a substitution function on terms turned out to be slightly tricky.

**fun**

$subst\text{-}var :: var \Rightarrow var \Rightarrow var \Rightarrow var$  (*<-[:v=-]> [1000,100,100] 1000*)  
**where**  $x[y ::v= z] = (if\ x = y\ then\ z\ else\ x)$

**nominal-function** (*default case-sum* ( $\lambda x. Inl\ undefined$ ) ( $\lambda x. Inr\ undefined$ ),  
*invariant*  $\lambda a\ r. (\forall\ \Gamma\ y\ z. ((a = Inr\ (\Gamma, y, z) \wedge atom\ 'domA\ \Gamma\ \#* (y, z)) \longrightarrow$   
 $map\ (\lambda x. atom\ (fst\ x))\ (Sum\text{-}Type.proj\ r) = map\ (\lambda x. atom\ (fst\ x))\ \Gamma)))$

$subst :: exp \Rightarrow var \Rightarrow var \Rightarrow exp \langle \langle - ::= - \rangle \rangle [1000, 100, 100] 1000$   
**and**  
 $subst\text{-}heap :: heap \Rightarrow var \Rightarrow var \Rightarrow heap \langle \langle - ::= h = - \rangle \rangle [1000, 100, 100] 1000$   
**where**  
 $(Var\ x)[y ::= z] = Var\ (x[y ::= v = z])$   
 $| (App\ e\ v)[y ::= z] = App\ (e[y ::= z])\ (v[y ::= v = z])$   
 $| atom\ \langle\ domA\ \Gamma\ \#^*\ (y, z) \rangle \Longrightarrow$   
 $\quad (Let\ \Gamma\ body)[y ::= z] = Let\ (\Gamma[y ::= h = z])\ (body[y ::= z])$   
 $| atom\ x\ \# (y, z) \Longrightarrow (Lam\ [x].e)[y ::= z] = Lam\ [x].(e[y ::= z])$   
 $| (Bool\ b)[y ::= z] = Bool\ b$   
 $| (scrut\ ?\ e1\ : e2)[y ::= z] = (scrut[y ::= z]\ ?\ e1[y ::= z]\ : e2[y ::= z])$   
 $| [][y ::= h = z] = []$   
 $| ((v, e)\# \Gamma)[y ::= h = z] = (v, e[y ::= z])\# (\Gamma[y ::= h = z])$   
 $\langle proof \rangle$

**nominal-termination** (*eqvt*)  $\langle proof \rangle$

**lemma shows**

**True and**  $bn\text{-}subst[simp]: domA\ (subst\text{-}heap\ \Gamma\ y\ z) = domA\ \Gamma$   
 $\langle proof \rangle$

**lemma**  $subst\text{-}noop[simp]:$

**shows**  $e[y ::= y] = e$  **and**  $\Gamma[y ::= h = y] = \Gamma$   
 $\langle proof \rangle$

**lemma**  $subst\text{-}is\text{-}fresh[simp]:$

**assumes**  $atom\ y\ \# z$

**shows**

$atom\ y\ \# e[y ::= z]$

**and**

$atom\ \langle\ domA\ \Gamma\ \#^*\ y \rangle \Longrightarrow atom\ y\ \# \Gamma[y ::= h = z]$

$\langle proof \rangle$

**lemma**

$subst\text{-}pres\text{-}fresh: atom\ x\ \# e \vee x = y \Longrightarrow atom\ x\ \# z \Longrightarrow atom\ x\ \# e[y ::= z]$

**and**

$atom\ x\ \# \Gamma \vee x = y \Longrightarrow atom\ x\ \# z \Longrightarrow x \notin domA\ \Gamma \Longrightarrow atom\ x\ \# (\Gamma[y ::= h = z])$

$\langle proof \rangle$

**lemma**  $subst\text{-}fresh\text{-}noop: atom\ x\ \# e \Longrightarrow e[x ::= y] = e$

**and**  $subst\text{-}heap\text{-}fresh\text{-}noop: atom\ x\ \# \Gamma \Longrightarrow \Gamma[x ::= h = y] = \Gamma$

$\langle proof \rangle$

**lemma**  $supp\text{-}subst\text{-}eq: supp\ (e[y ::= x]) = (supp\ e - \{atom\ y\}) \cup (if\ atom\ y \in supp\ e\ then\ \{atom\ x\}\ else\ \{\})$

**and**  $atom\ \langle\ domA\ \Gamma\ \#^*\ y \rangle \Longrightarrow supp\ (\Gamma[y ::= h = x]) = (supp\ \Gamma - \{atom\ y\}) \cup (if\ atom\ y \in supp\ \Gamma\ then\ \{atom\ x\}\ else\ \{\})$

$\langle proof \rangle$

**lemma** *supp-subst*:  $\text{supp } (e[y::=x]) \subseteq (\text{supp } e - \{\text{atom } y\}) \cup \{\text{atom } x\}$   
 ⟨proof⟩

**lemma** *fv-subst-eq*:  $\text{fv } (e[y::=x]) = (\text{fv } e - \{y\}) \cup (\text{if } y \in \text{fv } e \text{ then } \{x\} \text{ else } \{\})$   
**and**  $\text{atom } \text{'domA } \Gamma \#* y \implies \text{fv } (\Gamma[y::h=x]) = (\text{fv } \Gamma - \{y\}) \cup (\text{if } y \in \text{fv } \Gamma \text{ then } \{x\} \text{ else } \{\})$   
 ⟨proof⟩

**lemma** *fv-subst-subset*:  $\text{fv } (e[y ::= x]) \subseteq (\text{fv } e - \{y\}) \cup \{x\}$   
 ⟨proof⟩

**lemma** *fv-subst-int*:  $x \notin S \implies y \notin S \implies \text{fv } (e[y ::= x]) \cap S = \text{fv } e \cap S$   
 ⟨proof⟩

**lemma** *fv-subst-int2*:  $x \notin S \implies y \notin S \implies S \cap \text{fv } (e[y ::= x]) = S \cap \text{fv } e$   
 ⟨proof⟩

**lemma** *subst-swap-same*:  $\text{atom } x \# e \implies (x \leftrightarrow y) \cdot e = e[y ::= x]$   
**and**  $\text{atom } x \# \Gamma \implies \text{atom } \text{'domA } \Gamma \#* y \implies (x \leftrightarrow y) \cdot \Gamma = \Gamma[y ::=h= x]$   
 ⟨proof⟩

**lemma** *subst-subst-back*:  $\text{atom } x \# e \implies e[y::=x][x::=y] = e$   
**and**  $\text{atom } x \# \Gamma \implies \text{atom } \text{'domA } \Gamma \#* y \implies \Gamma[y::h=x][x::h=y] = \Gamma$   
 ⟨proof⟩

**lemma** *subst-heap-delete[simp]*:  $(\text{delete } x \Gamma)[y ::=h= z] = \text{delete } x (\Gamma[y ::=h= z])$   
 ⟨proof⟩

**lemma** *subst-nil-iff[simp]*:  $\Gamma[x ::=h= z] = [] \iff \Gamma = []$   
 ⟨proof⟩

**lemma** *subst-SmartLet[simp]*:  
 $\text{atom } \text{'domA } \Gamma \#* (y, z) \implies (\text{SmartLet } \Gamma \text{ body})[y ::= z] = \text{SmartLet } (\Gamma[y ::=h= z]) (\text{body}[y ::= z])$   
 ⟨proof⟩

**lemma** *subst-let-be[simp]*:  
 $\text{atom } x' \# y \implies \text{atom } x' \# x \implies (\text{let } x' \text{ be } e \text{ in } \text{exp})[y ::= x] = (\text{let } x' \text{ be } e[y ::= x] \text{ in } \text{exp}[y ::= x])$   
 ⟨proof⟩

**lemma** *isLam-subst[simp]*:  $\text{isLam } e[x ::= y] = \text{isLam } e$   
 ⟨proof⟩

**lemma** *isVal-subst[simp]*:  $\text{isVal } e[x ::= y] = \text{isVal } e$   
 ⟨proof⟩

**lemma** *thunks-subst[simp]*:  
 $\text{thunks } \Gamma[y ::=h= x] = \text{thunks } \Gamma$

*<proof>*

**lemma** *map-of-subst*:

*map-of*  $(\Gamma[x::h=y])$   $k = \text{map-option } (\lambda e . e[x::=y])$   $(\text{map-of } \Gamma k)$

*<proof>*

**lemma** *mapCollect-subst[simp]*:

$\{e k v \mid k \mapsto v \in \text{map-of } \Gamma[x::h=y]\} = \{e k v[x::=y] \mid k \mapsto v \in \text{map-of } \Gamma\}$

*<proof>*

**lemma** *subst-eq-Cons*:

$\Gamma[x::h=y] = (x', e) \# \Delta \longleftrightarrow (\exists e' \Gamma'. \Gamma = (x', e') \# \Gamma' \wedge e'[x::=y] = e \wedge \Gamma'[x::h=y] = \Delta)$

*<proof>*

**lemma** *nonrec-subst*:

*atom*  $' \text{dom}A \Gamma \#* x \implies \text{atom} ' \text{dom}A \Gamma \#* y \implies \text{nonrec } \Gamma[x::h=y] \longleftrightarrow \text{nonrec } \Gamma$

*<proof>*

**end**

### 3.4 Launchbury

**theory** *Launchbury*

**imports** *Terms Substitution*

**begin**

#### 3.4.1 The natural semantics

This is the semantics as in [Lau93], with two differences:

- Explicit freshness requirements for bound variables in the application and the Let rule.
- An additional parameter that stores variables that have to be avoided, but do not occur in the judgement otherwise, following [Ses97].

**inductive**

*reds* :: *heap*  $\Rightarrow$  *exp*  $\Rightarrow$  *var list*  $\Rightarrow$  *heap*  $\Rightarrow$  *exp*  $\Rightarrow$  *bool*

$(\langle - : - \Downarrow - : - \rangle [50, 50, 50, 50] 50)$

**where**

*Lambda*:

$\Gamma : (\text{Lam } [x]. e) \Downarrow_L \Gamma : (\text{Lam } [x]. e)$

| *Application*:  $\llbracket$

*atom*  $y \# (\Gamma, e, x, L, \Delta, \Theta, z)$  ;

$\Gamma : e \Downarrow_L \Delta : (\text{Lam } [y]. e')$  ;

$\Delta : e'[y ::= x] \Downarrow_L \Theta : z$

$\rrbracket \implies$

$\Gamma : \text{App } e x \Downarrow_L \Theta : z$

| *Variable*:  $\llbracket$

$map\text{-of } \Gamma \ x = \text{Some } e; \text{ delete } x \ \Gamma : e \Downarrow_{x\#L} \Delta : z$   
 $\Downarrow \Rightarrow$   
 $\Gamma : \text{Var } x \Downarrow_L (x, z) \# \Delta : z$   
| *Let*:  $\Downarrow$   
 $atom \text{ ' } domA \ \Delta \ \#* (\Gamma, L);$   
 $\Delta @ \Gamma : body \Downarrow_L \Theta : z$   
 $\Downarrow \Rightarrow$   
 $\Gamma : \text{Let } \Delta \ body \Downarrow_L \Theta : z$   
| *Bool*:  
 $\Gamma : \text{Bool } b \Downarrow_L \Gamma : \text{Bool } b$   
| *IfThenElse*:  $\Downarrow$   
 $\Gamma : scrut \Downarrow_L \Delta : (\text{Bool } b);$   
 $\Delta : (\text{if } b \text{ then } e_1 \text{ else } e_2) \Downarrow_L \Theta : z$   
 $\Downarrow \Rightarrow$   
 $\Gamma : (\text{scrut } ? \ e_1 : e_2) \Downarrow_L \Theta : z$

**equivariance** *reds*

**nominal-inductive** *reds*

**avoids** *Application*:  $y$   
 $\langle proof \rangle$

### 3.4.2 Example evaluations

**lemma** *eval-test*:

$\Downarrow : (\text{Let } [(x, Lam [y]. Var y)] (Var x)) \Downarrow_{\Downarrow} [(x, Lam [y]. Var y)] : (Lam [y]. Var y)$   
 $\langle proof \rangle$

**lemma** *eval-test2*:

$y \neq x \Rightarrow n \neq y \Rightarrow n \neq x \Rightarrow \Downarrow : (\text{Let } [(x, Lam [y]. Var y)] (App (Var x) x)) \Downarrow_{\Downarrow} [(x, Lam [y]. Var y)] : (Lam [y]. Var y)$   
 $\langle proof \rangle$

### 3.4.3 Better introduction rules

This variant do not require freshness.

**lemma** *reds-ApplicationI*:

**assumes**  $\Gamma : e \Downarrow_L \Delta : Lam [y]. e'$   
**assumes**  $\Delta : e'[y::=x] \Downarrow_L \Theta : z$   
**shows**  $\Gamma : App \ e \ x \Downarrow_L \Theta : z$   
 $\langle proof \rangle$

**lemma** *reds-SmartLet*:  $\Downarrow$

$atom \text{ ' } domA \ \Delta \ \#* (\Gamma, L);$   
 $\Delta @ \Gamma : body \Downarrow_L \Theta : z$   
 $\Downarrow \Rightarrow$   
 $\Gamma : \text{SmartLet } \Delta \ body \Downarrow_L \Theta : z$   
 $\langle proof \rangle$

A single rule for values

**lemma** *reds-isValI*:

$isVal\ z \implies \Gamma : z \Downarrow_L \Gamma : z$

*<proof>*

### 3.4.4 Properties of the semantics

Heap entries are never removed.

**lemma** *reds-doesnt-forget*:

$\Gamma : e \Downarrow_L \Delta : z \implies domA\ \Gamma \subseteq domA\ \Delta$

*<proof>*

Live variables are not added to the heap.

**lemma** *reds-avoids-live'*:

**assumes**  $\Gamma : e \Downarrow_L \Delta : z$

**shows**  $(domA\ \Delta - domA\ \Gamma) \cap set\ L = \{\}$

*<proof>*

**lemma** *reds-avoids-live*:

$\llbracket \Gamma : e \Downarrow_L \Delta : z;$

$x \in set\ L;$

$x \notin domA\ \Gamma$

$\rrbracket \implies x \notin domA\ \Delta$

*<proof>*

Fresh variables either stay fresh or are added to the heap.

**lemma** *reds-fresh*:  $\llbracket \Gamma : e \Downarrow_L \Delta : z;$

$atom\ (x::var)\ \#\ (\Gamma, e)$

$\rrbracket \implies atom\ x\ \#\ (\Delta, z) \vee x \in (domA\ \Delta - set\ L)$

*<proof>*

**lemma** *reds-fresh-fv*:  $\llbracket \Gamma : e \Downarrow_L \Delta : z;$

$x \in fv\ (\Delta, z) \wedge (x \notin domA\ \Delta \vee x \in set\ L)$

$\rrbracket \implies x \in fv\ (\Gamma, e)$

*<proof>*

**lemma** *new-free-vars-on-heap*:

**assumes**  $\Gamma : e \Downarrow_L \Delta : z$

**shows**  $fv\ (\Delta, z) - domA\ \Delta \subseteq fv\ (\Gamma, e) - domA\ \Gamma$

*<proof>*

**lemma** *reds-pres-closed*:

**assumes**  $\Gamma : e \Downarrow_L \Delta : z$

**and**  $fv\ (\Gamma, e) \subseteq set\ L \cup domA\ \Gamma$

**shows**  $fv\ (\Delta, z) \subseteq set\ L \cup domA\ \Delta$

*<proof>*

Reducing the set of variables to avoid is always possible.

**lemma** *reds-smaller-L*:  $\llbracket \Gamma : e \Downarrow_L \Delta : z ;$   
 $set\ L' \subseteq set\ L$   
 $\rrbracket \implies \Gamma : e \Downarrow_{L'} \Delta : z$   
 $\langle proof \rangle$

Things are evaluated to a lambda expression, and the variable can be freely chose.

**lemma** *result-evaluated*:  
 $\Gamma : e \Downarrow_L \Delta : z \implies isVal\ z$   
 $\langle proof \rangle$

**lemma** *result-evaluated-fresh*:  
**assumes**  $\Gamma : e \Downarrow_L \Delta : z$   
**obtains**  $y\ e'$   
**where**  $z = (Lam\ [y].\ e')$  **and**  $atom\ y \# (c::'a::fs) \mid b$  **where**  $z = Bool\ b$   
 $\langle proof \rangle$

**end**

## 4 Denotational domain

### 4.1 Value

**theory** *Value*  
**imports** *HOLCF*  
**begin**

#### 4.1.1 The semantic domain for values and environments

**domain** *Value* =  $Fn\ (lazy\ Value \rightarrow Value) \mid B\ (lazy\ bool\ discr)$

**fixrec** *Fn-project* ::  $Value \rightarrow Value \rightarrow Value$   
**where**  $Fn-project.(Fn.f) = f$

**abbreviation** *Fn-project-abbr* (**infix**  $\langle \Downarrow_{Fn} \rangle\ 55$ )  
**where**  $f \Downarrow_{Fn}\ v \equiv Fn-project.f.v$

**lemma** [*simp*]:  
 $\perp \Downarrow_{Fn}\ x = \perp$   
 $(B.b) \Downarrow_{Fn}\ x = \perp$   
 $\langle proof \rangle$

**fixrec** *B-project* ::  $Value \rightarrow Value \rightarrow Value \rightarrow Value$  **where**  
 $B-project.(B.db).v_1.v_2 = (if\ undiscr\ db\ then\ v_1\ else\ v_2)$

**lemma** [*simp*]:

$B\text{-project} \cdot (B \cdot (\text{Discr } b)) \cdot v_1 \cdot v_2 = (\text{if } b \text{ then } v_1 \text{ else } v_2)$   
 $B\text{-project} \cdot \perp \cdot v_1 \cdot v_2 = \perp$   
 $B\text{-project} \cdot (Fn \cdot f) \cdot v_1 \cdot v_2 = \perp$   
 <proof>

A chain in the domain *Value* is either always bottom, or eventually *Fn* of another chain

**lemma** *Value-chainE*[consumes 1, case-names bot B Fn]:

**assumes** *chain* *Y*  
**obtains**  $Y = (\lambda \cdot \perp) \mid$   
 $n \ b \ \mathbf{where} \ Y = (\lambda \ m. (\text{if } m < n \text{ then } \perp \text{ else } B \cdot b)) \mid$   
 $n \ Y' \ \mathbf{where} \ Y = (\lambda \ m. (\text{if } m < n \text{ then } \perp \text{ else } Fn \cdot (Y' (m-n)))) \ \mathit{chain} \ Y'$   
 <proof>

end

## 4.2 Value-Nominal

**theory** *Value-Nominal*

**imports** *Value Nominal-Utils Nominal-HOLCF*

**begin**

Values are pure, i.e. contain no variables.

**instantiation** *Value* :: *pure*

**begin**

**definition**  $p \cdot (v :: \text{Value}) = v$

**instance**

<proof>

**end**

**instance** *Value* :: *pcpo-pt*

<proof>

**end**

## 5 Denotational semantics

### 5.1 Iterative

```
theory Iterative
imports Env-HOLCF
begin
```

A setup for defining a fixed point of mutual recursive environments iteratively

```
locale iterative =
  fixes  $\rho :: 'a::type \Rightarrow 'b::pcpo$ 
  and  $e1 :: ('a \Rightarrow 'b) \rightarrow ('a \Rightarrow 'b)$ 
  and  $e2 :: ('a \Rightarrow 'b) \rightarrow 'b$ 
  and  $S :: 'a \text{ set}$  and  $x :: 'a$ 
  assumes  $ne:x \notin S$ 
begin
  abbreviation  $L == (\Lambda \rho'. (\rho \text{ ++}_S e1 \cdot \rho')(x := e2 \cdot \rho'))$ 
  abbreviation  $H == (\lambda \rho'. \Lambda \rho''. \rho' \text{ ++}_S e1 \cdot \rho'')$ 
  abbreviation  $R == (\Lambda \rho'. (\rho \text{ ++}_S (\text{fix} \cdot (H \rho')))(x := e2 \cdot \rho'))$ 
  abbreviation  $R' == (\Lambda \rho'. (\rho \text{ ++}_S (\text{fix} \cdot (H \rho')))(x := e2 \cdot (\text{fix} \cdot (H \rho'))))$ 

  lemma split-x:
    fixes  $y$ 
    obtains  $y = x$  and  $y \notin S \mid y \in S$  and  $y \neq x \mid y \notin S$  and  $y \neq x$   $\langle$ proof $\rangle$ 
  lemmas below = fun-belowI[OF split-x, where  $y1 = \lambda x. x$ ]
  lemmas eq = ext[OF split-x, where  $y1 = \lambda x. x$ ]

  lemma lookup-fix[simp]:
    fixes  $y$  and  $F :: ('a \Rightarrow 'b) \rightarrow ('a \Rightarrow 'b)$ 
    shows  $(\text{fix} \cdot F) y = (F \cdot (\text{fix} \cdot F)) y$ 
     $\langle$ proof $\rangle$ 

  lemma R-S:  $\bigwedge y. y \in S \implies (\text{fix} \cdot R) y = (e1 \cdot (\text{fix} \cdot (H (\text{fix} \cdot R)))) y$ 
     $\langle$ proof $\rangle$ 

  lemma R'-S:  $\bigwedge y. y \in S \implies (\text{fix} \cdot R') y = (e1 \cdot (\text{fix} \cdot (H (\text{fix} \cdot R')))) y$ 
     $\langle$ proof $\rangle$ 

  lemma HR-is-R[simp]:  $\text{fix} \cdot (H (\text{fix} \cdot R)) = \text{fix} \cdot R$ 
     $\langle$ proof $\rangle$ 

  lemma HR'-is-R'[simp]:  $\text{fix} \cdot (H (\text{fix} \cdot R')) = \text{fix} \cdot R'$ 
     $\langle$ proof $\rangle$ 

  lemma H-noop:
    fixes  $\rho' \rho''$ 
    assumes  $\bigwedge y. y \in S \implies y \neq x \implies (e1 \cdot \rho'') y \sqsubseteq \rho' y$ 
    shows  $H \rho' \cdot \rho'' \sqsubseteq \rho'$ 
     $\langle$ proof $\rangle$ 
```

**lemma** *HL-is-L[simp]*:  $fix \cdot (H (fix \cdot L)) = fix \cdot L$   
 ⟨*proof*⟩

**lemma** *iterative-override-on*:  
 shows  $fix \cdot L = fix \cdot R$   
 ⟨*proof*⟩

**lemma** *iterative-override-on'*:  
 shows  $fix \cdot L = fix \cdot R'$   
 ⟨*proof*⟩

**end**

**end**

## 5.2 HasESem

**theory** *HasESem*  
**imports** *Nominal-HOLCF Env-HOLCF*  
**begin**

A locale to work abstract in the expression type and semantics.

**locale** *has-ESem* =  
 fixes *ESem* ::  $'exp::pt \Rightarrow ('var::at-base \Rightarrow 'value) \rightarrow 'value::\{pure,pcpo\}$   
**begin**  
 abbreviation *ESem-syn* ( $\langle \llbracket - \rrbracket_{\varrho} \rangle [0,0] 110$ ) **where**  $\llbracket e \rrbracket_{\varrho} \equiv ESem \ e \cdot \varrho$   
**end**

**locale** *has-ignore-fresh-ESem* = *has-ESem* +  
 assumes *fv-supp*:  $supp \ e = atom \ ' (fv \ e :: 'b \ set)$   
 assumes *ESem-considers-fv*:  $\llbracket e \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho} f | ' (fv \ e)$

**end**

## 5.3 HeapSemantics

**theory** *HeapSemantics*  
**imports** *EvalHeap AList-Utills-Nominal HasESem Iterative Env-Nominal*  
**begin**

### 5.3.1 A locale for heap semantics, abstract in the expression semantics

**context** *has-ESem*  
**begin**

**abbreviation** *EvalHeapSem-syn* ( $\langle \llbracket - \rrbracket_{\varrho} \rangle [0,0] 110$ )  
**where**  $EvalHeapSem \ \Gamma \ \varrho \equiv evalHeap \ \Gamma \ (\lambda \ e. \llbracket e \rrbracket_{\varrho})$

**definition**

$HSem :: ('var \times 'exp) list \Rightarrow ('var \Rightarrow 'value) \rightarrow ('var \Rightarrow 'value)$   
**where**  $HSem \Gamma = (\Lambda \varrho \cdot (\mu \varrho'. \varrho ++_{domA} \Gamma \llbracket \Gamma \rrbracket_{\varrho'}))$

**abbreviation**  $HSem-syn (\langle \{ \cdot \} \rangle \rightarrow [0,60] 60)$ 

**where**  $\{\Gamma\}\varrho \equiv HSem \Gamma \cdot \varrho$

**lemma**  $HSem-def'$ :  $\{\Gamma\}\varrho = (\mu \varrho'. \varrho ++_{domA} \Gamma \llbracket \Gamma \rrbracket_{\varrho'})$ 

$\langle proof \rangle$

**5.3.2 Induction and other lemmas about  $HSem$** **lemma**  $HSem-ind$ :

**assumes**  $adm P$

**assumes**  $P \perp$

**assumes**  $step: \bigwedge \varrho'. P \varrho' \Longrightarrow P (\varrho ++_{domA} \Gamma \llbracket \Gamma \rrbracket_{\varrho'})$

**shows**  $P (\{\Gamma\}\varrho)$

$\langle proof \rangle$

**lemma**  $HSem-below$ :

**assumes**  $rho: \bigwedge x. x \notin domA h \Longrightarrow \varrho x \sqsubseteq r x$

**assumes**  $h: \bigwedge x. x \in domA h \Longrightarrow \llbracket the (map-of h x) \rrbracket_r \sqsubseteq r x$

**shows**  $\{h\}\varrho \sqsubseteq r$

$\langle proof \rangle$

**lemma**  $HSem-bot-below$ :

**assumes**  $h: \bigwedge x. x \in domA h \Longrightarrow \llbracket the (map-of h x) \rrbracket_r \sqsubseteq r x$

**shows**  $\{h\}\perp \sqsubseteq r$

$\langle proof \rangle$

**lemma**  $HSem-bot-ind$ :

**assumes**  $adm P$

**assumes**  $P \perp$

**assumes**  $step: \bigwedge \varrho'. P \varrho' \Longrightarrow P (\llbracket \Gamma \rrbracket_{\varrho'})$

**shows**  $P (\{\Gamma\}\perp)$

$\langle proof \rangle$

**lemma**  $parallel-HSem-ind$ :

**assumes**  $adm (\lambda \varrho'. P (fst \varrho') (snd \varrho'))$

**assumes**  $P \perp \perp$

**assumes**  $step: \bigwedge y z. P y z \Longrightarrow$

$P (\varrho_1 ++_{domA} \Gamma_1 \llbracket \Gamma_1 \rrbracket y) (\varrho_2 ++_{domA} \Gamma_2 \llbracket \Gamma_2 \rrbracket z)$

**shows**  $P (\{\Gamma_1\}\varrho_1) (\{\Gamma_2\}\varrho_2)$

$\langle proof \rangle$

**lemma**  $HSem-eq$ :

**shows**  $\{\Gamma\}\varrho = \varrho ++_{domA} \Gamma \llbracket \Gamma \rrbracket_{\{\Gamma\}\varrho}$

$\langle proof \rangle$

**lemma** *HSem-bot-eq*:

**shows**  $\{\Gamma\}^\perp = \llbracket \Gamma \rrbracket \{\Gamma\}^\perp$

*<proof>*

**lemma** *lookup-HSem-other*:

**assumes**  $y \notin \text{dom} A \ h$

**shows**  $(\{h\}^\varrho) y = \varrho y$

*<proof>*

**lemma** *lookup-HSem-heap*:

**assumes**  $y \in \text{dom} A \ h$

**shows**  $(\{h\}^\varrho) y = \llbracket \text{the } (\text{map-of } h \ y) \rrbracket \{h\}^\varrho$

*<proof>*

**lemma** *HSem-edom-subset*:  $\text{edom } (\{\Gamma\}^\varrho) \subseteq \text{edom } \varrho \cup \text{dom} A \ \Gamma$

*<proof>*

**lemma** (*in*  $-$ ) *env-restr-override-onI*:  $-S2 \subseteq S \implies \text{env-restr } S \ \varrho1 \ ++_{S2} \ \varrho2 = \varrho1 \ ++_{S2} \ \varrho2$

*<proof>*

**lemma** *HSem-restr*:

$\{h\}^\varrho (f |' (- \text{dom} A \ h)) = \{h\}^\varrho$

*<proof>*

**lemma** *HSem-restr-cong*:

**assumes**  $\varrho f |' (- \text{dom} A \ h) = \varrho' f |' (- \text{dom} A \ h)$

**shows**  $\{h\}^\varrho = \{h\}^{\varrho'}$

*<proof>*

**lemma** *HSem-restr-cong-below*:

**assumes**  $\varrho f |' (- \text{dom} A \ h) \sqsubseteq \varrho' f |' (- \text{dom} A \ h)$

**shows**  $\{h\}^\varrho \sqsubseteq \{h\}^{\varrho'}$

*<proof>*

**lemma** *HSem-reorder*:

**assumes**  $\text{map-of } \Gamma = \text{map-of } \Delta$

**shows**  $\{\Gamma\}^\varrho = \{\Delta\}^\varrho$

*<proof>*

**lemma** *HSem-reorder-head*:

**assumes**  $x \neq y$

**shows**  $\{(x, e1) \# (y, e2) \# \Gamma\}^\varrho = \{(y, e2) \# (x, e1) \# \Gamma\}^\varrho$

*<proof>*

**lemma** *HSem-reorder-head-append*:

**assumes**  $x \notin \text{dom} A \ \Gamma$

**shows**  $\{(x, e) \# \Gamma @ \Delta\}^\varrho = \{\Gamma @ ((x, e) \# \Delta)\}^\varrho$

*<proof>*

**lemma** *env-restr-HSem*:  
**assumes**  $\text{dom}A \ \Gamma \cap S = \{\}$   
**shows**  $(\{\Gamma\} \rho) f |' S = \rho f |' S$   
 $\langle \text{proof} \rangle$

**lemma** *env-restr-HSem-noop*:  
**assumes**  $\text{dom}A \ \Gamma \cap \text{edom} \ \rho = \{\}$   
**shows**  $(\{\Gamma\} \rho) f |' \text{edom} \ \rho = \rho$   
 $\langle \text{proof} \rangle$

**lemma** *HSem-Nil[simp]*:  $\{\{\}\} \rho = \rho$   
 $\langle \text{proof} \rangle$

### 5.3.3 Substitution

**lemma** *HSem-subst-exp*:  
**assumes**  $\bigwedge \rho'. \llbracket e \rrbracket_{\rho'} = \llbracket e' \rrbracket_{\rho'}$   
**shows**  $\{(x, e) \# \Gamma\} \rho = \{(x, e') \# \Gamma\} \rho$   
 $\langle \text{proof} \rangle$

**lemma** *HSem-subst-expr-below*:  
**assumes** *below*:  $\llbracket e1 \rrbracket \{(x, e2) \# \Gamma\} \rho \sqsubseteq \llbracket e2 \rrbracket \{(x, e2) \# \Gamma\} \rho$   
**shows**  $\{(x, e1) \# \Gamma\} \rho \sqsubseteq \{(x, e2) \# \Gamma\} \rho$   
 $\langle \text{proof} \rangle$

**lemma** *HSem-subst-expr*:  
**assumes** *below1*:  $\llbracket e1 \rrbracket \{(x, e2) \# \Gamma\} \rho \sqsubseteq \llbracket e2 \rrbracket \{(x, e2) \# \Gamma\} \rho$   
**assumes** *below2*:  $\llbracket e2 \rrbracket \{(x, e1) \# \Gamma\} \rho \sqsubseteq \llbracket e1 \rrbracket \{(x, e1) \# \Gamma\} \rho$   
**shows**  $\{(x, e1) \# \Gamma\} \rho = \{(x, e2) \# \Gamma\} \rho$   
 $\langle \text{proof} \rangle$

### 5.3.4 Re-calculating the semantics of the heap is idempotent

**lemma** *HSem-redo*:  
**shows**  $\{\Gamma\}(\{\Gamma \ @ \ \Delta\} \rho) f |' (\text{edom} \ \rho \cup \text{dom}A \ \Delta) = \{\Gamma \ @ \ \Delta\} \rho$  (is ?LHS = ?RHS)  
 $\langle \text{proof} \rangle$

### 5.3.5 Iterative definition of the heap semantics

**lemma** *iterative-HSem*:  
**assumes**  $x \notin \text{dom}A \ \Gamma$   
**shows**  $\{(x, e) \# \Gamma\} \rho = (\mu \ \rho'. (\rho \ ++_{\text{dom}A \ \Gamma} (\{\Gamma\} \rho')) (x := \llbracket e \rrbracket_{\rho'}))$   
 $\langle \text{proof} \rangle$

**lemma** *iterative-HSem'*:  
**assumes**  $x \notin \text{dom}A \ \Gamma$   
**shows**  $(\mu \ \rho'. (\rho \ ++_{\text{dom}A \ \Gamma} (\{\Gamma\} \rho')) (x := \llbracket e \rrbracket_{\rho'}))$   
 $= (\mu \ \rho'. (\rho \ ++_{\text{dom}A \ \Gamma} (\{\Gamma\} \rho')) (x := \llbracket e \rrbracket_{\{\Gamma\} \rho'}))$   
 $\langle \text{proof} \rangle$

### 5.3.6 Fresh variables on the heap are irrelevant

**lemma** *HSem-ignores-fresh-restr'*:

**assumes**  $fv \Gamma \subseteq S$

**assumes**  $\bigwedge x \varrho. x \in dom A \Gamma \implies \llbracket the (map-of \Gamma x) \rrbracket_{\varrho} = \llbracket the (map-of \Gamma x) \rrbracket_{\varrho} f|' (fv (the (map-of \Gamma x)))$

**shows**  $(\{\Gamma\}_{\varrho}) f|' S = \{\Gamma\}_{\varrho} f|' S$

*<proof>*

**end**

### 5.3.7 Freshness

**context** *has-ignore-fresh-ESem* **begin**

**lemma** *ESem-fresh-cong*:

**assumes**  $\varrho f|' (fv e) = \varrho' f|' (fv e)$

**shows**  $\llbracket e \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho'}$

*<proof>*

**lemma** *ESem-fresh-cong-subset*:

**assumes**  $fv e \subseteq S$

**assumes**  $\varrho f|' S = \varrho' f|' S$

**shows**  $\llbracket e \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho'}$

*<proof>*

**lemma** *ESem-fresh-cong-below*:

**assumes**  $\varrho f|' (fv e) \subseteq \varrho' f|' (fv e)$

**shows**  $\llbracket e \rrbracket_{\varrho} \subseteq \llbracket e \rrbracket_{\varrho'}$

*<proof>*

**lemma** *ESem-fresh-cong-below-subset*:

**assumes**  $fv e \subseteq S$

**assumes**  $\varrho f|' S \subseteq \varrho' f|' S$

**shows**  $\llbracket e \rrbracket_{\varrho} \subseteq \llbracket e \rrbracket_{\varrho'}$

*<proof>*

**lemma** *ESem-ignores-fresh-restr*:

**assumes**  $atom' S \#* e$

**shows**  $\llbracket e \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho} f|' (- S)$

*<proof>*

**lemma** *ESem-ignores-fresh-restr'*:

**assumes**  $atom' (edom \varrho - S) \#* e$

**shows**  $\llbracket e \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho} f|' S$

*<proof>*

**lemma** *HSem-ignores-fresh-restr''*:

**assumes**  $fv \Gamma \subseteq S$

**shows**  $(\{\Gamma\}_{\varrho}) f|' S = \{\Gamma\}_{\varrho} f|' S$

*<proof>*

**lemma** *HSem-ignores-fresh-restr:*  
**assumes**  $atom \ ' S \ \#^* \ \Gamma$   
**shows**  $(\{\Gamma\}\varrho) f|' (- S) = \{\Gamma\}\varrho f|' (- S)$   
 $\langle proof \rangle$

**lemma** *HSem-fresh-cong-below:*  
**assumes**  $\varrho f|' ((S \cup fv \ \Gamma) - domA \ \Gamma) \sqsubseteq \varrho' f|' ((S \cup fv \ \Gamma) - domA \ \Gamma)$   
**shows**  $(\{\Gamma\}\varrho) f|' S \sqsubseteq (\{\Gamma\}\varrho') f|' S$   
 $\langle proof \rangle$

**lemma** *HSem-fresh-cong:*  
**assumes**  $\varrho f|' ((S \cup fv \ \Gamma) - domA \ \Gamma) = \varrho' f|' ((S \cup fv \ \Gamma) - domA \ \Gamma)$   
**shows**  $(\{\Gamma\}\varrho) f|' S = (\{\Gamma\}\varrho') f|' S$   
 $\langle proof \rangle$

### 5.3.8 Adding a fresh variable to a heap does not affect its semantics

**lemma** *HSem-add-fresh':*  
**assumes**  $fresh: atom \ x \ \# \ \Gamma$   
**assumes**  $x \notin edom \ \varrho$   
**assumes**  $step: \bigwedge e \ \varrho'. e \in snd \ ' set \ \Gamma \implies \llbracket e \rrbracket_{\varrho'} = \llbracket e \rrbracket_{env-delete \ x \ \varrho'}$   
**shows**  $env-delete \ x \ (\{(x, e) \ \# \ \Gamma\}\varrho) = \{\Gamma\}\varrho$   
 $\langle proof \rangle$

**lemma** *HSem-add-fresh:*  
**assumes**  $atom \ x \ \# \ \Gamma$   
**assumes**  $x \notin edom \ \varrho$   
**shows**  $env-delete \ x \ (\{(x, e) \ \# \ \Gamma\}\varrho) = \{\Gamma\}\varrho$   
 $\langle proof \rangle$

### 5.3.9 Mutual recursion with fresh variables

**lemma** *HSem-subset-below:*  
**assumes**  $fresh: atom \ ' domA \ \Gamma \ \#^* \ \Delta$   
**shows**  $\{\Delta\}(\varrho f|' (- domA \ \Gamma)) \sqsubseteq (\{\Delta@ \ \Gamma\}\varrho) f|' (- domA \ \Gamma)$   
 $\langle proof \rangle$

In the following lemma we show that the semantics of fresh variables can be calculated together with the presently bound variables, or separately.

**lemma** *HSem-merge:*  
**assumes**  $fresh: atom \ ' domA \ \Gamma \ \#^* \ \Delta$   
**shows**  $\{\Gamma\}\{\Delta\}\varrho = \{\Gamma@ \ \Delta\}\varrho$   
 $\langle proof \rangle$   
**end**

### 5.3.10 Parallel induction

**lemma** *parallel-HSem-ind-different-ESem:*

```

assumes adm ( $\lambda \varrho'. P$  ( $\text{fst } \varrho'$ ) ( $\text{snd } \varrho'$ ))
assumes  $P \perp \perp$ 
assumes  $\bigwedge y z. P y z \implies P (\varrho \text{ ++ domA } h \text{ evalHeap } h (\lambda e. \text{ESem1 } e \cdot y)) (\varrho' \text{ ++ domA } h' \text{ evalHeap } h' (\lambda e. \text{ESem2 } e \cdot z))$ 
shows  $P (\text{has-ESem.HSem } \text{ESem1 } h \cdot \varrho) (\text{has-ESem.HSem } \text{ESem2 } h' \cdot \varrho')$ 
<proof>

```

### 5.3.11 Congruence rule

```

lemma HSem-cong[fundef-cong]:
   $\llbracket (\bigwedge e. e \in \text{snd } \text{'set heap2} \implies \text{ESem1 } e = \text{ESem2 } e); \text{heap1} = \text{heap2} \rrbracket$ 
   $\implies \text{has-ESem.HSem } \text{ESem1 } \text{heap1} = \text{has-ESem.HSem } \text{ESem2 } \text{heap2}$ 
<proof>

```

### 5.3.12 Equivariance of the heap semantics

```

lemma HSem-eqvt[eqvt]:
   $\pi \cdot \text{has-ESem.HSem } \text{ESem } \Gamma = \text{has-ESem.HSem } (\pi \cdot \text{ESem}) (\pi \cdot \Gamma)$ 
<proof>

```

end

## 5.4 AbstractDenotational

```

theory AbstractDenotational
imports HeapSemantics Terms
begin

```

### 5.4.1 The denotational semantics for expressions

Because we need to define two semantics later on, we are abstract in the actual domain.

```

locale semantic-domain =
  fixes Fn :: ('Value  $\rightarrow$  'Value)  $\rightarrow$  ('Value::{pcpo-pt,pure})
  fixes Fn-project :: 'Value  $\rightarrow$  ('Value  $\rightarrow$  'Value)
  fixes B :: bool discr  $\rightarrow$  'Value
  fixes B-project :: 'Value  $\rightarrow$  'Value  $\rightarrow$  'Value  $\rightarrow$  'Value
  fixes tick :: 'Value  $\rightarrow$  'Value
begin

```

#### nominal-function

```

  ESem :: exp  $\Rightarrow$  (var  $\Rightarrow$  'Value)  $\rightarrow$  'Value
where
  ESem (Lam [x]. e) = ( $\Lambda \varrho. \text{tick} \cdot (\text{Fn} \cdot (\Lambda v. \text{ESem } e \cdot ((\varrho \text{ f} | \text{'fv } (\text{Lam } [x]. e))(x := v))))$ )
| ESem (App e x) = ( $\Lambda \varrho. \text{tick} \cdot (\text{Fn-project} \cdot (\text{ESem } e \cdot \varrho) \cdot (\varrho \text{ x}))$ )
| ESem (Var x) = ( $\Lambda \varrho. \text{tick} \cdot (\varrho \text{ x})$ )
| ESem (Let as body) = ( $\Lambda \varrho. \text{tick} \cdot (\text{ESem } \text{body} \cdot (\text{has-ESem.HSem } \text{ESem } \text{as} \cdot (\varrho \text{ f} | \text{'fv } (\text{Let } \text{as } \text{body}))))$ )
| ESem (Bool b) = ( $\Lambda \varrho. \text{tick} \cdot (\text{B} \cdot (\text{Discr } b))$ )

```

|  $ESem$  (*scrut* ?  $e1 : e2$ ) = ( $\Lambda \varrho. tick \cdot ((B\text{-project} \cdot (ESem \text{ scrut} \cdot \varrho)) \cdot (ESem \ e1 \cdot \varrho)) \cdot (ESem \ e2 \cdot \varrho)$ )  
 $\langle proof \rangle$

**nominal-termination** (in *semantic-domain*) (*no-eqvt*)  $\langle proof \rangle$

**sublocale** *has-ESem ESem*  $\langle proof \rangle$

**notation** *ESem-syn* ( $\langle \llbracket - \rrbracket \rangle$  [60,60] 60)

**notation** *EvalHeapSem-syn* ( $\langle \llbracket - \rrbracket \rangle$  [0,0] 110)

**notation** *HSem-syn* ( $\langle \{\!-\!\} \rangle$  [60,60] 60)

**abbreviation** *AHSem-bot* ( $\langle \{\!-\!\} \rangle$  [60] 60) **where**  $\{\Gamma\} \equiv \{\Gamma\} \perp$

**end**

**end**

## 5.5 Abstract-Denotational-Props

**theory** *Abstract-Denotational-Props*

**imports** *AbstractDenotational Substitution*

**begin**

**context** *semantic-domain*

**begin**

### 5.5.1 The semantics ignores fresh variables

**lemma** *ESem-considers-fv'*:  $\llbracket e \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho} f |' (fv \ e)$   
 $\langle proof \rangle$

**sublocale** *has-ignore-fresh-ESem ESem*  
 $\langle proof \rangle$

### 5.5.2 Nicer equations for ESem, without freshness requirements

**lemma** *ESem-Lam[simp]*:  $\llbracket Lam \ [x]. \ e \rrbracket_{\varrho} = tick \cdot (Fn \cdot (\Lambda \ v. \llbracket e \rrbracket_{\varrho}(x := v)))$   
 $\langle proof \rangle$

**declare** *ESem.simps(1)[simp del]*

**lemma** *ESem-Let[simp]*:  $\llbracket Let \ as \ body \rrbracket_{\varrho} = tick \cdot (\llbracket body \rrbracket_{\{\!as\!\}}_{\varrho})$   
 $\langle proof \rangle$

**declare** *ESem.simps(4)[simp del]*

### 5.5.3 Denotation of Substitution

**lemma** *ESem-subst-same*:  $\varrho \ x = \varrho \ y \implies \llbracket e \rrbracket_{\varrho} = \llbracket e[x ::= y] \rrbracket_{\varrho}$   
**and**

$\varrho \ x = \varrho \ y \implies (\llbracket as \rrbracket_{\varrho}) = \llbracket as[x ::= h=y] \rrbracket_{\varrho}$   
 $\langle proof \rangle$

**lemma** *ESem-subst*:  
**shows**  $\llbracket e \rrbracket_{\sigma}(x := \sigma y) = \llbracket e[x::= y] \rrbracket_{\sigma}$   
 $\langle proof \rangle$

**end**

**end**

## 5.6 Denotational

**theory** *Denotational*  
**imports** *Abstract-Denotational-Props Value-Nominal*  
**begin**

This is the actual denotational semantics as found in [Lau93].

**interpretation** *semantic-domain Fn Fn-project B B-project*  $(\Lambda x. x)$  $\langle proof \rangle$

**notation** *ESem-syn*  $(\langle \llbracket - \rrbracket \rangle \ [60,60] \ 60)$   
**notation** *EvalHeapSem-syn*  $(\langle \llbracket - \rrbracket \rangle \ [0,0] \ 110)$   
**notation** *HSem-syn*  $(\langle \llbracket - \rrbracket \rangle \ [60,60] \ 60)$   
**notation** *AHSem-bot*  $(\langle \llbracket - \rrbracket \rangle \ [60] \ 60)$

**lemma** *ESem-simps-as-defined*:  
 $\llbracket Lam [x]. e \rrbracket_{\varrho} = Fn.(\Lambda v. \llbracket e \rrbracket_{(\varrho f |' (fv (Lam [x]. e)))(x := v)})$   
 $\llbracket App e x \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho} \downarrow Fn \ \varrho \ x$   
 $\llbracket Var x \rrbracket_{\varrho} = \varrho \ x$   
 $\llbracket Bool b \rrbracket_{\varrho} = B.(Discr \ b)$   
 $\llbracket (scrut \ ? \ e_1 : e_2) \rrbracket_{\varrho} = B-project.(\llbracket scrut \rrbracket_{\varrho}).(\llbracket e_1 \rrbracket_{\varrho}).(\llbracket e_2 \rrbracket_{\varrho})$   
 $\llbracket Let \ \Gamma \ body \rrbracket_{\varrho} = \llbracket body \rrbracket_{\{\Gamma\}(\varrho f |' fv (Let \ \Gamma \ body))}$   
 $\langle proof \rangle$

**lemma** *ESem-simps*:  
 $\llbracket Lam [x]. e \rrbracket_{\varrho} = Fn.(\Lambda v. \llbracket e \rrbracket_{\varrho}(x := v))$   
 $\llbracket App e x \rrbracket_{\varrho} = \llbracket e \rrbracket_{\varrho} \downarrow Fn \ \varrho \ x$   
 $\llbracket Var x \rrbracket_{\varrho} = \varrho \ x$   
 $\llbracket Bool b \rrbracket_{\varrho} = B.(Discr \ b)$   
 $\llbracket (scrut \ ? \ e_1 : e_2) \rrbracket_{\varrho} = B-project.(\llbracket scrut \rrbracket_{\varrho}).(\llbracket e_1 \rrbracket_{\varrho}).(\llbracket e_2 \rrbracket_{\varrho})$   
 $\llbracket Let \ \Gamma \ body \rrbracket_{\varrho} = \llbracket body \rrbracket_{\{\Gamma\}\varrho}$   
 $\langle proof \rangle \langle proof \rangle \langle proof \rangle$

**end**

## 6 Resourced denotational domain

### 6.1 C

```
theory C
imports HOLCF Mono-Nat-Fun
begin
```

```
default-sort cpo
```

The initial solution to the domain equation  $C = C_{\perp}$ , i.e. the completion of the natural numbers.

```
domain C = C (lazy C)
```

```
lemma below-C:  $x \sqsubseteq C \cdot x$ 
  <proof>
```

```
definition Cinf ( $\langle C^{\infty} \rangle$ ) where  $C^{\infty} = \text{fix} \cdot C$ 
```

```
lemma C-Cinf[simp]:  $C \cdot C^{\infty} = C^{\infty}$  <proof>
```

```
abbreviation Cpow ( $\langle C^{\cdot} \rangle$ ) where  $C^n \equiv \text{iterate } n \cdot C \cdot \perp$ 
```

```
lemma C-below-C[simp]:  $(C^i \sqsubseteq C^j) \longleftrightarrow i \leq j$ 
  <proof>
```

```
lemma below-Cinf[simp]:  $r \sqsubseteq C^{\infty}$ 
  <proof>
```

```
lemma C-eq-Cinf[simp]:  $C^i \neq C^{\infty}$ 
  <proof>
```

```
lemma Cinf-eq-C[simp]:  $C^{\infty} = C \cdot r \longleftrightarrow C^{\infty} = r$ 
  <proof>
```

```
lemma C-eq-C[simp]:  $(C^i = C^j) \longleftrightarrow i = j$ 
  <proof>
```

```
lemma case-of-C-below:  $(\text{case } r \text{ of } C \cdot y \Rightarrow x) \sqsubseteq x$ 
  <proof>
```

```
lemma C-case-below:  $C \cdot \text{case} \cdot f \sqsubseteq f$ 
  <proof>
```

```
lemma C-case-bot[simp]:  $C \cdot \text{case} \cdot \perp = \perp$ 
  <proof>
```

```
lemma C-case-cong:
```

**assumes**  $\bigwedge r'. r = C.r' \implies f.r' = g.r'$   
**shows**  $C\text{-case}.f.r = C\text{-case}.g.r$   
 $\langle\text{proof}\rangle$

**lemma**  $C\text{-cases}$ :  
**obtains**  $n$  **where**  $r = C^n \mid r = C^\infty$   
 $\langle\text{proof}\rangle$

**lemma**  $C\text{-case}\text{-Cinf}[simp]$ :  $C\text{-case} . f . C^\infty = f . C^\infty$   
 $\langle\text{proof}\rangle$

**end**

## 6.2 C-Meet

**theory**  $C\text{-Meet}$   
**imports**  $C\text{ HOLCF-Meet}$   
**begin**

**instantiation**  $C :: \text{Finite-Meet-cpo}$  **begin**  
**fixrec**  $C\text{-meet} :: C \rightarrow C \rightarrow C$   
**where**  $C\text{-meet}.(C.a).(C.b) = C.(C\text{-meet}.a.b)$

**lemma** $[simp]$ :  $C\text{-meet}.\perp.y = \perp \ C\text{-meet}.x.\perp = \perp$   $\langle\text{proof}\rangle$

**instance**  
 $\langle\text{proof}\rangle$   
**end**

**lemma**  $C\text{-meet-is-meet}$ :  $(z \sqsubseteq C\text{-meet}.x.y) = (z \sqsubseteq x \wedge z \sqsubseteq y)$   
 $\langle\text{proof}\rangle$

**instance**  $C :: \text{cont-binary-meet}$   
 $\langle\text{proof}\rangle$

**lemma**  $[simp]$ :  $C.r \sqcap r = r$   
 $\langle\text{proof}\rangle$

**lemma**  $[simp]$ :  $r \sqcap C.r = r$   
 $\langle\text{proof}\rangle$

**lemma**  $[simp]$ :  $C.r \sqcap C.r' = C.(r \sqcap r')$   
 $\langle\text{proof}\rangle$

**end**

## 6.3 C-restr

```
theory C-restr
imports C C-Meet HOLCF-Utills
begin
```

### 6.3.1 The demand of a C-function

The demand is the least amount of resources required to produce a non-bottom element, if at all.

**definition** *demand* ::  $(C \rightarrow 'a::pcpo) \Rightarrow C$  **where**  
*demand*  $f = (if\ f \cdot C^\infty \neq \perp\ then\ C^{(LEAST\ n.\ f \cdot C^n \neq \perp)}\ else\ C^\infty)$

Because of continuity, a non-bottom value can always be obtained with finite resources.

**lemma** *finite-resources-suffice*:  
**assumes**  $f \cdot C^\infty \neq \perp$   
**obtains**  $n$  **where**  $f \cdot C^n \neq \perp$   
*<proof>*

Because of monotonicity, a non-bottom value can always be obtained with more resources.

**lemma** *more-resources-suffice*:  
**assumes**  $f \cdot r \neq \perp$  **and**  $r \sqsubseteq r'$   
**shows**  $f \cdot r' \neq \perp$   
*<proof>*

**lemma** *infinite-resources-suffice*:  
**shows**  $f \cdot r \neq \perp \implies f \cdot C^\infty \neq \perp$   
*<proof>*

**lemma** *demand-suffices*:  
**assumes**  $f \cdot C^\infty \neq \perp$   
**shows**  $f \cdot (demand\ f) \neq \perp$   
*<proof>*

**lemma** *not-bot-demand*:  
 $f \cdot r \neq \perp \iff demand\ f \neq C^\infty \wedge demand\ f \sqsubseteq r$   
*<proof>*

**lemma** *infinity-bot-demand*:  
 $f \cdot C^\infty = \perp \iff demand\ f = C^\infty$   
*<proof>*

**lemma** *demand-suffices'*:  
**assumes**  $demand\ f = C^n$   
**shows**  $f \cdot (demand\ f) \neq \perp$   
*<proof>*

**lemma** *demand-Suc-Least*:

**assumes** *[simp]*:  $f \cdot \perp = \perp$

**assumes** *demand*  $f \neq C^\infty$

**shows**  $\text{demand } f = C^{(\text{Suc } (\text{LEAST } n. f \cdot C^{\text{Suc } n} \neq \perp))}$

*<proof>*

**lemma** *demand-C-case**[simp]*:  $\text{demand } (C\text{-case}\cdot f) = C \cdot (\text{demand } f)$

*<proof>*

**lemma** *demand-contravariant*:

**assumes**  $f \sqsubseteq g$

**shows**  $\text{demand } g \sqsubseteq \text{demand } f$

*<proof>*

### 6.3.2 Restricting functions with domain C

**fixrec** *C-restr* ::  $C \rightarrow (C \rightarrow 'a::\text{pcpo}) \rightarrow (C \rightarrow 'a)$

**where**  $C\text{-restr}\cdot r \cdot f \cdot r' = (f \cdot (r \sqcap r'))$

**abbreviation** *C-restr-syn* ::  $(C \rightarrow 'a::\text{pcpo}) \Rightarrow C \Rightarrow (C \rightarrow 'a)$  ( $\langle \cdot | \cdot \rangle$  [111,110] 110)

**where**  $f|_r \equiv C\text{-restr}\cdot r \cdot f$

**lemma** *[simp]*:  $\perp|_r = \perp$  *<proof>*

**lemma** *[simp]*:  $f \cdot \perp = \perp \implies f|_\perp = \perp$  *<proof>*

**lemma** *C-restr-C-restr**[simp]*:  $(v|_{r'})|_r = v|_{(r' \sqcap r)}$

*<proof>*

**lemma** *C-restr-eqD*:

**assumes**  $f|_r = g|_r$

**assumes**  $r' \sqsubseteq r$

**shows**  $f \cdot r' = g \cdot r'$

*<proof>*

**lemma** *C-restr-eq-lower*:

**assumes**  $f|_r = g|_r$

**assumes**  $r' \sqsubseteq r$

**shows**  $f|_{r'} = g|_{r'}$

*<proof>*

**lemma** *C-restr-below**[intro, simp]*:

$x|_r \sqsubseteq x$

*<proof>*

**lemma** *C-restr-below-cong*:

$(\bigwedge r'. r' \sqsubseteq r \implies f \cdot r' \sqsubseteq g \cdot r') \implies f|_r \sqsubseteq g|_r$

*<proof>*

**lemma** *C-restr-cong*:

$$(\bigwedge r'. r' \sqsubseteq r \implies f \cdot r' = g \cdot r') \implies f|_r = g|_r$$

*<proof>*

**lemma** *C-restr-C-cong*:

$$(\bigwedge r'. r' \sqsubseteq r \implies f \cdot (C \cdot r') = g \cdot (C \cdot r')) \implies f \cdot \perp = g \cdot \perp \implies f|_{C \cdot r} = g|_{C \cdot r}$$

*<proof>*

**lemma** *C-restr-C-case[simp]*:

$$(C\text{-case} \cdot f)|_{C \cdot r} = C\text{-case} \cdot (f|_r)$$

*<proof>*

**lemma** *C-restr-bot-demand*:

**assumes**  $C \cdot r \sqsubseteq \text{demand } f$

**shows**  $f|_r = \perp$

*<proof>*

### 6.3.3 Restricting maps of C-ranged functions

**definition** *env-C-restr* ::  $C \rightarrow ('var::type \Rightarrow (C \rightarrow 'a::pcpo)) \rightarrow ('var \Rightarrow (C \rightarrow 'a))$  **where**  
 $\text{env-C-restr} = (\bigwedge r f. \text{cfun-comp} \cdot (C\text{-restr} \cdot r) \cdot f)$

**abbreviation** *env-C-restr-syn* ::  $('var::type \Rightarrow (C \rightarrow 'a::pcpo)) \Rightarrow C \Rightarrow ('var \Rightarrow (C \rightarrow 'a))$  (  
 $\langle \cdot |^\circ \cdot \rangle$  [111,110] 110)

**where**  $f|^\circ_r \equiv \text{env-C-restr} \cdot r \cdot f$

**lemma** *env-C-restr-upd[simp]*:  $(\varrho(x := v))|^\circ_r = (\varrho|^\circ_r)(x := v|_r)$   
*<proof>*

**lemma** *env-C-restr-lookup[simp]*:  $(\varrho|^\circ_r) v = \varrho v|_r$   
*<proof>*

**lemma** *env-C-restr-bot[simp]*:  $\perp|^\circ_r = \perp$   
*<proof>*

**lemma** *env-C-restr-restr-below[intro]*:  $\varrho|^\circ_r \sqsubseteq \varrho$   
*<proof>*

**lemma** *env-C-restr-env-C-restr[simp]*:  $(v|^\circ_{r'})|^\circ_r = v|^\circ_{(r' \sqcap r)}$   
*<proof>*

**lemma** *env-C-restr-cong*:

$$(\bigwedge x r'. r' \sqsubseteq r \implies f x \cdot r' = g x \cdot r') \implies f|^\circ_r = g|^\circ_r$$

*<proof>*

**end**

## 6.4 CValue

**theory** *CValue*

**imports** *C*

**begin**

**domain** *CValue*

= *CFn* (**lazy** (*C* → *CValue*) → (*C* → *CValue*))  
 | *CB* (**lazy** *bool* *discr*)

**fixrec** *CFn-project* :: *CValue* → (*C* → *CValue*) → (*C* → *CValue*)

**where** *CFn-project*.(*CFn.f*).*v* = *f* · *v*

**abbreviation** *CFn-project-abbr* (**infix**  $\langle \downarrow CFn \rangle$  55)

**where**  $f \downarrow CFn v \equiv CFn-project.f \cdot v$

**lemma** *CFn-project-strict[simp]*:

$\perp \downarrow CFn v = \perp$   
 $CB \cdot b \downarrow CFn v = \perp$   
 $\langle proof \rangle$

**lemma** *CB-below[simp]*:  $CB \cdot b \sqsubseteq v \longleftrightarrow v = CB \cdot b$

$\langle proof \rangle$

**fixrec** *CB-project* :: *CValue* → *CValue* → *CValue* → *CValue* **where**

*CB-project*.(*CB.db*).*v*<sub>1</sub>·*v*<sub>2</sub> = (if *undiscr db* then *v*<sub>1</sub> else *v*<sub>2</sub>)

**lemma** [*simp*]:

*CB-project*.(*CB*.(*Discr b*)).*v*<sub>1</sub>·*v*<sub>2</sub> = (if *b* then *v*<sub>1</sub> else *v*<sub>2</sub>)  
*CB-project*. $\perp$ ·*v*<sub>1</sub>·*v*<sub>2</sub> =  $\perp$   
*CB-project*.(*CFn.f*).*v*<sub>1</sub>·*v*<sub>2</sub> =  $\perp$

$\langle proof \rangle$

**lemma** *CB-project-not-bot*:

*CB-project*.*scrut*·*v*<sub>1</sub>·*v*<sub>2</sub>  $\neq \perp \longleftrightarrow (\exists b. scrut = CB \cdot (Discr b) \wedge (if b then v_1 else v_2) \neq \perp)$   
 $\langle proof \rangle$

HOLCF provides us *CValue-take*::*nat* ⇒ *CValue* → *CValue*; we want a similar function for *C* → *CValue*.

**abbreviation** *C-to-CValue-take* :: *nat* ⇒ (*C* → *CValue*) → (*C* → *CValue*)

**where** *C-to-CValue-take* *n* ≡ *cfun-map*·*ID*·(*CValue-take* *n*)

**lemma** *C-to-CValue-chain-take*: *chain* *C-to-CValue-take*

$\langle proof \rangle$

**lemma** *C-to-CValue-reach*:  $(\bigsqcup n. C-to-CValue-take n \cdot x) = x$

$\langle proof \rangle$

end

## 6.5 CValue-Nominal

**theory** *CValue-Nominal*  
**imports** *CValue Nominal-Utills Nominal-HOLCF*  
**begin**

**instantiation**  $C :: \text{pure}$   
**begin**  
  **definition**  $p \cdot (c::C) = c$   
**instance**  $\langle \text{proof} \rangle$   
**end**  
**instance**  $C :: \text{pcpo-pt}$   
   $\langle \text{proof} \rangle$

**instantiation**  $CValue :: \text{pure}$   
**begin**  
  **definition**  $p \cdot (v::CValue) = v$   
**instance**  
   $\langle \text{proof} \rangle$   
**end**

**instance**  $CValue :: \text{pcpo-pt}$   
   $\langle \text{proof} \rangle$

end

## 6.6 ResourcedDenotational

**theory** *ResourcedDenotational*  
**imports** *Abstract-Denotational-Props CValue-Nominal C-restr*  
**begin**

**type-synonym**  $CEnv = \text{var} \Rightarrow (C \rightarrow CValue)$

**interpretation** *semantic-domain*  
   $\Lambda f . \Lambda r . CFn \cdot (\Lambda v . (f \cdot v)|_r)$   
   $\Lambda x y . (\Lambda r . (x \cdot r \downarrow CFn y|_r) \cdot r)$   
   $\Lambda b r . CB \cdot b$   
   $\Lambda scrut v1 v2 r . CB\text{-project} \cdot (scrut \cdot r) \cdot (v1 \cdot r) \cdot (v2 \cdot r)$   
   $C\text{-case} \langle \text{proof} \rangle$

**notation**  $ESem\text{-syn} \ (\langle \mathcal{N}[\![ - ]\!] \rangle \ [60,60] \ 60)$   
**notation**  $EvalHeapSem\text{-syn} \ (\langle \mathcal{N}[\![ - ]\!] \rangle \ [0,0] \ 110)$   
**notation**  $HSem\text{-syn} \ (\langle \mathcal{N}\{\!\{-\}\!\} \rangle \ [60,60] \ 60)$   
**notation**  $AHSem\text{-bot} \ (\langle \mathcal{N}\{\!\{-\}\!\} \rangle \ [60] \ 60)$

Here we re-state the simplification rules, cleaned up by beta-reducing the locale parameters.

**lemma** *CESem-simps*:

$$\begin{aligned}
\mathcal{N} \llbracket \text{Lam } [x]. e \rrbracket_{\varrho} &= (\Lambda (C \cdot r). \text{CFn} \cdot (\Lambda v. (\mathcal{N} \llbracket e \rrbracket_{\varrho}(x := v)) | r)) \\
\mathcal{N} \llbracket \text{App } e x \rrbracket_{\varrho} &= (\Lambda (C \cdot r). ((\mathcal{N} \llbracket e \rrbracket_{\varrho}) \cdot r \downarrow \text{CFn } \varrho x | r) \cdot r) \\
\mathcal{N} \llbracket \text{Var } x \rrbracket_{\varrho} &= (\Lambda (C \cdot r). (\varrho x) \cdot r) \\
\mathcal{N} \llbracket \text{Bool } b \rrbracket_{\varrho} &= (\Lambda (C \cdot r). \text{CB} \cdot (\text{Discr } b)) \\
\mathcal{N} \llbracket (\text{scrut } ? e_1 : e_2) \rrbracket_{\varrho} &= (\Lambda (C \cdot r). \text{CB-project} \cdot ((\mathcal{N} \llbracket \text{scrut} \rrbracket_{\varrho}) \cdot r) \cdot ((\mathcal{N} \llbracket e_1 \rrbracket_{\varrho}) \cdot r) \cdot ((\mathcal{N} \llbracket e_2 \rrbracket_{\varrho}) \cdot r)) \\
\mathcal{N} \llbracket \text{Let as body} \rrbracket_{\varrho} &= (\Lambda (C \cdot r). (\mathcal{N} \llbracket \text{body} \rrbracket_{\mathcal{N} \{as\} \varrho}) \cdot r) \\
&\langle \text{proof} \rangle
\end{aligned}$$

**lemma** *CESem-bot[simp]*:  $(\mathcal{N} \llbracket e \rrbracket_{\sigma}) \cdot \perp = \perp$

$\langle \text{proof} \rangle$

**lemma** *CHSem-bot[simp]*:  $(\mathcal{N} \{ \Gamma \} x) \cdot \perp = \perp$

$\langle \text{proof} \rangle$

Sometimes we do not care much about the resource usage and just want a simpler formula.

**lemma** *CESem-simps-no-tick*:

$$\begin{aligned}
(\mathcal{N} \llbracket \text{Lam } [x]. e \rrbracket_{\varrho}) \cdot r &\sqsubseteq \text{CFn} \cdot (\Lambda v. (\mathcal{N} \llbracket e \rrbracket_{\varrho}(x := v)) | r) \\
(\mathcal{N} \llbracket \text{App } e x \rrbracket_{\varrho}) \cdot r &\sqsubseteq ((\mathcal{N} \llbracket e \rrbracket_{\varrho}) \cdot r \downarrow \text{CFn } \varrho x | r) \cdot r \\
\mathcal{N} \llbracket \text{Var } x \rrbracket_{\varrho} &\sqsubseteq \varrho x \\
(\mathcal{N} \llbracket (\text{scrut } ? e_1 : e_2) \rrbracket_{\varrho}) \cdot r &\sqsubseteq \text{CB-project} \cdot ((\mathcal{N} \llbracket \text{scrut} \rrbracket_{\varrho}) \cdot r) \cdot ((\mathcal{N} \llbracket e_1 \rrbracket_{\varrho}) \cdot r) \cdot ((\mathcal{N} \llbracket e_2 \rrbracket_{\varrho}) \cdot r) \\
\mathcal{N} \llbracket \text{Let as body} \rrbracket_{\varrho} &\sqsubseteq \mathcal{N} \llbracket \text{body} \rrbracket_{\mathcal{N} \{as\} \varrho} \\
&\langle \text{proof} \rangle
\end{aligned}$$

**lemma** *CELam-no-restr*:  $(\mathcal{N} \llbracket \text{Lam } [x]. e \rrbracket_{\varrho}) \cdot r \sqsubseteq \text{CFn} \cdot (\Lambda v. (\mathcal{N} \llbracket e \rrbracket_{\varrho}(x := v)))$

$\langle \text{proof} \rangle$

**lemma** *CEApp-no-restr*:  $(\mathcal{N} \llbracket \text{App } e x \rrbracket_{\varrho}) \cdot r \sqsubseteq ((\mathcal{N} \llbracket e \rrbracket_{\varrho}) \cdot r \downarrow \text{CFn } \varrho x) \cdot r$

$\langle \text{proof} \rangle$

**end**

## 7 Correctness of the natural semantics

### 7.1 CorrectnessOriginal

```
theory CorrectnessOriginal
imports Denotational Launchbury
begin
```

This is the main correctness theorem, Theorem 2 from [Lau93].

```
theorem correctness:
  assumes  $\Gamma : e \Downarrow_L \Delta : v$ 
  and  $fv(\Gamma, e) \subseteq set\ L \cup dom\ A\ \Gamma$ 
  shows  $\llbracket e \rrbracket_{\{\Gamma\}\varrho} = \llbracket v \rrbracket_{\{\Delta\}\varrho}$ 
  and  $(\{\Gamma\}\varrho) f|' dom\ A\ \Gamma = (\{\Delta\}\varrho) f|' dom\ A\ \Gamma$ 
  <proof>

end
```

### 7.2 CorrectnessResourced

```
theory CorrectnessResourced
imports ResourcedDenotational Launchbury
begin
```

```
theorem correctness:
  assumes  $\Gamma : e \Downarrow_L \Delta : z$ 
  and  $fv(\Gamma, e) \subseteq set\ L \cup dom\ A\ \Gamma$ 
  shows  $\mathcal{N}\llbracket e \rrbracket_{\mathcal{N}\{\Gamma\}\varrho} \sqsubseteq \mathcal{N}\llbracket z \rrbracket_{\mathcal{N}\{\Delta\}\varrho}$  and  $(\mathcal{N}\{\Gamma\}\varrho) f|' dom\ A\ \Gamma \sqsubseteq (\mathcal{N}\{\Delta\}\varrho) f|' dom\ A\ \Gamma$ 
  <proof>
```

```
corollary correctness-empty-env:
```

```
  assumes  $\Gamma : e \Downarrow_L \Delta : z$ 
  and  $fv(\Gamma, e) \subseteq set\ L$ 
  shows  $\mathcal{N}\llbracket e \rrbracket_{\mathcal{N}\{\Gamma\}} \sqsubseteq \mathcal{N}\llbracket z \rrbracket_{\mathcal{N}\{\Delta\}}$  and  $\mathcal{N}\{\Gamma\} \sqsubseteq \mathcal{N}\{\Delta\}$ 
  <proof>
```

```
end
```

## 8 Equivalence of the denotational semantics

### 8.1 ValueSimilarity

```
theory ValueSimilarity
imports Value CValue Pointwise
begin
```

This theory formalizes Section 3 of [SGHHOM11]. Their domain  $D$  is our type  $Value$ , their domain  $E$  is our type  $CValue$  and  $A$  corresponds to  $C \rightarrow CValue$ .

In our case, the construction of the domains was taken care of by the HOLCF package ([Huf12]), so where [SGHHOM11] refers to elements of the domain approximations  $D_n$  resp.  $E_n$ , these are just elements of  $Value$  resp.  $CValue$  here. Therefore the  $n$ -injection  $\phi_n^E: E_n \rightarrow E$  is the identity here.

The projections correspond to the take-functions generated by the HOLCF package:

$$\begin{aligned} \psi_n^E: E \rightarrow E_n & \text{ corresponds to } & CValue\text{-take}::nat \Rightarrow CValue \rightarrow CValue \\ \psi_n^A: A \rightarrow A_n & \text{ corresponds to } & C\text{-to-}CValue\text{-take}::nat \Rightarrow (C \rightarrow CValue) \rightarrow C \rightarrow CValue \\ \psi_n^D: D \rightarrow D_n & \text{ corresponds to } & Value\text{-take}::nat \Rightarrow Value \rightarrow Value. \end{aligned}$$

The syntactic overloading of  $e(a)(c)$  to mean either  $\text{Ap}_{E_n}^\perp$  or  $\text{AP}_E^\perp$  turns into our non-overloaded  $\downarrow CFn \text{ } :: CValue \Rightarrow (C \rightarrow CValue) \Rightarrow C \rightarrow CValue$ .

To have our presentation closer to [SGHHOM11], we introduce some notation:

```
notation Value-take (⟨ψD_.⟩)
notation C-to-CValue-take (⟨ψA_.⟩)
notation CValue-take (⟨ψE_.⟩)
```

#### 8.1.1 A note about section 2.3

Section 2.3 of [SGHHOM11] contains equations (2) and (3) which do not hold in general. We demonstrate that fact here using our corresponding definition, but the counter-example carries over to the original formulation. Lemma (2) is a generalisation of (3) to the resourced semantics, so the counter-example for (3) is the simpler and more educating:

**lemma** *counter-example:*

**assumes** Equation (3):  $\bigwedge n d d'. \psi_n^D.(d \downarrow Fn d') = \psi_{Suc\ n}^D.d \downarrow Fn \psi_n^D.d'$

**shows** *False*

*<proof>*

For completeness, and to avoid making false assertions, the counter-example to equation (2):

**lemma** *counter-example2:*

**assumes** *Equation (2)*:  $\bigwedge n \ e \ a \ c. \psi^E_n \cdot ((e \downarrow CFn \ a) \cdot c) = (\psi^E_{Suc \ n} \cdot e \downarrow CFn \ \psi^A_n \cdot a) \cdot c$   
**shows** *False*  
 ⟨*proof*⟩

A suitable substitute for the lemma can be found in 4.3.5 (1) in [AO93], which in our setting becomes the following (note the extra invocation of  $\psi^D_n$  on the left hand side):

**lemma** *Abramsky 4,3,5 (1)*:  
 $\psi^D_n \cdot (d \downarrow Fn \ \psi^D_n \cdot d') = \psi^D_{Suc \ n} \cdot d \downarrow Fn \ \psi^D_n \cdot d'$   
 ⟨*proof*⟩

The problematic equations are used in the proof of the only-if direction of proposition 9 in [SGHHOM11]. It can be fixed by applying take-induction, which inserts the extra call to  $\psi^D_n$  in the right spot.

### 8.1.2 Working with *Value* and *CValue*

Combined case distinguishing and induction rules.

**lemma** *value-CValue-cases*:  
**obtains**  
 $x = \perp \ y = \perp \mid$   
 $f \ \mathbf{where} \ x = Fn \cdot f \ y = \perp \mid$   
 $g \ \mathbf{where} \ x = \perp \ y = CFn \cdot g \mid$   
 $f \ g \ \mathbf{where} \ x = Fn \cdot f \ y = CFn \cdot g \mid$   
 $b_1 \ \mathbf{where} \ x = B \cdot (Discr \ b_1) \ y = \perp \mid$   
 $b_1 \ g \ \mathbf{where} \ x = B \cdot (Discr \ b_1) \ y = CFn \cdot g \mid$   
 $b_1 \ b_2 \ \mathbf{where} \ x = B \cdot (Discr \ b_1) \ y = CB \cdot (Discr \ b_2) \mid$   
 $f \ b_2 \ \mathbf{where} \ x = Fn \cdot f \ y = CB \cdot (Discr \ b_2) \mid$   
 $b_2 \ \mathbf{where} \ x = \perp \ y = CB \cdot (Discr \ b_2)$   
 ⟨*proof*⟩

**lemma** *Value-CValue-take-induct*:  
**assumes** *adm (case-prod P)*  
**assumes**  $\bigwedge n. P (\psi^D_n \cdot x) (\psi^A_n \cdot y)$   
**shows**  $P \ x \ y$   
 ⟨*proof*⟩

### 8.1.3 Restricted similarity is defined recursively

The base case

**inductive** *similar'-base* ::  $Value \Rightarrow CValue \Rightarrow bool$  **where**  
*bot-similar'-base*[*simp,intro*]: *similar'-base*  $\perp \ \perp$

**inductive-cases** [*elim!*]:  
*similar'-base*  $x \ y$

The inductive case

**inductive** *similar'-step* :: (Value  $\Rightarrow$  CValue  $\Rightarrow$  bool)  $\Rightarrow$  Value  $\Rightarrow$  CValue  $\Rightarrow$  bool **for** *s* **where**  
*bot-similar'-step*[intro!]: *similar'-step* *s*  $\perp$   $\perp$  |  
*bool-similar'-step*[intro]: *similar'-step* *s* (B·b) (CB·b) |  
*Fun-similar'-step*[intro]: ( $\bigwedge x y . s x (y \cdot C^\infty) \Longrightarrow s (f \cdot x) (g \cdot y \cdot C^\infty)$ )  $\Longrightarrow$  *similar'-step* *s* (Fn·f)  
(CFn·g)

**inductive-cases** [elim!]:  
*similar'-step* *s*  $x \perp$   
*similar'-step* *s*  $\perp y$   
*similar'-step* *s* (B·f) (CB·g)  
*similar'-step* *s* (Fn·f) (CFn·g)

We now create the restricted similarity relation, by primitive recursion over *n*.

This cannot be done using an inductive definition, as it would not be monotone.

**fun** *similar'* **where**  
*similar'* 0 = *similar'-base* |  
*similar'* (Suc *n*) = *similar'-step* (*similar'* *n*)  
**declare** *similar'.simps*[simp del]

**abbreviation** *similar'-syn* ( $\langle - \triangleleft_n - \rangle$  [50,50,50] 50)  
**where** *similar'-syn* *x n y*  $\equiv$  *similar'* *n x y*

**lemma** *similar'-botI*[intro!,simp]:  $\perp \triangleleft_n \perp$   
 $\langle$ proof $\rangle$

**lemma** *similar'-FnI*[intro]:  
**assumes**  $\bigwedge x y . x \triangleleft_n y \cdot C^\infty \Longrightarrow f \cdot x \triangleleft_n g \cdot y \cdot C^\infty$   
**shows**  $Fn \cdot f \triangleleft_{Suc\ n} CFn \cdot g$   
 $\langle$ proof $\rangle$

**lemma** *similar'-FnE*[elim!]:  
**assumes**  $Fn \cdot f \triangleleft_{Suc\ n} CFn \cdot g$   
**assumes** ( $\bigwedge x y . x \triangleleft_n y \cdot C^\infty \Longrightarrow f \cdot x \triangleleft_n g \cdot y \cdot C^\infty$ )  $\Longrightarrow$  *P*  
**shows** *P*  
 $\langle$ proof $\rangle$

**lemma** *bot-or-not-bot'*:  
 $x \triangleleft_n y \Longrightarrow (x = \perp \longleftrightarrow y = \perp)$   
 $\langle$ proof $\rangle$

**lemma** *similar'-bot*[elim-format, elim!]:  
 $\perp \triangleleft_n x \Longrightarrow x = \perp$   
 $y \triangleleft_n \perp \Longrightarrow y = \perp$   
 $\langle$ proof $\rangle$

**lemma** *similar'-typed*[simp]:  
 $\neg B \cdot b \triangleleft_n CFn \cdot g$   
 $\neg Fn \cdot f \triangleleft_n CB \cdot b$

*<proof>*

**lemma** *similar'-bool[simp]*:

$B \cdot b_1 \triangleleft_{Suc\ n} CB \cdot b_2 \iff b_1 = b_2$

*<proof>*

### 8.1.4 Moving up and down the similarity relations

These correspond to Lemma 7 in [SGHHOM11].

**lemma** *similar'-down*:  $d \triangleleft_{Suc\ n} e \implies \psi^D_n \cdot d \triangleleft_n \psi^E_n \cdot e$

**and** *similar'-up*:  $d \triangleleft_n e \implies \psi^D_n \cdot d \triangleleft_{Suc\ n} \psi^E_n \cdot e$

*<proof>*

A generalisation of the above, doing multiple steps at once.

**lemma** *similar'-up-le*:  $n \leq m \implies \psi^D_n \cdot d \triangleleft_n \psi^E_n \cdot e \implies \psi^D_n \cdot d \triangleleft_m \psi^E_n \cdot e$

*<proof>*

**lemma** *similar'-down-le*:  $n \leq m \implies \psi^D_m \cdot d \triangleleft_m \psi^E_m \cdot e \implies \psi^D_n \cdot d \triangleleft_n \psi^E_n \cdot e$

*<proof>*

**lemma** *similar'-take*:  $d \triangleleft_n e \implies \psi^D_n \cdot d \triangleleft_n \psi^E_n \cdot e$

*<proof>*

### 8.1.5 Admissibility

A technical prerequisite for induction is admissibility of the predicate, i.e. that the predicate holds for the limit of a chain, given that it holds for all elements.

**lemma** *similar'-base-adm*:  $adm\ (\lambda x. similar'\text{-base}\ (fst\ x)\ (snd\ x))$

*<proof>*

**lemma** *similar'-step-adm*:

**assumes**  $adm\ (\lambda x. s\ (fst\ x)\ (snd\ x))$

**shows**  $adm\ (\lambda x. similar'\text{-step}\ s\ (fst\ x)\ (snd\ x))$

*<proof>*

**lemma** *similar'-adm*:  $adm\ (\lambda x. fst\ x \triangleleft_n snd\ x)$

*<proof>*

**lemma** *similar'-admI*:  $cont\ f \implies cont\ g \implies adm\ (\lambda x. f\ x \triangleleft_n g\ x)$

*<proof>*

### 8.1.6 The real similarity relation

This is the goal of the theory: A relation between *Value* and *CValue*.

**definition** *similar* ::  $Value \Rightarrow CValue \Rightarrow bool$  (**infix**  $\triangleleft$  50) **where**

$$x \triangleleft y \iff (\forall n. \psi^D_n \cdot x \triangleleft_n \psi^E_n \cdot y)$$

**lemma** *similarI*:

$$(\bigwedge n. \psi^D_n \cdot x \triangleleft_n \psi^E_n \cdot y) \implies x \triangleleft y$$

*<proof>*

**lemma** *similarE*:

$$x \triangleleft y \implies \psi^D_n \cdot x \triangleleft_n \psi^E_n \cdot y$$

*<proof>*

**lemma** *similar-bot[simp]*:  $\perp \triangleleft \perp$  *<proof>*

**lemma** *similar-bool[simp]*:  $B \cdot b \triangleleft CB \cdot b$   
*<proof>*

**lemma** [*elim-format, elim!*]:  $x \triangleleft \perp \implies x = \perp$   
*<proof>*

**lemma** [*elim-format, elim!*]:  $x \triangleleft CB \cdot b \implies x = B \cdot b$   
*<proof>*

**lemma** [*elim-format, elim!*]:  $\perp \triangleleft y \implies y = \perp$   
*<proof>*

**lemma** [*elim-format, elim!*]:  $B \cdot b \triangleleft y \implies y = CB \cdot b$   
*<proof>*

**lemma** *take-similar'-similar*:

**assumes**  $x \triangleleft_n y$

**shows**  $\psi^D_n \cdot x \triangleleft \psi^E_n \cdot y$

*<proof>*

**lemma** *bot-or-not-bot*:

$$x \triangleleft y \implies (x = \perp \iff y = \perp)$$

*<proof>*

**lemma** *bool-or-not-bool*:

$$x \triangleleft y \implies (x = B \cdot b \iff y = CB \cdot b)$$

*<proof>*

**lemma** *similar-bot-cases[consumes 1, case-names bot bool Fn]*:

**assumes**  $x \triangleleft y$

**obtains**  $x = \perp \ y = \perp \mid$

$b$  **where**  $x = B \cdot (Discr\ b) \ y = CB \cdot (Discr\ b) \mid$

$f\ g$  **where**  $x = Fn \cdot f \ y = CFn \cdot g$

*<proof>*

**lemma** *similar-adm*:  $adm\ (\lambda x. fst\ x \triangleleft snd\ x)$

*<proof>*

**lemma** *similar-admI*:  $cont\ f \implies cont\ g \implies adm\ (\lambda x. f\ x \triangleleft g\ x)$   
 ⟨proof⟩

Having constructed the relation we can now show that it indeed is the desired relation, relating  $\perp$  with  $\perp$  and functions with functions, if they take related arguments to related values. This corresponds to Proposition 9 in [SGHHOM11].

**lemma** *similar-nice-def*:  $x \triangleleft y \iff (x = \perp \wedge y = \perp \vee (\exists b. x = B.(Discr\ b) \wedge y = CB.(Discr\ b)) \vee (\exists f\ g. x = Fn.f \wedge y = CFn.g \wedge (\forall a\ b. a \triangleleft b.C^\infty \implies f.a \triangleleft g.b.C^\infty)))$   
 (is ?L  $\iff$  ?R)  
 ⟨proof⟩

**lemma** *similar-FnI[intro]*:  
 assumes  $\bigwedge x\ y. x \triangleleft y.C^\infty \implies f.x \triangleleft g.y.C^\infty$   
 shows  $Fn.f \triangleleft CFn.g$   
 ⟨proof⟩

**lemma** *similar-FnD[elim!]*:  
 assumes  $Fn.f \triangleleft CFn.g$   
 assumes  $x \triangleleft y.C^\infty$   
 shows  $f.x \triangleleft g.y.C^\infty$   
 ⟨proof⟩

**lemma** *similar-FnE[elim]*:  
 assumes  $Fn.f \triangleleft CFn.g$   
 assumes  $(\bigwedge x\ y. x \triangleleft y.C^\infty \implies f.x \triangleleft g.y.C^\infty) \implies P$   
 shows  $P$   
 ⟨proof⟩

### 8.1.7 The similarity relation lifted pointwise to functions.

**abbreviation** *fun-similar* ::  $('a::type \implies Value) \implies ('a \implies (C \rightarrow CValue)) \implies bool$  (infix  $\triangleleft^*$ )  
 50) **where**  
 $fun-similar \equiv pointwise\ (\lambda x\ y. x \triangleleft y.C^\infty)$

**lemma** *fun-similar-fmap-bottom[simp]*:  $\perp \triangleleft^* \perp$   
 ⟨proof⟩

**lemma** *fun-similarE[elim]*:  
 assumes  $m \triangleleft^* m'$   
 assumes  $(\bigwedge x. (m\ x) \triangleleft (m'\ x).C^\infty) \implies Q$   
 shows  $Q$   
 ⟨proof⟩

**end**

## 8.2 Denotational-Related

**theory** *Denotational-Related*  
**imports** *Denotational ResourcedDenotational ValueSimilarity*  
**begin**

Given the similarity relation it is straight-forward to prove that the standard and the re-sourced denotational semantics produce similar results. (Theorem 10 in [SGHHOM11]).

**theorem** *denotational-semantics-similar*:

**assumes**  $\rho \triangleleft^* \sigma$

**shows**  $\llbracket e \rrbracket_\rho \triangleleft (\mathcal{N} \llbracket e \rrbracket_\sigma) \cdot C^\infty$

*<proof>*

**corollary** *evalHeap-similar*:

$\bigwedge y z. y \triangleleft^* z \implies \llbracket \Gamma \rrbracket_y \triangleleft^* \mathcal{N} \llbracket \Gamma \rrbracket_z$

*<proof>*

**theorem** *heaps-similar*:  $\{\Gamma\} \triangleleft^* \mathcal{N} \{\Gamma\}$

*<proof>*

**end**

## 9 Adequacy

### 9.1 ResourcedAdequacy

**theory** *ResourcedAdequacy*  
**imports** *ResourcedDenotational Launchbury AList–Utils CorrectnessResourced*  
**begin**

**lemma** *demand-not-0*:  $\text{demand } (\mathcal{N} \llbracket e \rrbracket_{\rho}) \neq \perp$   
*<proof>*

The semantics of an expression, given only  $r$  resources, will only use values from the environment with less resources.

**lemma** *restr-can-restrict-env*:  $(\mathcal{N} \llbracket e \rrbracket_{\rho})|_{C \cdot r} = (\mathcal{N} \llbracket e \rrbracket_{\rho|^\circ r})|_{C \cdot r}$   
*<proof>*

**lemma** *can-restrict-env*:  
 $(\mathcal{N} \llbracket e \rrbracket_{\rho}) \cdot (C \cdot r) = (\mathcal{N} \llbracket e \rrbracket_{\rho|^\circ r}) \cdot (C \cdot r)$   
*<proof>*

When an expression  $e$  terminates, then we can remove such an expression from the heap and it still terminates. This is the crucial trick to handle black-holing in the resourced semantics.

**lemma** *add-BH*:  
**assumes** *map-of*  $\Gamma x = \text{Some } e$   
**assumes**  $(\mathcal{N} \llbracket e \rrbracket_{\mathcal{N} \setminus \{ \Gamma \}}) \cdot r' \neq \perp$   
**shows**  $(\mathcal{N} \llbracket e \rrbracket_{\mathcal{N} \setminus \{ \text{delete } x \Gamma \}}) \cdot r' \neq \perp$   
*<proof>*

The semantics is continuous, so we can apply induction here:

**lemma** *resourced-adequacy*:  
**assumes**  $(\mathcal{N} \llbracket e \rrbracket_{\mathcal{N} \setminus \{ \Gamma \}}) \cdot r \neq \perp$   
**shows**  $\exists \Delta v. \Gamma : e \Downarrow_{\mathcal{S}} \Delta : v$   
*<proof>*

**end**

### 9.2 Adequacy

**theory** *Adequacy*  
**imports** *ResourcedAdequacy Denotational–Related*  
**begin**

**theorem** *adequacy*:  
**assumes**  $\llbracket e \rrbracket_{\Gamma} \neq \perp$

**shows**  $\exists \Delta v. \Gamma : e \Downarrow_S \Delta : v$   
*<proof>*

**end**

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