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**A Formally Specified Type System
and Operational Semantics
for Higher-Order Procedural Variables**

Tristan Crolard Emmanuel Polonowski

May 2009

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Laboratory of Algorithmics, Complexity and Logic (LACL)
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T. Crolard and E. Polonowski

May 14, 2009

Abstract

We formally specified the type system and operational semantics of Loop^ω with Ott and Isabelle/HOL proof assistant. Moreover, both the type system and the semantics of Loop^ω have been tested using Isabelle/HOL program extraction facility for inductively defined relations. In particular, the program that computes the Ackermann function type checks and behaves as expected. The main difference (apart from the choice of an Ada-like concrete syntax) with Loop^ω comes from the treatment of parameter passing. Indeed, since Ott does not currently fully support α -conversion, we rephrased the operational semantics with explicit aliasing in order to implement the **out** parameter passing mode.

Introduction

We formally specified the type system and operational semantics of Loop^ω as described in [CPV09] with Ott [SNO⁺07] and Isabelle/HOL proof assistant [NPW02]. Moreover, both the type system and the semantics of Loop^ω have been tested using Isabelle/HOL program extraction facility for inductively defined relations [BN02]. In particular, the program that computes the Ackermann function (reproduced below) type checks and behaves as expected.

The main difference (apart from the choice of an Ada-like concrete syntax) with the description given in [CPV09] comes from the treatment of parameter passing. Indeed, since Ott does not currently fully support α -conversion, we rephrased the operational semantics with explicit aliasing in order to implement the **out** parameter passing mode (instead of a simpler substitution-based semantics as in [CPV09]). On the other hand, the **in** parameter passing mode is implemented exactly as in [CPV09] and relies on Ott generated substitution (see the Isabelle/HOL code given in appendix).

Section 1 contains the description of an Ada-like grammar for Loop^ω . We then present the type system in Section 2 and the structural operational semantic in section 3. Finally, in the appendix we include the Isabelle/HOL theory generated by Ott (all source files are available on request).

Example: the Ackermann function

```
procedure Ack(M : in int; N : in int; R : out int) is
  P : proc(in int, out int) := Incr;
begin
  for I in 1 .. M loop
    declare
      Q : constant proc(in int, out int) := P;
      procedure Aux(S : in int; R : out int) is
        X : int := 0;
      begin
        Q(1, X);
        for J in 1 .. S loop
          Q(X, X);
        end loop;
        R := X;
      end;
    begin
      P := Aux;
    end;
  end loop;
  P(N, R);
end;
```

1 Syntax

index, i, j, l, n indices
ident, x, y, z, p, f idents
number, q

terminals ::=

| \rightarrow

| \rightarrow

| \Rightarrow

| \leftarrow

| \mapsto

| \rightsquigarrow

| \vdash

| \emptyset

| \times

| \neq

| $::=$

| \langle

| \rangle

| \sim

| \notin

| \triangleright

mode, m ::= modes:

| in S

| out

| in out

integer, k ::=

| q

| $\{ k_1 + k_2 \}$

| $\{ k_1 - k_2 \}$

| $\{ k_1 \times k_2 \}$

boolean, b ::=

| true

| false

| $\{ b_1 \text{ and } b_2 \}$

| $\{ b_1 \text{ or } b_2 \}$

| $\{ \text{not } b \}$

| $\{ k_1 = k_2 \}$

| $k_1 > k_2$

| $k_1 < k_2$

exp, e ::= terms:

| x var

| v value

| $e_1 + e_2$ addition

| $e_1 - e_2$ subtraction

| $e_1 \times e_2$ multiplication

| $e_1 = e_2$ equality

| $e_1 > e_2$ greater

| $e_1 < e_2$ less

| $e_1 \text{ and } e_2$ conjunction

| $e_1 \text{ or } e_2$ disjunction

| not e negation

| (e) S parentheses

store, μ ::= store

	?	S	
	\square		
	$(\mu, x \leftarrow v)$		
	$[z_1 \leftarrow v_1, \dots, z_n \leftarrow v_n]$		
<i>trace, tr</i>	::=		
	?	S	
	$[\langle c_1, \mu_1 \rangle .. \langle c_n, \mu_n \rangle]$		
<i>formula</i>	::=		
	$formula_1 .. formula_n$		
	<i>judgement</i>		
	$x = x'$		
	$x \neq x'$		
	$\delta = \delta'$		
	$\delta \neq \delta'$		
	$m = m'$		
	$m \neq m'$		
	$k > k'$		
	$k \leq k'$		
<i>env, Γ</i>	::=		contexts:
	$\{ \}$		empty context
	$\{ x_1 \delta_1, \dots, x_n \delta_n \}$		explicit context
	$\Gamma, x \delta$		ident declaration
	Γ	S	parentheses
	$\Gamma, x_1 \delta_1, \dots, x_n \delta_n$		idents declaration
	Γ, δ		anonymous declaration
<i>cmd, c</i>	::=		commands:
	null		null
	$x := e$		assignment
	$c_1 ; c_2$		sequence
	if e then c_1 ; else c_2 ; end if		conditional
	while e loop c ; end loop		while loop
	(c)	S	
	?	S	
	declare d		declaration
	for x in $e .. e'$ loop c ; end loop	bind x in c	for loop
	$e(e_1, .., e_n)$		Procedure call
<i>va, v</i>	::=		constants:
	?	S	
	k		integer constant
	b		boolean true
	$\text{proc}(x_1 : m_1 \tau_1 ; .. ; x_n : m_n \tau_n) \text{ is } d$	bind $x_1..x_n$ in d	
<i>ty, τ</i>	::=		types:
	int		
	bool		
	$\text{proc}(m_1 \tau_1, .., m_n \tau_n)$		Procedure
	void		void
δ	::=		
	$: m \tau$		
	$\hookrightarrow \tau$		
<i>dcl, d</i>	::=		

		$d[v/x]$	M	
		begin end		Empty
		begin c; end		Block
		$x : \tau; d$	bind x in d	Uninit. variable
		$x : \tau := e; d$	bind x in d	Init. variable
		$x : \text{constant } \tau := e; d$	bind x in d	Constant
		procedure p ($x_1 : m_1 \tau_1; \dots; x_n : m_n \tau_n$) is $d_1; d_2$	bind $x_1..x_n$ in d_1	Proc
		$[x_1 : m_1 \tau_1 = e_1, \dots, x_n : m_n \tau_n = e_n] d$	bind $x_1..x_n$ in d	Aliases
		$(x : m \tau = e) d$	bind x in d	Alias
<i>value</i>	::=			value
		v		
<i>eval_exp</i>	::=			Fetch
		$\mu(x) = v$		Expression evaluation
		$e =_{\mu} v$		
<i>typing</i>	::=			Lookup
		$x \delta \in \Gamma$		Expression typing
		$\Gamma \vdash e : \tau$		LookupD
		$\delta \in \Gamma$		Match
		$\Gamma \vdash e \sim m \tau$		MatchList
		$\Gamma \vdash (e_1, \dots, e_l) \sim (m_1 \tau_1, \dots, m_n \tau_n)$		Declaration typing
		$\Gamma \vdash d : \text{decl}$		Command typing
		$\Gamma \vdash c : \text{comm}$		
<i>eval_comm</i>	::=			Store Update
		$\mu \{x \leftarrow v\} \mapsto \mu'$		Many Steps
		$\langle c, \mu \rangle \mapsto^k \langle c', \mu' \rangle$		Trace
		$\langle c; \mu \rangle \Rightarrow^k tr$		Full evaluation
		$\langle c; \mu \rangle \rightsquigarrow \mu'$		Compatibility
		$(x'_i : m'_i \tau'_i) \# (e'_j) = [x_n : m_n \tau_n = e_n]$		One step evaluation
		$\langle c, \mu \rangle \mapsto \langle c', \mu' \rangle$		Declaration evaluation
		$\langle d, \mu \rangle \mapsto \langle d', \mu' \rangle$		
<i>judgement</i>	::=			
		<i>eval_exp</i>		
		<i>typing</i>		
		<i>eval_comm</i>		
<i>user_syntax</i>	::=			
		<i>index</i>		
		<i>ident</i>		
		<i>number</i>		
		<i>terminals</i>		
		<i>mode</i>		
		<i>integer</i>		
		<i>boolean</i>		
		<i>exp</i>		
		<i>store</i>		
		<i>trace</i>		
		<i>formula</i>		
		<i>env</i>		
		<i>cmd</i>		
		<i>va</i>		
		<i>ty</i>		
		δ		
		<i>dcl</i>		
		<i>value</i>		

2 Type System

Lookup

$$\boxed{x \delta \in \Gamma}$$

$$\overline{x \delta \in \Gamma, x \delta} \quad (\text{Lookup1})$$

$$\frac{x \neq x' \quad x \delta \in \Gamma}{x \delta \in \Gamma, x' \delta'} \quad (\text{Lookup2})$$

Expression typing

$$\boxed{\Gamma \vdash e : \tau}$$

$$\frac{m \neq \text{out} \quad x : m\tau \in \Gamma}{\Gamma \vdash x : \tau} \quad (\text{Var})$$

$$\overline{\Gamma \vdash q : \text{int}} \quad (\text{IntCst})$$

$$\overline{\Gamma \vdash \text{true} : \text{bool}} \quad (\text{BoolTrue})$$

$$\overline{\Gamma \vdash \text{false} : \text{bool}} \quad (\text{BoolFalse})$$

$$\frac{\Gamma \vdash e_1 : \text{int} \quad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 + e_2 : \text{int}} \quad (\text{Plus})$$

$$\frac{\Gamma \vdash e_1 : \text{int} \quad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 - e_2 : \text{int}} \quad (\text{Minus})$$

$$\frac{\Gamma \vdash e_1 : \text{int} \quad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 \times e_2 : \text{int}} \quad (\text{Times})$$

$$\frac{\Gamma \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1 = e_2 : \text{bool}} \quad (\text{Equal})$$

$$\frac{\Gamma \vdash e_1 : \text{int} \quad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 > e_2 : \text{bool}} \quad (\text{Greater})$$

$$\frac{\Gamma \vdash e_1 : \text{int} \quad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 < e_2 : \text{bool}} \quad (\text{Less})$$

$$\frac{\Gamma \vdash e_1 : \text{bool} \quad \Gamma \vdash e_2 : \text{bool}}{\Gamma \vdash e_1 \text{ and } e_2 : \text{bool}} \quad (\text{And})$$

$$\frac{\Gamma \vdash e_1 : \text{bool} \quad \Gamma \vdash e_2 : \text{bool}}{\Gamma \vdash e_1 \text{ or } e_2 : \text{bool}} \quad (\text{Or})$$

$$\frac{\Gamma \vdash e : \text{bool}}{\Gamma \vdash \text{not } e : \text{bool}} \quad (\text{Not})$$

LookupD

$$\boxed{\delta \in \Gamma}$$

$$\overline{\delta \in \Gamma, x \delta} \quad (\text{LookupD1})$$

$$\frac{\delta \neq \delta' \quad \delta \in \Gamma}{\delta \in \Gamma, x \delta'} \quad (\text{LookupD2})$$

Match $\Gamma \vdash e \sim m \tau$

$$\frac{\Gamma \vdash e : \tau}{\Gamma \vdash e \sim \text{in } \tau} \quad (\text{Match1})$$

$$\frac{x : m \tau \in \Gamma \quad m \neq \text{in}}{\Gamma \vdash x \sim \text{out } \tau} \quad (\text{Match2})$$

$$\frac{x : \text{in out } \tau \in \Gamma}{\Gamma \vdash x \sim \text{in out } \tau} \quad (\text{Match3})$$

MatchList $\Gamma \vdash (e_1, \dots, e_l) \sim (m_1 \tau_1, \dots, m_n \tau_n)$

$$\overline{\Gamma \vdash () \sim ()} \quad (\text{MatchList1})$$

$$\frac{\Gamma \vdash e \sim m \tau \quad \Gamma \vdash (e_1, \dots, e_l) \sim (m_1 \tau_1, \dots, m_n \tau_n)}{\Gamma \vdash (e, e_1, \dots, e_l) \sim (m \tau, m_1 \tau_1, \dots, m_n \tau_n)} \quad (\text{MatchList2})$$

Declaration typing $\Gamma \vdash d : \text{decl}$

$$\overline{\Gamma \vdash \text{begin end} : \text{decl}} \quad (\text{Empty})$$

$$\frac{\Gamma \vdash c : \text{comm}}{\Gamma \vdash \text{begin } c; \text{end} : \text{decl}} \quad (\text{Block})$$

$$\frac{\Gamma, x : \text{in out } \tau \vdash d : \text{decl}}{\Gamma \vdash x : \tau; d : \text{decl}} \quad (\text{UnitVar})$$

$$\frac{\Gamma \vdash e : \tau \quad \Gamma, x : \text{in out } \tau \vdash d : \text{decl}}{\Gamma \vdash x : \tau := e; d : \text{decl}} \quad (\text{InitVar})$$

$$\frac{\Gamma \vdash e : \tau \quad \Gamma, x : \text{in } \tau \vdash d : \text{decl}}{\Gamma \vdash x : \text{constant } \tau := e; d : \text{decl}} \quad (\text{Constant})$$

$$\frac{\Gamma, x_1 : m_1 \tau_1, \dots, x_n : m_n \tau_n \vdash d_1 : \text{decl} \quad \Gamma, p : \text{in proc}(m_1 \tau_1, \dots, m_n \tau_n) \vdash d_2 : \text{decl}}{\Gamma \vdash \text{procedure } p(x_1 : m_1 \tau_1; \dots; x_n : m_n \tau_n) \text{ is } d_1; d_2 : \text{decl}} \quad (\text{Proc})$$

Command typing $\Gamma \vdash c : \text{comm}$

$$\overline{\Gamma \vdash \text{null} : \text{comm}} \quad (\text{Null})$$

$$\frac{\Gamma \vdash c_1 : \text{comm} \quad \Gamma \vdash c_2 : \text{comm}}{\Gamma \vdash c_1; c_2 : \text{comm}} \quad (\text{Seq})$$

$$\frac{m \neq \text{in} \quad x : m \tau \in \Gamma \quad \Gamma \vdash e : \tau}{\Gamma \vdash x := e : \text{comm}} \quad (\text{Assign})$$

$$\frac{\Gamma \vdash e : \text{bool} \quad \Gamma \vdash c_1 : \text{comm} \quad \Gamma \vdash c_2 : \text{comm}}{\Gamma \vdash \text{if } e \text{ then } c_1; \text{else } c_2; \text{end if} : \text{comm}} \quad (\text{IfThenElse})$$

$$\frac{\Gamma \vdash e : \text{bool} \quad \Gamma \vdash c : \text{comm}}{\Gamma \vdash \text{while } e \text{ loop } c; \text{end loop} : \text{comm}} \quad (\text{While})$$

$$\frac{\Gamma \vdash e : \text{int} \quad \Gamma \vdash e' : \text{int} \quad \Gamma, x : \text{in int} \vdash c : \text{comm}}{\Gamma \vdash \text{for } x \text{ in } e \dots e' \text{ loop } c; \text{end loop} : \text{comm}} \quad (\text{For})$$

$$\frac{\Gamma \vdash d : \text{decl}}{\Gamma \vdash \text{declare } d : \text{comm}} \quad (\text{Decl})$$

$$\frac{\Gamma \vdash e : \text{proc}(m_1 \tau_1, \dots, m_n \tau_n) \quad \Gamma \vdash (e_1, \dots, e_l) \sim (m_1 \tau_1, \dots, m_n \tau_n)}{\Gamma \vdash e(e_1, \dots, e_l) : \text{comm}} \quad (\text{ProcCall})$$

3 Structural Operational Semantics

Fetch

$$\mu(x) = v$$

$$\overline{(\mu, x \leftarrow v)(x) = v} \quad (\text{Fetch1})$$

$$\frac{x \neq x' \quad \mu(x) = v}{(\mu, x' \leftarrow v')(x) = v} \quad (\text{Fetch2})$$

Expression evaluation

$$e =_{\mu} v$$

$$\overline{v =_{\mu} v} \quad (\text{E-Value})$$

$$\frac{\mu(x) = v}{x =_{\mu} v} \quad (\text{E-Ident})$$

$$\frac{e_1 =_{\mu} k_1 \quad e_2 =_{\mu} k_2}{e_1 + e_2 =_{\mu} \{k_1 + k_2\}} \quad (\text{E-Plus})$$

$$\frac{e_1 =_{\mu} k_1 \quad e_2 =_{\mu} k_2}{e_1 - e_2 =_{\mu} \{k_1 - k_2\}} \quad (\text{E-Minus})$$

$$\frac{e_1 =_{\mu} k_1 \quad e_2 =_{\mu} k_2}{e_1 \times e_2 =_{\mu} \{k_1 \times k_2\}} \quad (\text{E-Times})$$

$$\frac{e_1 =_{\mu} k_1 \quad e_2 =_{\mu} k_2}{e_1 > e_2 =_{\mu} \{k_1 > k_2\}} \quad (\text{E-Greater})$$

$$\frac{e_1 =_{\mu} k_1 \quad e_2 =_{\mu} k_2}{e_1 < e_2 =_{\mu} \{k_1 < k_2\}} \quad (\text{E-Less})$$

$$\frac{e_1 =_{\mu} k_1 \quad e_2 =_{\mu} k_2}{e_1 = e_2 =_{\mu} \{k_1 = k_2\}} \quad (\text{E-Equal})$$

$$\frac{e_1 =_{\mu} b_1 \quad e_2 =_{\mu} b_2}{e_1 \text{ and } e_2 =_{\mu} \{b_1 \text{ and } b_2\}} \quad (\text{E-And})$$

$$\frac{e_1 =_{\mu} b_1 \quad e_2 =_{\mu} b_2}{e_1 \text{ or } e_2 =_{\mu} \{b_1 \text{ or } b_2\}} \quad (\text{E-Or})$$

$$\frac{e =_{\mu} b}{\text{not } e =_{\mu} \{\text{not } b\}} \quad (\text{E-Not})$$

Store Update

$$\mu \{x \leftarrow v\} \mapsto \mu'$$

$$\overline{(\mu, x \leftarrow v) \{x \leftarrow v'\} \mapsto (\mu, x \leftarrow v')} \quad (\text{Update1})$$

$$\frac{x \neq x' \quad \mu \{x \leftarrow v'\} \mapsto \mu'}{(\mu, x' \leftarrow v) \{x \leftarrow v'\} \mapsto (\mu', x' \leftarrow v)} \quad (\text{Update2})$$

Many Steps

$$\langle c, \mu \rangle \mapsto^k \langle c', \mu' \rangle$$

$$\overline{\langle c, \mu \rangle \mapsto^0 \langle c, \mu \rangle} \quad (\text{ManySteps1})$$

$$\overline{\langle \text{null}, \mu \rangle \mapsto^k \langle \text{null}, \mu \rangle} \quad (\text{ManySteps2})$$

$$\frac{\langle c, \mu \rangle \mapsto \langle c', \mu' \rangle \quad \langle c', \mu' \rangle \mapsto^{\{k-1\}} \langle c'', \mu'' \rangle}{\langle c, \mu \rangle \mapsto^k \langle c'', \mu'' \rangle} \quad (\text{ManySteps3})$$

Trace

$$\langle c; \mu \rangle \Rightarrow^k \text{tr}$$

$$\overline{\langle c; \mu \rangle \Rightarrow^0 []} \quad (\text{Trace1})$$

$$\overline{\langle \text{null}; \mu \rangle \Rightarrow^k []} \quad (\text{Trace2})$$

$$\frac{\langle c, \mu \rangle \mapsto \langle c', \mu' \rangle \quad \langle c'; \mu' \rangle \Rightarrow^{\{k-1\}} [\langle c'_1, \mu'_1 \rangle .. \langle c'_n, \mu'_n \rangle]}{\langle c; \mu \rangle \Rightarrow^k [\langle c', \mu' \rangle \langle c'_1, \mu'_1 \rangle .. \langle c'_n, \mu'_n \rangle]} \quad (\text{Trace3})$$

Full evaluation

$$\langle c; \mu \rangle \rightsquigarrow \mu'$$

$$\overline{\langle \text{null}; \mu \rangle \rightsquigarrow \mu} \quad (\text{Eval1})$$

$$\frac{\langle c, \mu \rangle \mapsto \langle c', \mu' \rangle \quad \langle c'; \mu' \rangle \rightsquigarrow \mu''}{\langle c; \mu \rangle \rightsquigarrow \mu''} \quad (\text{Eval2})$$

Compatibility

$$\overline{(|x'_i : m'_i \tau'_i|) \# (|e'_j|) = [|x_n : m_n \tau_n = e_n|]}$$

$$\overline{() \# () = []} \quad (\text{E-Compat1})$$

$$\frac{(|x'_i : m'_i \tau'_i|) \# (|e'_j|) = [|x_n : m_n \tau_n = e_n|]}{(x : m \tau |x'_i : m'_i \tau'_i|) \# (e |e'_j|) = [x : m \tau = e |x_n : m_n \tau_n = e_n|]} \quad (\text{E-Compat2})$$

One step evaluation

$$\langle c, \mu \rangle \mapsto \langle c', \mu' \rangle$$

$$\overline{\langle (\text{null}; c), \mu \rangle \mapsto \langle c, \mu \rangle} \quad (\text{E_Null})$$

$$\frac{\langle c_1, \mu \rangle \mapsto \langle c'_1, \mu' \rangle}{\langle (c_1; c_2), \mu \rangle \mapsto \langle (c'_1; c_2), \mu' \rangle} \quad (\text{E_Seq})$$

$$\frac{e =_{\mu} v \quad \mu \{ x \leftarrow v \} \mapsto \mu'}{\langle (x := e), \mu \rangle \mapsto \langle \text{null}, \mu' \rangle} \quad (\text{E_Assign})$$

$$\frac{e =_{\mu} \text{true}}{\langle (\text{if } e \text{ then } c_1; \text{ else } c_2; \text{ end if}), \mu \rangle \mapsto \langle c_1, \mu \rangle} \quad (\text{E_IfThenElse1})$$

$$\frac{e =_{\mu} \text{false}}{\langle (\text{if } e \text{ then } c_1; \text{ else } c_2; \text{ end if}), \mu \rangle \mapsto \langle c_2, \mu \rangle} \quad (\text{E_IfThenElse2})$$

$$\frac{e =_{\mu} \text{false}}{\langle (\text{while } e \text{ loop } c; \text{ end loop}), \mu \rangle \mapsto \langle \text{null}, \mu \rangle} \quad (\text{E_While1})$$

$$\frac{e =_{\mu} \text{true}}{\langle (\text{while } e \text{ loop } c; \text{ end loop}), \mu \rangle \mapsto \langle (c; \text{while } e \text{ loop } c; \text{ end loop}), \mu \rangle} \quad (E_While2)$$

$$\overline{\langle \text{declare begin end}, \mu \rangle \mapsto \langle \text{null}, \mu \rangle} \quad (E_Decl1)$$

$$\frac{\langle d, \mu \rangle \mapsto \langle d', \mu' \rangle}{\langle \text{declare } d, \mu \rangle \mapsto \langle \text{declare } d', \mu' \rangle} \quad (E_Decl2)$$

$$\frac{e =_{\mu} k \quad e' =_{\mu} k' \quad k > k'}{\langle (\text{for } x \text{ in } e \dots e' \text{ loop } c; \text{ end loop}), \mu \rangle \mapsto \langle \text{null}, \mu \rangle} \quad (E_For1)$$

$$\overline{\langle (\text{for } x \text{ in } e \dots e' \text{ loop } c; \text{ end loop}), \mu \rangle \mapsto \langle (\text{declare } x : \text{constant int } := k; \text{begin } c; \text{end}; \text{for } x \text{ in } \{k + 1\} \dots k' \text{ loop } c; \text{end loop}), \mu \rangle} \quad (E_For2)$$

$$\frac{e =_{\mu} \text{proc}(|x'_i : m'_i \tau'_i|) \text{ is } d \quad (|x'_i : m'_i \tau'_i|) \# (|e'_j|) = [|x_n : m_n \tau_n = e_n|]}{\langle e(|e'_j|), \mu \rangle \mapsto \langle \text{declare}[|x_n : m_n \tau_n = e_n|] d, \mu \rangle} \quad (E_ProcCall)$$

Declaration evaluation

$$\boxed{\langle d, \mu \rangle \mapsto \langle d', \mu' \rangle}$$

$$\overline{\langle \text{begin null}; \text{end}, \mu \rangle \mapsto \langle \text{begin end}, \mu \rangle} \quad (E_Block1)$$

$$\frac{\langle c, \mu \rangle \mapsto \langle c', \mu' \rangle}{\langle \text{begin } c; \text{end}, \mu \rangle \mapsto \langle \text{begin } c'; \text{end}, \mu' \rangle} \quad (E_Block2)$$

$$\overline{\langle x : \tau := e; \text{begin end}, \mu \rangle \mapsto \langle \text{begin end}, \mu \rangle} \quad (E_InitVar1)$$

$$\frac{e =_{\mu} v \quad \langle d, (\mu, x \leftarrow v) \rangle \mapsto \langle d', (\mu', x \leftarrow v') \rangle}{\langle x : \tau := e; d, \mu \rangle \mapsto \langle x : \tau := v'; d', \mu' \rangle} \quad (E_InitVar2)$$

$$\overline{\langle x : \text{constant } \tau := e; \text{begin end}, \mu \rangle \mapsto \langle \text{begin end}, \mu \rangle} \quad (E_Const1)$$

$$\frac{e =_{\mu} v \quad \langle d[v/x], \mu \rangle \mapsto \langle d', \mu' \rangle}{\langle x : \text{constant } \tau := e; d, \mu \rangle \mapsto \langle x : \text{constant } \tau := v; d', \mu' \rangle} \quad (E_Const2)$$

$$\overline{\langle \text{procedure } p(|x_n : m_n \tau_n|) \text{ is } d_1; d, \mu \rangle \mapsto \langle d[\text{proc}(|x_n : m_n \tau_n|) \text{ is } d_1 / p], \mu \rangle} \quad (E_Proc)$$

$$\overline{\langle (x : m \tau = e) \text{begin end}, \mu \rangle \mapsto \langle \text{begin end}, \mu \rangle} \quad (E_Alias1)$$

$$\frac{e =_{\mu} v \quad \langle d[v/x], \mu \rangle \mapsto \langle d', \mu' \rangle}{\langle (x : \text{in } \tau = e) d, \mu \rangle \mapsto \langle d', \mu' \rangle} \quad (E_Alias2)$$

$$\frac{m \neq \text{in} \quad \mu(y) = v \quad \langle d, (\mu, x \leftarrow v) \rangle \mapsto \langle d', (\mu', x \leftarrow v') \rangle \quad \mu' \{y \leftarrow v'\} \mapsto \mu''}{\langle (x : m \tau = y) d, \mu \rangle \mapsto \langle (x : m \tau = y) d', \mu'' \rangle} \quad (E_Alias3)$$

$$\overline{\langle [] d, \mu \rangle \mapsto \langle d, \mu \rangle} \quad (E_Aliases1)$$

$$\overline{\langle [|x_n : m_n \tau_n = e_n|] \text{begin end}, \mu \rangle \mapsto \langle \text{begin end}, \mu \rangle} \quad (E_Aliases2)$$

$$\frac{\langle (x : m \tau = e)[|x_n : m_n \tau_n = e_n|] d, \mu \rangle \mapsto \langle d', \mu' \rangle}{\langle [x : m \tau = e, |x_n : m_n \tau_n = e_n|] d, \mu \rangle \mapsto \langle d', \mu' \rangle} \quad (E_Aliases3)$$

A Generated Isabelle/HOL theory

```
(* generated by Ott 0.10.15 from: _source-1-s.ott _source-1.ott _source-2-s.ott _source-2.ott
_source-3-s.ott _source-3.ott _source-4.ott source.ott *)
theory source imports Main Multiset begin
```

```
(** syntax *)
types index = "nat"
types ident = "string"
types number = "int"
types integer = "int"
datatype
mode =
  M_In
  | M_Out
  | M_InOut

types boolean = "bool"
datatype
ty =
  T_Int
  | T_Boolean
  | T_Proc "(mode*ty) list"
  | T_Void

datatype
dcl =
  D_Empty
  | D_Block "cmd"
  | D_UninitVar "ident" "ty" "dcl"
  | D_InitVar "ident" "ty" "exp" "dcl"
  | D_Constant "ident" "ty" "exp" "dcl"
  | D_Proc "ident" "(ident*mode*ty) list" "dcl" "dcl"
  | D_Aliases "(ident*mode*ty*exp) list" "dcl"
  | D_Alias "ident" "mode" "ty" "exp" "dcl"
and va =
  V_Int "integer"
  | V_Boolean "boolean"
  | V_Proc "(ident*mode*ty) list" "dcl"
and cmd =
  C_Null
  | C_Assign "ident" "exp"
  | C_Seq "cmd" "cmd"
  | C_IfThenElse "exp" "cmd" "cmd"
  | C_While "exp" "cmd"
  | C_Decl "dcl"
  | C_For "ident" "exp" "exp" "cmd"
  | C_ProcCall "exp" "exp list"
and exp =
  E_Var "ident"
  | E_Value "va"
  | E_Plus "exp" "exp"
  | E_Minus "exp" "exp"
  | E_Times "exp" "exp"
  | E_Equal "exp" "exp"
  | E_Greater "exp" "exp"
  | E_Less "exp" "exp"
  | E_And "exp" "exp"
  | E_Or "exp" "exp"
  | E_Not "exp"

datatype
df =
  VarDecl "mode" "ty"
  | ReturnTy "ty"

types store = "(ident*va) list"
```

```

types env = "(ident*df) list"
types trace = "(cmd*store) list"

(** library functions *)
lemma [mono]:"
  (!! x. f x --> g x) ==> list_all (%b. b) (map f foo_list)-->
    list_all (%b. b) (map g foo_list) "
  apply(induct_tac foo_list, auto) done

lemma [mono]: "split f p = f (fst p) (snd p)" by (simp add: split_def)

(** subrules *)
consts
is_value_of_exp :: "exp => bool"
primrec
"is_value_of_exp (E_Var x) = (False)"
"is_value_of_exp (E_Value v) = ((True))"
"is_value_of_exp (E_Plus e1 e2) = (False)"
"is_value_of_exp (E_Minus e1 e2) = (False)"
"is_value_of_exp (E_Times e1 e2) = (False)"
"is_value_of_exp (E_Equal e1 e2) = (False)"
"is_value_of_exp (E_Greater e1 e2) = (False)"
"is_value_of_exp (E_Less e1 e2) = (False)"
"is_value_of_exp (E_And e1 e2) = (False)"
"is_value_of_exp (E_Or e1 e2) = (False)"
"is_value_of_exp (E_Not e) = (False)"

(** substitutions *)
consts
subst_ty_exp :: "exp => ident => (ty*exp) => (ty*exp)"
subst_mode_ty_exp :: "exp => ident => mode*(ty*exp) => mode*(ty*exp)"
subst_ident_mode_ty_exp :: "exp => ident => ident*(mode*ty*exp) => ident*(mode*ty*exp)"
subst_ident_mode_ty_exp_list :: "exp => ident => (ident*mode*ty*exp) list =>
  (ident*mode*ty*exp) list"
subst_dcl :: "exp => ident => dcl => dcl"
subst_va :: "exp => ident => va => va"
subst_exp_list :: "exp => ident => exp list => exp list"
subst_cmd :: "exp => ident => cmd => cmd"
subst_exp :: "exp => ident => exp => exp"
primrec
"subst_ty_exp e_5 x_5 (ty1,exp1) = (ty1 , subst_exp e_5 x_5 exp1)"
"subst_mode_ty_exp e_5 x_5 (mode1,ty_exp1) = (mode1 , subst_ty_exp e_5 x_5 ty_exp1)"
"subst_ident_mode_ty_exp e_5 x_5 (ident1,mode_ty_exp1) = (ident1 , subst_mode_ty_exp e_5 x_5
mode_ty_exp1)"
"subst_ident_mode_ty_exp_list e_5 x_5 Nil = (Nil)"
"subst_ident_mode_ty_exp_list e_5 x_5 (ident_mode_ty_exp_0#ident_mode_ty_exp_list_0) =
((subst_ident_mode_ty_exp e_5 x_5 ident_mode_ty_exp_0) # (subst_ident_mode_ty_exp_list e_5 x_5
ident_mode_ty_exp_list_0))"
"subst_dcl e_5 x_5 D_Empty = (D_Empty )"
"subst_dcl e_5 x_5 (D_Block c) = (D_Block (subst_cmd e_5 x_5 c))"
"subst_dcl e_5 x_5 (D_UninitVar x T d) = (D_UninitVar x T (if x_5 mem [x] then d else
(subst_dcl e_5 x_5 d)))"
"subst_dcl e_5 x_5 (D_InitVar x T e d) = (D_InitVar x T (subst_exp e_5 x_5 e) (if x_5 mem [x]
then d else (subst_dcl e_5 x_5 d)))"
"subst_dcl e_5 x_5 (D_Constant x T e d) = (D_Constant x T (subst_exp e_5 x_5 e) (if x_5 mem [x]
then d else (subst_dcl e_5 x_5 d)))"
"subst_dcl e_5 x_5 (D_Proc p (x_m_T_list) d1 d2) = (D_Proc p x_m_T_list (if x_5 mem (List.map
(%((x_0::ident),(m_0::mode),(T_0::ty)).x_0) x_m_T_list) then d1 else (subst_dcl e_5 x_5 d1))
(subst_dcl e_5 x_5 d2))"
"subst_dcl e_5 x_5 (D_Aliases (x_m_T_e_list) d) = (D_Aliases (subst_ident_mode_ty_exp_list e_5
x_5 x_m_T_e_list) (if x_5 mem (List.map (%((x_0::ident),(m_0::mode),(T_0::ty),(e_0::exp)).x_0)
x_m_T_e_list) then d else (subst_dcl e_5 x_5 d)))"
"subst_dcl e_5 x_5 (D_Alias x m T e d) = (D_Alias x m T (subst_exp e_5 x_5 e) (if x_5 mem [x]
then d else (subst_dcl e_5 x_5 d)))"
"subst_va e5 x_5 (V_Int k) = (V_Int k)"

```

```

"subst_va e5 x_5 (V_Bool b) = (V_Bool b)"
"subst_va e5 x_5 (V_Proc (x_m_T_list) d) = (V_Proc x_m_T_list (if x_5 mem (List.map
(%((x_0::ident),(m_0::mode),(T_0::ty)).x_0) x_m_T_list) then d else (subst_dcl e5 x_5 d)))"
"subst_exp_list e_5 x5 Nil = (Nil)"
"subst_exp_list e_5 x5 (exp_0#exp_list_0) = ((subst_exp e_5 x5 exp_0) # (subst_exp_list e_5 x5
exp_list_0))"
"subst_cmd e_5 x5 C_Null = (C_Null )"
"subst_cmd e_5 x5 (C_Assign x e) = (C_Assign x (subst_exp e_5 x5 e))"
"subst_cmd e_5 x5 (C_Seq c1 c2) = (C_Seq (subst_cmd e_5 x5 c1) (subst_cmd e_5 x5 c2))"
"subst_cmd e_5 x5 (C_IfThenElse e c1 c2) = (C_IfThenElse (subst_exp e_5 x5 e) (subst_cmd e_5 x5
c1) (subst_cmd e_5 x5 c2))"
"subst_cmd e_5 x5 (C_While e c) = (C_While (subst_exp e_5 x5 e) (subst_cmd e_5 x5 c))"
"subst_cmd e_5 x5 (C_Decl d) = (C_Decl (subst_dcl e_5 x5 d))"
"subst_cmd e_5 x5 (C_For x e e' c) = (C_For x (subst_exp e_5 x5 e) (subst_exp e_5 x5 e') (if x5
mem [x] then c else (subst_cmd e_5 x5 c)))"
"subst_cmd e_5 x5 (C_ProcCall e (e_list)) = (C_ProcCall (subst_exp e_5 x5 e) (subst_exp_list
e_5 x5 e_list))"
"subst_exp e_5 x5 (E_Var x) = ((if x=x5 then e_5 else (E_Var x)))"
"subst_exp e_5 x5 (E_Value v) = (E_Value (subst_va e_5 x5 v))"
"subst_exp e_5 x5 (E_Plus e1 e2) = (E_Plus (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_Minus e1 e2) = (E_Minus (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_Times e1 e2) = (E_Times (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_Equal e1 e2) = (E_Equal (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_Greater e1 e2) = (E_Greater (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_Less e1 e2) = (E_Less (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_And e1 e2) = (E_And (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_Or e1 e2) = (E_Or (subst_exp e_5 x5 e1) (subst_exp e_5 x5 e2))"
"subst_exp e_5 x5 (E_Not e) = (E_Not (subst_exp e_5 x5 e))"

```

```

(** definitions *)

```

```

(*defs eval_exp *)

```

```

inductive_set Fetch :: "(store*ident*va) set"

```

```

and ExpEval :: "(exp*store*va) set"

```

```

where

```

```

(* defn Fetch *)

```

```

Fetch1I: " ( (( x , v )# mu ) , x , v ) : Fetch"

```

```

| Fetch2I: "[| x ~ = x' ;
( mu , x , v ) : Fetch|] ==>
( (( x' , v' )# mu ) , x , v ) : Fetch"

```

```

| (* defn ExpEval *)

```

```

E_ValueI: " ( (E_Value v) , mu , v ) : ExpEval"

```

```

| E_IdentI: "[| ( mu , x , v ) : Fetch|] ==>
( (E_Var x) , mu , v ) : ExpEval"

```

```

| E_PlusI: "[| ( e1 , mu , (V_Int k1) ) : ExpEval ;
( e2 , mu , (V_Int k2) ) : ExpEval|] ==>
( (E_Plus e1 e2) , mu , (V_Int ( k1 + k2 ) ) ) : ExpEval"

```

```

| E_MinusI: "[| ( e1 , mu , (V_Int k1) ) : ExpEval ;
( e2 , mu , (V_Int k2) ) : ExpEval|] ==>
( (E_Minus e1 e2) , mu , (V_Int ( k1 - k2 ) ) ) : ExpEval"

```

```

| E_TimesI: "[| ( e1 , mu , (V_Int k1) ) : ExpEval ;
( e2 , mu , (V_Int k2) ) : ExpEval|] ==>
( (E_Times e1 e2) , mu , (V_Int ( k1 * k2 ) ) ) : ExpEval"

```

```

| E_GreaterI: "[| ( e1 , mu , (V_Int k1) ) : ExpEval ;
( e2 , mu , (V_Int k2) ) : ExpEval|] ==>
( (E_Greater e1 e2) , mu , (V_Bool ( k1 > k2 ) ) ) : ExpEval"

```

```

| E_LessI: "[| ( e1 , mu , (V_Int k1) ) : ExpEval ;

```

```

(e2 , mu , (V_Int k2) ) : ExpEval]] ==>
(E_Less e1 e2) , mu , (V_Bool ( k1 < k2 ) ) ) : ExpEval"

| E_EqualI: "[| ( e1 , mu , (V_Int k1) ) : ExpEval ;
(e2 , mu , (V_Int k2) ) : ExpEval]] ==>
(E_Equal e1 e2) , mu , (V_Bool ( k1 = k2 ) ) ) : ExpEval"

| E_AndI: "[| ( e1 , mu , (V_Bool b1) ) : ExpEval ;
(e2 , mu , (V_Bool b2) ) : ExpEval]] ==>
(E_And e1 e2) , mu , (V_Bool ( b1 & b2 ) ) ) : ExpEval"

| E_OrI: "[| ( e1 , mu , (V_Bool b1) ) : ExpEval ;
(e2 , mu , (V_Bool b2) ) : ExpEval]] ==>
(E_Or e1 e2) , mu , (V_Bool ( b1 | b2 ) ) ) : ExpEval"

| E_NotI: "[| ( e , mu , (V_Bool b) ) : ExpEval]] ==>
(E_Not e) , mu , (V_Bool (¬ b ) ) ) : ExpEval"

(*defns typing *)
inductive_set Lookup :: "(ident*df*env) set"
and ExpTyping :: "(env*exp*ty) set"
and LookupD :: "(df*env) set"
and Match :: "(env*exp*mode*ty) set"
and MatchList :: "(env*exp list*(mode*ty) list) set"
and DeclTyping :: "(env*dcl) set"
and CommTyping :: "(env*cmd) set"
where
(* defn Lookup *)

Lookup1I: " ( x , df , (( x , df ) # G ) ) : Lookup"

| Lookup2I: "[| x ~ = x' ;
(x , df , G ) : Lookup]] ==>
(x , df , (( x' , df' ) # G ) ) : Lookup"

| (* defn ExpTyping *)

VarI: "[| m ~ = M_Out ;
(x , (VarDecl m T) , G ) : Lookup]] ==>
(G , (E_Var x) , T ) : ExpTyping"

| IntCstI: " ( G , (E_Value (V_Int q) ) , T_Int ) : ExpTyping"

| BoolTrueI: " ( G , (E_Value (V_Bool true) ) , T_Bool ) : ExpTyping"

| BoolFalseI: " ( G , (E_Value (V_Bool false) ) , T_Bool ) : ExpTyping"

| PlusI: "[| ( G , e1 , T_Int ) : ExpTyping ;
(G , e2 , T_Int ) : ExpTyping]] ==>
(G , (E_Plus e1 e2) , T_Int ) : ExpTyping"

| MinusI: "[| ( G , e1 , T_Int ) : ExpTyping ;
(G , e2 , T_Int ) : ExpTyping]] ==>
(G , (E_Minus e1 e2) , T_Int ) : ExpTyping"

| TimesI: "[| ( G , e1 , T_Int ) : ExpTyping ;
(G , e2 , T_Int ) : ExpTyping]] ==>
(G , (E_Times e1 e2) , T_Int ) : ExpTyping"

| EqualI: "[| ( G , e1 , T ) : ExpTyping ;
(G , e2 , T ) : ExpTyping]] ==>
(G , (E_Equal e1 e2) , T_Bool ) : ExpTyping"

| GreaterI: "[| ( G , e1 , T_Int ) : ExpTyping ;
(G , e2 , T_Int ) : ExpTyping]] ==>
(G , (E_Greater e1 e2) , T_Bool ) : ExpTyping"

```



```

| LessI: "[| ( G , e1 , T_Int ) : ExpTyping ;
( G , e2 , T_Int ) : ExpTyping|] ==>
( G , (E_Less e1 e2) , T_Bool ) : ExpTyping"

| AndI: "[| ( G , e1 , T_Bool ) : ExpTyping ;
( G , e2 , T_Bool ) : ExpTyping|] ==>
( G , (E_And e1 e2) , T_Bool ) : ExpTyping"

| OrI: "[| ( G , e1 , T_Bool ) : ExpTyping ;
( G , e2 , T_Bool ) : ExpTyping|] ==>
( G , (E_Or e1 e2) , T_Bool ) : ExpTyping"

| NotI: "[| ( G , e , T_Bool ) : ExpTyping|] ==>
( G , (E_Not e) , T_Bool ) : ExpTyping"

| (* defn LookupD *)

LookupD1I: " ( df , (( x , df ) # G ) ) : LookupD"

| LookupD2I: "[| df ~ = df' ;
( df , G ) : LookupD|] ==>
( df , (( x , df' ) # G ) ) : LookupD"

| (* defn Match *)

Match1I: "[| ( G , e , T ) : ExpTyping|] ==>
( G , e , M_In , T ) : Match"

| Match2I: "[| ( x , (VarDecl m T) , G ) : Lookup ;
m ~ = M_In |] ==>
( G , (E_Var x) , M_Out , T ) : Match"

| Match3I: "[| ( x , (VarDecl M_InOut T) , G ) : Lookup|] ==>
( G , (E_Var x) , M_InOut , T ) : Match"

| (* defn MatchList *)

MatchList1I: " ( G , [] , [] ) : MatchList"

| MatchList2I: "[| ( G , e , m , T ) : Match ;
( G , (e_list) , (m_T_list) ) : MatchList|] ==>
( G , ((e) # e_list) , ((m,T) # m_T_list) ) : MatchList"

| (* defn DeclTyping *)

EmptyI: " ( G , D_Empty ) : DeclTyping"

| BlockI: "[| ( G , c ) : CommTyping|] ==>
( G , (D_Block c) ) : DeclTyping"

| UunitVarI: "[| ( (( x , (VarDecl M_InOut T) ) # G ) , d ) : DeclTyping|] ==>
( G , (D_UunitVar x T d) ) : DeclTyping"

| InitVarI: "[| ( G , e , T ) : ExpTyping ;
( (( x , (VarDecl M_InOut T) ) # G ) , d ) : DeclTyping|] ==>
( G , (D_InitVar x T e d) ) : DeclTyping"

| ConstantI: "[| ( G , e , T ) : ExpTyping ;
( (( x , (VarDecl M_In T) ) # G ) , d ) : DeclTyping|] ==>
( G , (D_Constant x T e d) ) : DeclTyping"

| ProcI: "[| ( ( (List.rev ((List.map (%((x_0::ident),(m_0::mode),(T_0::ty)).(x_0,(VarDecl
m_0 T_0))) x_m_T_list)) @ G ) , d1 ) : DeclTyping ;
( (( p , (VarDecl M_In (T_Proc ((List.map (%((x_0::ident),(m_0::mode),(T_0::ty)).(m_0,T_0))
x_m_T_list)))) ) # G ) , d2 ) : DeclTyping|] ==>
( G , (D_Proc p (x_m_T_list) d1 d2) ) : DeclTyping"

```

```

| (* defn CommTyping *)

NullI: " ( G , C_Null ) : CommTyping"

| SeqI: "[| ( G , c1 ) : CommTyping ;
( G , c2 ) : CommTyping|] ==>
( G , (C_Seq c1 c2) ) : CommTyping"

| AssignI: "[| m ~ = M_In ;
( x , (VarDecl m T) , G ) : Lookup ;
( G , e , T ) : ExpTyping|] ==>
( G , (C_Assign x e) ) : CommTyping"

| IfThenElseI: "[| ( G , e , T_Bool ) : ExpTyping ;
( G , c1 ) : CommTyping ;
( G , c2 ) : CommTyping|] ==>
( G , (C_IfThenElse e c1 c2) ) : CommTyping"

| WhileI: "[| ( G , e , T_Bool ) : ExpTyping ;
( G , c ) : CommTyping|] ==>
( G , (C_While e c) ) : CommTyping"

| ForI: "[| ( G , e , T_Int ) : ExpTyping ;
( G , e' , T_Int ) : ExpTyping ;
( ( ( x , (VarDecl M_In T_Int) ) # G ) , c ) : CommTyping|] ==>
( G , (C_For x e e' c) ) : CommTyping"

| DeclI: "[| ( G , d ) : DeclTyping|] ==>
( G , (C_Decl d) ) : CommTyping"

| ProcCallI: "[| ( G , e , (T_Proc (m_T_list)) ) : ExpTyping ;
( G , (e_list) , (m_T_list) ) : MatchList|] ==>
( G , (C_ProcCall e (e_list)) ) : CommTyping"

(*defns eval_comm *)
inductive_set StoreUpdate :: "(store*ident*va*store) set"
and ManySteps :: "(cmd*store*integer*cmd*store) set"
and Trace :: "(cmd*store*integer*trace) set"
and FullEvaluation :: "(cmd*store*store) set"
and Compat :: "((ident*mode*ty) list*exp list*(ident*mode*ty*exp) list) set"
and OneStep :: "(cmd*store*cmd*store) set"
and DeclEval :: "(dcl*store*dcl*store) set"
where
(* defn StoreUpdate *)

Update1I: " ( ( ( x , v ) # mu ) , x , v' , ( ( x , v' ) # mu ) ) : StoreUpdate"

| Update2I: "[| x ~ = x' ;
( mu , x , v' , mu' ) : StoreUpdate|] ==>
( ( ( x' , v ) # mu ) , x , v' , ( ( x' , v ) # mu' ) ) : StoreUpdate"

| (* defn ManySteps *)

ManySteps1I: " ( c , mu , 0 , c , mu ) : ManySteps"

| ManySteps2I: " ( C_Null , mu , k , C_Null , mu ) : ManySteps"

| ManySteps3I: "[| ( c , mu , c' , mu' ) : OneStep ;
( c' , mu' , ( k - 1 ) , c'' , mu'' ) : ManySteps|] ==>
( c , mu , k , c'' , mu'' ) : ManySteps"

| (* defn Trace *)

Trace1I: " ( c , mu , 0 , [] ) : Trace"

| Trace2I: " ( C_Null , mu , k , [] ) : Trace"

```

```

| Trace3I: "[| ( c , mu , c' , mu' ) : OneStep ;
( c' , mu' , ( k - 1 ) , (c'_mu'_list) ) : Trace[] ==>
( c , mu , k , ((c',mu') # c'_mu'_list) ) : Trace"

| (* defn FullEvaluation *)

Eval1I: " ( C_Null , mu , mu ) : FullEvaluation"

| Eval2I: "[| ( c , mu , c' , mu' ) : OneStep ;
( c' , mu' , mu'' ) : FullEvaluation[] ==>
( c , mu , mu'' ) : FullEvaluation"

| (* defn Compat *)

E_Compat1I: " ( [] , [] , [] ) : Compat"

| E_Compat2I: "[| ( (x'_m'_T'_list) , (e'_list) , (x_m_T_e_list) ) : Compat[] ==>
( ((x,m,T) # x'_m'_T'_list) , ((e) # e'_list) , ((x,m,T,e) # x_m_T_e_list) ) : Compat"

| (* defn OneStep *)

E_NullI: " ( (C_Seq C_Null c) , mu , c , mu ) : OneStep"

| E_SeqI: "[| ( c1 , mu , c1' , mu' ) : OneStep[] ==>
( (C_Seq c1 c2) , mu , (C_Seq c1' c2) , mu' ) : OneStep"

| E_AssignI: "[| ( e , mu , v ) : ExpEval ;
( mu , x , v , mu' ) : StoreUpdate[] ==>
( (C_Assign x e) , mu , C_Null , mu' ) : OneStep"

| E_IfThenElse1I: "[| ( e , mu , (V_Bool true) ) : ExpEval[] ==>
( (C_IfThenElse e c1 c2) , mu , c1 , mu ) : OneStep"

| E_IfThenElse2I: "[| ( e , mu , (V_Bool false) ) : ExpEval[] ==>
( (C_IfThenElse e c1 c2) , mu , c2 , mu ) : OneStep"

| E_While1I: "[| ( e , mu , (V_Bool false) ) : ExpEval[] ==>
( (C_While e c) , mu , C_Null , mu ) : OneStep"

| E_While2I: "[| ( e , mu , (V_Bool true) ) : ExpEval[] ==>
( (C_While e c) , mu , (C_Seq c (C_While e c)) , mu ) : OneStep"

| E_Decl1I: " ( (C_Decl D_Empty) , mu , C_Null , mu ) : OneStep"

| E_Decl2I: "[| ( d , mu , d' , mu' ) : DeclEval[] ==>
( (C_Decl d) , mu , (C_Decl d') , mu' ) : OneStep"

| E_For1I: "[| ( e , mu , (V_Int k) ) : ExpEval ;
( e' , mu , (V_Int k') ) : ExpEval ;
( k > k' ) |] ==>
( (C_For x e e' c) , mu , C_Null , mu ) : OneStep"

| E_For2I: "[| ( e , mu , (V_Int k) ) : ExpEval ;
( e' , mu , (V_Int k') ) : ExpEval ;
( k <= k' ) |] ==>
( (C_For x e e' c) , mu , (C_Seq (C_Decl (D_Constant x T_Int (E_Value (V_Int k))) (D_Block
c))) (C_For x (E_Value (V_Int (k + 1))) (E_Value (V_Int k'))) c) , mu ) : OneStep"

| E_ProcCallI: "[| ( e , mu , (V_Proc (x'_m'_T'_list) d) ) : ExpEval ;
( (x'_m'_T'_list) , (e'_list) , (x_m_T_e_list) ) : Compat[] ==>
( (C_ProcCall e (e'_list)) , mu , (C_Decl (D_Aliases (x_m_T_e_list) d)) , mu ) : OneStep"

| (* defn DeclEval *)

E_Block1I: " ( (D_Block C_Null) , mu , D_Empty , mu ) : DeclEval"

| E_Block2I: "[| ( c , mu , c' , mu' ) : OneStep[] ==>

```

```

( (D_Block c) , mu , (D_Block c') , mu' ) : DeclEval"

| E_InitVar1I: " ( (D_InitVar x T e D_Empty) , mu , D_Empty , mu ) : DeclEval"

| E_InitVar2I: "[| ( e , mu , v ) : ExpEval ;
( d , (( x , v)# mu ) , d' , (( x , v')# mu' ) ) : DeclEval|] ==>
( (D_InitVar x T e d) , mu , (D_InitVar x T (E_Value v') d') , mu' ) : DeclEval"

| E_Const1I: " ( (D_Constant x T e D_Empty) , mu , D_Empty , mu ) : DeclEval"

| E_Const2I: "[| ( e , mu , v ) : ExpEval ;
( (subst_dc1 (E_Value v) x d) , mu , d' , mu' ) : DeclEval|] ==>
( (D_Constant x T e d) , mu , (D_Constant x T (E_Value v) d') , mu' ) : DeclEval"

| E_ProcI: " ( (D_Proc p (x_m_T_list) d1 d) , mu , (subst_dc1 (E_Value (V_Proc (x_m_T_list)
d1) ) p d) , mu ) : DeclEval"

| E_Alias1I: " ( (D_Alias x m T e D_Empty) , mu , D_Empty , mu ) : DeclEval"

| E_Alias2I: "[| ( e , mu , v ) : ExpEval ;
( (subst_dc1 (E_Value v) x d) , mu , d' , mu' ) : DeclEval|] ==>
( (D_Alias x M_In T e d) , mu , d' , mu' ) : DeclEval"

| E_Alias3I: "[| m ~ = M_In ;
( mu , y , v ) : Fetch ;
( d , (( x , v)# mu ) , d' , (( x , v')# mu' ) ) : DeclEval ;
( mu' , y , v' , mu'' ) : StoreUpdate|] ==>
( (D_Alias x m T (E_Var y) d) , mu , (D_Alias x m T (E_Var y) d') , mu'' ) : DeclEval"

| E_Aliases1I: " ( (D_Aliases [] d) , mu , d , mu ) : DeclEval"

| E_Aliases2I: " ( (D_Aliases (x_m_T_e_list) D_Empty) , mu , D_Empty , mu ) : DeclEval"

| E_Aliases3I: "[| ( (D_Alias x m T e (D_Aliases (x_m_T_e_list) d)) , mu , d' , mu' ) :
DeclEval|] ==>
( (D_Aliases ((x,m,T,e) # x_m_T_e_list) d) , mu , d' , mu' ) : DeclEval"

```

```

code_module Evaluation
contains

```

```

test1 = " ( ( (E_Plus (E_Value (V_Int 2)) (E_Value (V_Int 3))) ) , Nil , _ ) :
ExpEval"
test2 = " ( ( (E_Plus (E_Var ''X'') (E_Value (V_Int 3))) ) , ([(''X'',(V_Int 5))]) , _
) : ExpEval"

```

```

ML {* DSeq.hd Evaluation.test1 *}

```

```

code_module Typing (* file "Typing.sml" *)
contains

```

```

test1 = " ( Nil , (E_Var ''X'') , T_Int ) : ExpTyping"

test2 = " ( ((''X'',(VarDecl M_In T_Int)) # [('',Y'',(VarDecl M_In T_Int))]) , (E_Equal (
(E_Plus (E_Var ''X'') (E_Value (V_Int 1))) ) (E_Var ''Y'')) , T_Boolean ) : ExpTyping"

```

```

ML {* Typing.test1 *}
ML {* Typing.test2 *}

```

```

code_module Evaluation
contains

```

```

test1 = " ( ( (E_Plus (E_Value (V_Int 2)) (E_Value (V_Int 3))) ) , Nil , _ ) :
ExpEval"

```

```

test2 = " ( (('X'',(V_Int 2)) # [('Y'',(V_Int 3))]) , 'X' , (V_Int 3) , _ ) :
StoreUpdate"

test3 = " ( (C_Assign 'X' (E_Plus (E_Var 'X') (E_Value (V_Int 1)))) , ([('X'',(V_Int
2))]) , 1 , _ , _ ) : ManySteps"

test4 = " ( (C_Seq (C_Assign 'X' (E_Plus (E_Var 'X') (E_Var 'Y'))) (C_Assign 'Y'
(E_Plus (E_Var 'X') (E_Var 'Y')))) , (('X'',(V_Int 42)) # [('Y'',(V_Int 12))]) ,
_ ) : FullEvaluation"

test5 = " ( (C_IfThenElse (E_Var 'B') (C_Assign 'X' (E_Value (V_Int 1))) (C_Assign 'Y'
(E_Value (V_Int 1)))) , (('B'',(V_Bool true)) # ('X'',(V_Int 0)) # [('Y'',(V_Int 0
))]) , _ ) : FullEvaluation"

ML {* DSeq.hd Evaluation.test1 *}
ML {* DSeq.hd Evaluation.test2 *}
ML {* DSeq.hd Evaluation.test3 *}
ML {* DSeq.hd Evaluation.test4 *}
ML {* DSeq.hd Evaluation.test5 *}

code_module Typing (* file "Extraction.sml" *)
contains

test1 = " ( ([('X'',(VarDecl M_InOut T_Int))]) , (C_Assign 'X' (E_Plus (E_Var 'X')
(E_Value (V_Int 1)))) ) : CommTyping"

test2 = " ( (('X'',(VarDecl M_InOut T_Int)) # ('Y'',(VarDecl M_In T_Bool)) #
[('B'',(VarDecl M_In T_Bool))]) , (C_IfThenElse (E_Var 'B') (C_Assign 'X' (E_Value (V_Int
1))) (C_Assign 'Y' (E_Value (V_Int 1)))) ) : CommTyping"

ML {* Typing.test1 *}
ML {* Typing.test2 *}

code_module Evaluation
contains

test1 = " ( (C_Decl (D_Constant 'B' T_Bool (E_Value (V_Bool false))) (D_Block (C_IfThenElse
(E_Var 'B') (C_Assign 'X' (E_Value (V_Int 1))) (C_Assign 'Y' (E_Value (V_Int 1))))))
, (('X'',(V_Int 0)) # [('Y'',(V_Int 0))]) , _ ) : FullEvaluation"

test2 = " ( (C_For 'I' (E_Value (V_Int 1)) (E_Var 'X') (C_Assign 'Y' (E_Plus (E_Var
'Y') (E_Var 'X')))) , (('X'',(V_Int 5)) # [('Y'',(V_Int 0))]) , _ ) :
FullEvaluation"

ML {* DSeq.hd Evaluation.test1 *}
ML {* DSeq.hd Evaluation.test2 *}

code_module Typing (* file "Extraction.sml" *)
contains

test1 = " ( ([('X'',(VarDecl M_InOut T_Int))]) , (C_Assign 'X' (E_Plus (E_Var 'X')
(E_Value (V_Int 1)))) ) : CommTyping"

test2 = " ( ([('X'',(VarDecl M_InOut T_Int))]) , (C_Decl (D_InitVar 'X' T_Int (E_Value
(V_Int 42))) (D_Block (C_Seq (C_Assign 'X' (E_Plus (E_Var 'Y') (E_Value (V_Int 1))))
(C_Seq (C_Assign 'X' (E_Plus (E_Var 'X') (E_Value (V_Int 1)))) (C_Assign 'Y' (E_Minus
(E_Var 'Y') (E_Value (V_Int 1)))))))) ) : CommTyping"

test3 = " ( ([('X'',(VarDecl M_InOut T_Int))]) , (C_Decl (D_InitVar 'Y' T_Bool (E_Value
(V_Bool false))) (D_Block (C_For 'I' (E_Value (V_Int 1)) (E_Var 'X') (C_Assign 'X'
(E_Plus (E_Var 'Y') (E_Value (V_Int 1)))))))) ) : CommTyping"

ML {* Typing.test1 *}
ML {* Typing.test2 *}

```

```
ML {* Typing.test3 *}
```

```
code_module Typing
contains
```

```
test1 = " ( ([('R',(VarDecl M_Out T_Bool))]) , (C_Decl (D_InitVar 'Y' T_Int (E_Value
(V_Int 42 )) (D_Proc 'P' (('I',M_InOut,T_Int) # [('B',M_Out,T_Bool])) (D_Block (C_Assign
'B' ( (E_Equal (E_Var 'I') (E_Value (V_Int 1 ))) ) ) (D_Block (C_ProcCall (E_Var 'P')
((E_Var 'Y')) # [(E_Var 'R')])))) ) : CommTyping"
```

```
test2 = " ( ([('R',(VarDecl M_Out T_Int))]) , (C_Decl (D_Proc 'Incr' (('N',M_In,T_Int)
# [('R',M_Out,T_Int])) (D_Block (C_Assign 'R' (E_Plus (E_Var 'N') (E_Value (V_Int 1
)))) (D_Proc 'Ack' (('M',M_In,T_Int) # ('N',M_In,T_Int) # [('R',M_Out,T_Int]))
(D_InitVar 'P' (T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])) (E_Var 'Incr') (D_Block (C_Seq
(C_For 'I' (E_Value (V_Int 1 )) (E_Var 'M') (C_Decl (D_Proc 'Aux' (('S',M_In,T_Int) #
[('R',M_Out,T_Int])) (D_InitVar 'X' T_Int (E_Value (V_Int 0 )) (D_Block (C_Seq (C_ProcCall
(E_Var 'P') ((E_Value (V_Int 1 ))) # [(E_Var 'X')])) (C_Seq (C_For 'J' (E_Value
(V_Int 1 )) (E_Var 'S') (C_ProcCall (E_Var 'P') ((E_Var 'X')) # [(E_Var 'X')]))
(C_Assign 'R' (E_Var 'X')))) (D_Block (C_Assign 'P' (E_Var 'Aux')))) (C_ProcCall
(E_Var 'P') ((E_Var 'N') # [(E_Var 'R')])))) (D_Block (C_ProcCall (E_Var 'Ack')
((E_Value (V_Int 2 )) # (E_Value (V_Int 2 )) # [(E_Var 'R')])))) ) : CommTyping"
```

```
test24 = " ( ([('R',(VarDecl M_Out T_Int))]) , (C_Decl (D_Proc 'Comp'
([('P1',M_In,(T_Proc ((M_In,T_Int) # [(M_Out,T_Int)]))]) @ [('P2',M_In,(T_Proc
((M_In,T_Int) # [(M_Out,T_Int)]))]) @ [('P3',M_Out,(T_Proc ((M_In,T_Int) #
[(M_Out,T_Int)]))]) (D_Proc 'P' (('N',M_In,T_Int) # [('R',M_Out,T_Int])) (D_InitVar
'X' T_Int (E_Value (V_Int 0 )) (D_Block (C_Seq (C_ProcCall (E_Var 'P1') ((E_Var 'N')) #
[(E_Var 'X')])) (C_ProcCall (E_Var 'P2') ((E_Var 'X')) # [(E_Var 'R')]))))
(D_Block (C_Assign 'P3' (E_Var 'P')))) (D_Proc 'Incr' (('N',M_In,T_Int) #
[('R',M_Out,T_Int])) (D_Block (C_Assign 'R' (E_Plus (E_Var 'N') (E_Value (V_Int 1 ))))
(D_Proc 'IncrN' (('M',M_In,T_Int) # ('N',M_In,T_Int) # [('R',M_Out,T_Int])) (D_InitVar
'P' (T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])) (E_Var 'Incr') (D_Block (C_Seq (C_For 'I'
(E_Value (V_Int 1 )) (E_Var 'N') (C_ProcCall (E_Var 'Comp') ((E_Var 'P')) # (E_Var
'P')) # [(E_Var 'P')])))) (C_ProcCall (E_Var 'P') ((E_Var 'M')) # [(E_Var
'R')])))) (D_Block (C_ProcCall (E_Var 'IncrN') ((E_Value (V_Int 3 )) # (E_Value
(V_Int 3 )) # [(E_Var 'R')])))) ) : CommTyping"
```

```
ML {* Typing.test1 *}
ML {* Typing.test2 *}
ML {* Typing.test24 *}
```

```
code_module Evaluation
contains
```

```
test1 = " ( (C_Decl (D_InitVar 'Y' T_Int (E_Value (V_Int 42 )) (D_Proc 'P'
(('I',M_InOut,T_Int) # [('B',M_Out,T_Bool])) (D_Block (C_Assign 'B' ( (E_Equal (E_Var
'I') (E_Value (V_Int 1 ))) ) ) (D_Block (C_ProcCall (E_Var 'P') ((E_Var 'Y')) #
[(E_Var 'R')])))) , ([('R',(V_Boolean false ))]) , 1 , _ , _ ) : ManySteps"
```

```
test2 = " ( (C_Decl (D_InitVar 'Y' T_Int (E_Value (V_Int 42 )) (D_Proc 'P'
(('I',M_InOut,T_Int) # [('B',M_Out,T_Bool])) (D_Block (C_Assign 'B' ( (E_Equal (E_Var
'I') (E_Value (V_Int 1 ))) ) ) (D_Block (C_ProcCall (E_Var 'P') ((E_Var 'Y')) #
[(E_Var 'R')])))) , ([('R',(V_Boolean false ))]) , 2 , _ , _ ) : ManySteps"
```

```
test3 = " ( (C_Decl (D_InitVar 'Y' T_Int (E_Value (V_Int 42 )) (D_Proc 'P'
(('I',M_In,T_Int) # [('B',M_Out,T_Bool])) (D_Block (C_Assign 'B' ( (E_Equal (E_Var
'I') (E_Value (V_Int 1 ))) ) ) (D_Block (C_ProcCall (E_Var 'P') ((E_Var 'Y')) #
[(E_Var 'R')])))) , ([('R',(V_Boolean false ))]) , 3 , _ , _ ) : ManySteps"
```

```
test10 = " ( (C_Decl (D_InitVar 'Y' T_Int (E_Value (V_Int 42 )) (D_Proc 'P'
(('I',M_In,T_Int) # [('B',M_Out,T_Bool])) (D_Block (C_Assign 'B' ( (E_Equal (E_Var
'I') (E_Value (V_Int 1 ))) ) ) (D_Block (C_ProcCall (E_Var 'P') ((E_Var 'Y')) #
[(E_Var 'R')])))) , ([('R',(V_Boolean true ))]) , _ ) : FullEvaluation"
```

```
test20 = " ( (C_Decl (D_InitVar 'Y' T_Int (E_Value (V_Int 42 )) (D_Proc 'P'
```

```
((('I'',M_In,T_Int) # [(''B'',M_Out,T_Boolean)])) (D_Block (C_Assign ''B'' ( (E_Equal (E_Var ''I'') (E_Value (V_Int 1))) ) ) ) (D_Block (C_ProcCall (E_Var ''P'') ((E_Var ''Y'') # [(E_Var ''R'')])))) , ([(''R'',(V_Boolean false))] ) , 20 , _ ) : Trace"
```

```
test24 = " ( (C_Decl (D_Proc ''Incr'' (('N'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_Block (C_Assign ''R'' (E_Plus (E_Var ''N'') (E_Value (V_Int 1)))))) (D_Proc ''Plus'' (('M'',M_In,T_Int) # ('N'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_InitVar ''X'' T_Int (E_Var ''M'')) (D_Block (C_Seq (C_For ''I'' (E_Value (V_Int 1)) (E_Var ''N'') (C_ProcCall (E_Var ''Incr'') ((E_Var ''X'') # [(E_Var ''X'')])))) (C_Assign ''R'' (E_Var ''X'')))) (D_Block (C_ProcCall (E_Var ''Plus'') ((E_Value (V_Int 3)) # (E_Value (V_Int 5)) # [(E_Var ''R'')])))) , ([(''R'',(V_Int 0))] ) , _ ) : FullEvaluation"
```

```
test25 = " ( (C_Decl (D_Proc ''Comp'' ([(''P1'',M_In,(T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])))] @ [(''P2'',M_In,(T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])))] @ [(''P3'',M_Out,(T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])))])) (D_Proc ''P'' (('N'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_InitVar ''X'' T_Int (E_Value (V_Int 0)) (D_Block (C_Seq (C_ProcCall (E_Var ''P1'') ((E_Var ''N'') # [(E_Var ''X'')])) (C_ProcCall (E_Var ''P2'') ((E_Var ''X'') # [(E_Var ''R'')])))) (D_Block (C_Assign ''P3'' (E_Var ''P'')))) (D_Proc ''Incr'' (('N'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_Block (C_Assign ''R'' (E_Plus (E_Var ''N'') (E_Value (V_Int 1)))))) (D_Proc ''IncrN'' (('M'',M_In,T_Int) # ('N'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_InitVar ''P'' (T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])) (E_Var ''Incr'')) (D_Block (C_Seq (C_For ''I'' (E_Value (V_Int 1)) (E_Var ''N'') (C_ProcCall (E_Var ''Comp'') ((E_Var ''P'') # (E_Var ''P'')) # [(E_Var ''P'')])) (C_ProcCall (E_Var ''P'') ((E_Var ''M'') # [(E_Var ''R'')])))) (D_Block (C_ProcCall (E_Var ''IncrN'') ((E_Value (V_Int 3)) # (E_Value (V_Int 3)) # [(E_Var ''R'')])))) , ([(''R'',(V_Int 0))] ) , _ ) : FullEvaluation"
```

```
test30 = " ( (C_Decl (D_Proc ''Incr'' (('N'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_Block (C_Assign ''R'' (E_Plus (E_Var ''N'') (E_Value (V_Int 1)))))) (D_Proc ''Ack'' (('M'',M_In,T_Int) # ('N'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_InitVar ''P'' (T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])) (E_Var ''Incr'')) (D_Block (C_Seq (C_For ''I'' (E_Value (V_Int 1)) (E_Var ''M'') (C_Decl (D_Constant ''Q'' (T_Proc ((M_In,T_Int) # [(M_Out,T_Int)])) (E_Var ''P'')) (D_Proc ''Aux'' (('S'',M_In,T_Int) # [(''R'',M_Out,T_Int)])) (D_InitVar ''X'' T_Int (E_Value (V_Int 0)) (D_Block (C_Seq (C_ProcCall (E_Var ''Q'') ((E_Value (V_Int 1)) # [(E_Var ''X'')])) (C_Block (C_For ''J'' (E_Value (V_Int 1)) (E_Var ''S'') (C_ProcCall (E_Var ''Q'') ((E_Var ''X'') # [(E_Var ''X'')])) (C_Assign ''R'' (E_Var ''X'')))) (D_Block (C_Assign ''P'' (E_Var ''Aux'')))) (C_ProcCall (E_Var ''P'') ((E_Var ''N'') # [(E_Var ''R'')])))) (D_Block (C_ProcCall (E_Var ''Ack'') ((E_Value (V_Int 3)) # (E_Value (V_Int 2)) # [(E_Var ''R'')])))) , ([(''R'',(V_Int 0))] ) , _ ) : FullEvaluation"
```

```
ML {* print_depth 1000 *}
ML {* DSeq.hd Evaluation.test24 *}
ML {* DSeq.hd Evaluation.test25 *}
ML {* DSeq.hd Evaluation.test30 *}
ML {* val trace = DSeq.hd Evaluation.test24 *}
ML {* List.nth (trace, 0) *}
ML {* List.nth (trace, 1) *}
ML {* List.nth (trace, 2) *
```

end

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