

CakeML

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Abstract

CakeML is a functional programming language with a proven-correct compiler and runtime system. This entry contains an unofficial version of the CakeML semantics that has been exported from the Lem specifications to Isabelle. Additionally, there are some hand-written theory files that adapt the exported code to Isabelle and port proofs from the HOL4 formalization, e.g. termination and equivalence proofs.

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Contributors

The export script has been written by Lars Hupel. Hand-written theory files, including definitions and proofs, have been developed by Lars Hupel and Yu Zhang.

Lem is a project by Peter Sewell et.al. Contributors can be found on its project page¹ and on GitHub.²

CakeML is a project with many developers and contributors that can be found on its project page³ and on GitHub.⁴

In particular, Fabian Immler and Johannes Åman Pohjola have contributed Isabelle mappings for constants in the Lem specification of the CakeML semantics.

¹<https://www.cl.cam.ac.uk/~pes20/lem/>

²<https://github.com/rem-s-project/lem/graphs/contributors>

³<https://cakeml.org/>

⁴<https://github.com/CakeML/cakeml/graphs/contributors>

Part I

Generated Isabelle code

Chapter 1

Generated by Lem from *misc/lem-lib-stub/lib.lem.*

theory *Lib*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
LEM.Lem-list-extra
LEM.Lem-string
Coinductive.Coinductive-List

begin

— *Extensions to Lem's built-in library to target things we need in HOL.*
— *open import Pervasives*
— *import List-extra*
— *import String*

— *TODO: look for these in the built-in library*

— *val rtc : forall 'a. ('a -> 'a -> bool) -> ('a -> 'a -> bool)*

— *val disjoint : forall 'a. set 'a -> set 'a -> bool*

— *val all2 : forall 'a 'b. ('a -> 'b -> bool) -> list 'a -> list 'b -> bool*

fun *the* :: 'a => 'a option => 'a **where**
the - (Some x) = (x) | the x None = (x)

— *val fapply : forall 'a 'b. MapKeyType 'b => 'a -> 'b -> Map.map 'b 'a -> 'a*

definition *fapply* :: 'a => 'b => ('b, 'a) Map.map => 'a **where**
fapply d x f = ((case f x of Some d => d | None => d))

```

function (sequential,domintros)
lunion :: 'a list => 'a list => 'a list where

lunion [] s = ( s )
|
lunion (x # xs) s = (
  if Set.member x (set s)
  then lunion xs s
  else x #(lunion xs s)
)
⟨proof⟩
type-synonym ('a, 'b) alist = ('a * 'b) list
— val alistToFmap : forall 'k 'v. alist 'k 'v -> Map.map 'k 'v

— val opt-bind : forall 'a 'b. maybe 'a -> 'b -> alist 'a 'b -> alist 'a 'b
fun opt-bind :: 'a option => 'b =>('a*'b)list =>('a*'b)list where
  opt-bind None v2 e = ( e )
| opt-bind (Some n') v2 e = ( (n',v2)# e )

— Lists of indices

fun
lshift :: nat =>(nat)list =>(nat)list where

lshift (n :: nat) ls = (
  List.map (λ v2 . v2 - n) (List.filter (λ v2 . n ≤ v2) ls)
)

— open import {hol} 'locationTheory'
datatype-record locn =
  row :: nat
  col :: nat
  offset :: nat

type-synonym locs = (locn * locn)
— val unknown-loc : locs
end

```


Chapter 2

Generated by Lem from *semantics/namespace.lem.*

theory *Namespace*

imports

Main

HOL-Library.Datatype-Records

LEM.Lem-pervasives

LEM.Lem-set-extra

begin

— *open import Pervasives*

— *open import Set-extra*

type-synonym(*'k, 'v*) *alist0 = ('k * 'v) list*

— *Identifiers*

datatype(*'m, 'n*) *id0 =*

Short 'n

| *Long 'm ('m, 'n) id0*

— *val mk-id : forall 'n 'm. list 'm -> 'n -> id 'm 'n*

fun *mk-id* :: *'m list => 'n => ('m, 'n)id0* **where**

mk-id [] n = (Short n)

| *mk-id (mn # mns) n = (Long mn (mk-id mns n))*

— *val id-to-n : forall 'n 'm. id 'm 'n -> 'n*

fun *id-to-n* :: *('m, 'n)id0 => 'n* **where**

id-to-n (Short n) = (n)

| *id-to-n (Long - id1) = (id-to-n id1)*

```

— val id-to-mods : forall 'n 'm. id 'm 'n -> list 'm
fun id-to-mods :: ('m,'n)id0 => 'm list where
  id-to-mods (Short -) = ( [])
  | id-to-mods (Long mn id1) = ( mn # id-to-mods id1 )

datatype( 'm, 'n, 'v) namespace =
  Bind ('n, 'v) alist0 ('m, ( ('m, 'n, 'v)namespace)) alist0

— val nsLookup : forall 'v 'm 'n. Eq 'n, Eq 'm => namespace 'm 'n 'v -> id 'm
'n -> maybe 'v
fun nsLookup :: ('m,'n,'v)namespace =>('m,'n)id0 => 'v option where
  nsLookup (Bind v2 m) (Short n) = ( Map.map-of v2 n )
  | nsLookup (Bind v2 m) (Long mn id1) = (
    (case Map.map-of m mn of
      None => None
      | Some env => nsLookup env id1
    ))

— val nsLookupMod : forall 'm 'n 'v. Eq 'n, Eq 'm => namespace 'm 'n 'v ->
list 'm -> maybe (namespace 'm 'n 'v)
fun nsLookupMod :: ('m,'n,'v)namespace => 'm list => (('m,'n,'v)namespace)option
where
  nsLookupMod e [] = ( Some e )
  | nsLookupMod (Bind v2 m) (mn # path) = (
    (case Map.map-of m mn of
      None => None
      | Some env => nsLookupMod env path
    ))

— val nsEmpty : forall 'v 'm 'n. namespace 'm 'n 'v
definition nsEmpty :: ('m,'n,'v)namespace where
  nsEmpty = ( Bind [] [])

— val nsAppend : forall 'v 'm 'n. namespace 'm 'n 'v -> namespace 'm 'n 'v ->
namespace 'm 'n 'v
fun nsAppend :: ('m,'n,'v)namespace =>('m,'n,'v)namespace =>('m,'n,'v)namespace
where
  nsAppend (Bind v1 m1) (Bind v2 m2) = ( Bind (v1 @ v2) (m1 @ m2))

— val nsLift : forall 'v 'm 'n. 'm -> namespace 'm 'n 'v -> namespace 'm 'n 'v
definition nsLift :: 'm =>('m,'n,'v)namespace =>('m,'n,'v)namespace where
  nsLift mn env = ( Bind [] [(mn, env)])

```

— *val alist-to-ns* : forall 'v 'm 'n. alist 'n 'v -> namespace 'm 'n 'v
definition *alist-to-ns* :: ('n*'v)list =>('m,'n,'v)namespace **where**
alist-to-ns a = (Bind a [])

— *val nsBind* : forall 'v 'm 'n. 'n -> 'v -> namespace 'm 'n 'v -> namespace 'm 'n 'v
fun *nsBind* :: 'n => 'v =>('m,'n,'v)namespace =>('m,'n,'v)namespace **where**
nsBind k x (Bind v2 m) = (Bind ((k,x)# v2) m)

— *val nsBindList* : forall 'v 'm 'n. list ('n * 'v) -> namespace 'm 'n 'v -> namespace 'm 'n 'v
definition *nsBindList* :: ('n*'v)list =>('m,'n,'v)namespace =>('m,'n,'v)namespace **where**
nsBindList l e = (List.foldr (λx .
(case x of (x,v2) => λ e . nsBind x v2 e)) l e)

— *val nsOptBind* : forall 'v 'm 'n. maybe 'n -> 'v -> namespace 'm 'n 'v -> namespace 'm 'n 'v
fun *nsOptBind* :: 'n option => 'v =>('m,'n,'v)namespace =>('m,'n,'v)namespace **where**
nsOptBind None x env = (env)
| *nsOptBind* (Some n') x env = (nsBind n' x env)

— *val nsSing* : forall 'v 'm 'n. 'n -> 'v -> namespace 'm 'n 'v
definition *nsSing* :: 'n => 'v =>('m,'n,'v)namespace **where**
nsSing n x = (Bind [(n,x)] [])

— *val nsSub* : forall 'v1 'v2 'm 'n. Eq 'm, Eq 'n, Eq 'v1, Eq 'v2 => (id 'm 'n -> 'v1 -> 'v2 -> bool) -> namespace 'm 'n 'v1 -> namespace 'm 'n 'v2 -> bool
definition *nsSub* :: (('m,'n)id0 => 'v1 => 'v2 => bool)&=>('m,'n,'v1)namespace =>('m,'n,'v2)namespace => bool **where**
nsSub r env1 env2 = (
((∀ id0. ∀ v1.
(nsLookup env1 id0 = Some v1)
→
((∃ v2. (nsLookup env2 id0 = Some v2) ∧ r id0 v1 v2))))
∧
((∀ path.
(nsLookupMod env2 path = None) → (nsLookupMod env1 path = None))))

— *val nsAll* : forall 'v 'm 'n. Eq 'm, Eq 'n, Eq 'v => (id 'm 'n -> 'v -> bool) -> namespace 'm 'n 'v -> bool

```

fun nsAll :: (('m,'n)id0 => 'v => bool) => ('m,'n,'v)namespace => bool where
  nsAll f env = (
    (( $\forall$  id0.  $\forall$  v1.
      (nsLookup env id0 = Some v1)
       $\longrightarrow$ 
      f id0 v1)))

```

```

— val eAll2 : forall 'v1 'v2 'm 'n. Eq 'm, Eq 'n, Eq 'v1, Eq 'v2 => (id 'm 'n ->
'v1 -> 'v2 -> bool) -> namespace 'm 'n 'v1 -> namespace 'm 'n 'v2 -> bool
definition nsAll2 :: (('d,'c)id0 => 'b => 'a => bool) => ('d,'c,'b)namespace => ('d,'c,'a)namespace
=> bool where
  nsAll2 r env1 env2 = (
    nsSub r env1 env2  $\wedge$ 
    nsSub ( $\lambda$  x y z . r x z y) env2 env1 )

```

```

— val nsDom : forall 'v 'm 'n. Eq 'm, Eq 'n, Eq 'v, SetType 'v => namespace 'm
'n 'v -> set (id 'm 'n)
definition nsDom :: ('m,'n,'v)namespace => (('m,'n)id0)set where
  nsDom env = ( let x2 =
    ({} in Finite-Set.fold
      ( $\lambda$ v2 x2 . Finite-Set.fold
        ( $\lambda$ n x2 .
          if nsLookup env n = Some v2 then Set.insert n x2
          else x2) x2 UNIV) x2 UNIV))

```

```

— val nsDomMod : forall 'v 'm 'n. SetType 'm, Eq 'm, Eq 'n, Eq 'v => namespace
'm 'n 'v -> set (list 'm)
definition nsDomMod :: ('m,'n,'v)namespace => ('m list)set where
  nsDomMod env = ( let x2 =
    ({} in Finite-Set.fold
      ( $\lambda$ v2 x2 . Finite-Set.fold
        ( $\lambda$ n x2 .
          if nsLookupMod env n = Some v2 then Set.insert n x2
          else x2) x2 UNIV) x2 UNIV))

```

```

— val nsMap : forall 'v 'w 'm 'n. ('v -> 'w) -> namespace 'm 'n 'v -> namespace
'm 'n 'w
function (sequential,domintros) nsMap :: ('v => 'w) => ('m,'n,'v)namespace => ('m,'n,'w)namespace
where
  nsMap f (Bind v2 m) = (
    Bind (List.map (  $\lambda$ x .
      (case x of (n,x) => (n, f x) )) v2)
      (List.map (  $\lambda$ x .
        (case x of (mn,e) => (mn, nsMap f e) )) m))
    <proof>

```

end

Chapter 3

Generated by Lem from *semantics/fpSem.lem.*

theory *FpSem*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
Lib
IEEE-Floating-Point.FP64

begin

— *open import Pervasives*
— *open import Lib*

— *open import {hol} 'machine-ieeeTheory'*
— *open import {isabelle} 'IEEE-Floating-Point.FP64'*

— *type rounding*

datatype *fp-cmp-op* = *FP-Less* | *FP-LessEqual* | *FP-Greater* | *FP-GreaterEqual*
| *FP-Equal*

datatype *fp-uop-op* = *FP-Abs* | *FP-Neg* | *FP-Sqrt*

datatype *fp-bop-op* = *FP-Add* | *FP-Sub* | *FP-Mul* | *FP-Div*

— *val fp64-lessThan* : *word64* -> *word64* -> *bool*
— *val fp64-lessEqual* : *word64* -> *word64* -> *bool*
— *val fp64-greaterThan* : *word64* -> *word64* -> *bool*
— *val fp64-greaterEqual* : *word64* -> *word64* -> *bool*
— *val fp64-equal* : *word64* -> *word64* -> *bool*

— *val fp64-abs* : *word64* -> *word64*
— *val fp64-negate* : *word64* -> *word64*

```

— val fp64-sqrt : rounding -> word64 -> word64

— val fp64-add : rounding -> word64 -> word64 -> word64
— val fp64-sub : rounding -> word64 -> word64 -> word64
— val fp64-mul : rounding -> word64 -> word64 -> word64
— val fp64-div : rounding -> word64 -> word64 -> word64

— val roundTiesToEven : rounding

— val fp-cmp : fp-cmp -> word64 -> word64 -> bool
fun fp-cmp :: fp-cmp-op => 64 word => 64 word => bool where
    fp-cmp FP-Less = ( fp64-lessThan )
| fp-cmp FP-LessEqual = ( fp64-lessEqual )
| fp-cmp FP-Greater = ( fp64-greaterThan )
| fp-cmp FP-GreaterEqual = ( fp64-greaterEqual )
| fp-cmp FP-Equal = ( fp64-equal )

— val fp-uop : fp-uop -> word64 -> word64
fun fp-uop :: fp-uop-op => 64 word => 64 word where
    fp-uop FP-Abs = ( fp64-abs )
| fp-uop FP-Neg = ( fp64-negate )
| fp-uop FP-Sqrt = ( fp64-sqrt To-nearest )

— val fp-bop : fp-bop -> word64 -> word64 -> word64
fun fp-bop :: fp-bop-op => 64 word => 64 word => 64 word where
    fp-bop FP-Add = ( fp64-add To-nearest )
| fp-bop FP-Sub = ( fp64-sub To-nearest )
| fp-bop FP-Mul = ( fp64-mul To-nearest )
| fp-bop FP-Div = ( fp64-div To-nearest )

end

```

Chapter 4

Generated by Lem from *semantics/ast.lem.*

theory *Ast*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
Lib
Namespace
FpSem

begin

— *open import Pervasives*
— *open import Lib*
— *open import Namespace*
— *open import FpSem*

— *Literal constants*

datatype *lit* =

IntLit int
| *Char char*
| *StrLit string*
| *Word8 8 word*
| *Word64 64 word*

— *Built-in binary operations*

datatype *opn* = *Plus* | *Minus* | *Times* | *Divide* | *Modulo*

datatype *opb* = *Lt* | *Gt* | *Leq* | *Geq*

datatype *opw* = *Andw* | *Orw* | *Xor* | *Add* | *Sub*

datatype *shift* = *Lsl* | *Lsr* | *Asr* | *Ror*

— *Module names*


```

type-synonym modN = string

— Variable names
type-synonym varN = string

— Constructor names (from datatype definitions)
type-synonym conN = string

— Type names
type-synonym typeN = string

— Type variable names
type-synonym tvarN = string

datatype word-size = W8 | W64

datatype op0 =
  — Operations on integers
  | Opn opn
  | Opb opb
  — Operations on words
  | Opw word-size opw
  | Shift word-size shift nat
  | Equality
  — FP operations
  | FP-cmp fp-cmp-op
  | FP-uop fp-uop-op
  | FP-bop fp-bop-op
  — Function application
  | Opapp
  — Reference operations
  | Opassign
  | Opref
  | Opderef
  — Word8Array operations
  | Aw8alloc
  | Aw8sub
  | Aw8length
  | Aw8update
  — Word/integer conversions
  | WordFromInt word-size
  | WordToInt word-size
  — string/bytearray conversions
  | CopyStrStr
  | CopyStrAw8
  | CopyAw8Str
  | CopyAw8Aw8
  — Char operations
  | Ord

```

```

| Chr
| Chopb opb
— String operations
| Implode
| Strsub
| Strlen
| Strcat
— Vector operations
| VfromList
| Vsub
| Vlength
— Array operations
| Aalloc
| AallocEmpty
| Asub
| Alength
| Aupdate
— Configure the GC
| ConfigGC
— Call a given foreign function
| FFI string

— Logical operations
datatype lop =
  And
  | Or

— Type constructors. * 0-ary type applications represent unparameterised types
(e.g., num or string)
datatype tctor =
  — User defined types
    TC-name (modN, typeN) id0
  — Built-in types
  | TC-int
  | TC-char
  | TC-string
  | TC-ref
  | TC-word8
  | TC-word64
  | TC-word8array
  | TC-fn
  | TC-tup
  | TC-exn
  | TC-vector
  | TC-array

— Types
datatype t =
  — Type variables that the user writes down ('a, 'b, etc.)

```

$Tvar\ tvarN$
— *deBruijn indexed type variables. The type system uses these internally.*
| $Tvar-db\ nat$
| $Tapp\ t\ list\ tctor$

— *Some abbreviations*

definition $Tint :: t$ **where**
 $Tint = (Tapp [] TC-int)$

definition $Tchar :: t$ **where**
 $Tchar = (Tapp [] TC-char)$

definition $Tstring :: t$ **where**
 $Tstring = (Tapp [] TC-string)$

definition $Tref :: t \Rightarrow t$ **where**
 $Tref\ t1 = (Tapp [t1] TC-ref)$

fun $TC-word :: word-size \Rightarrow tctor$ **where**
 $TC-word\ W8 = (TC-word8)$
| $TC-word\ W64 = (TC-word64)$

definition $Tword :: word-size \Rightarrow t$ **where**
 $Tword\ wz = (Tapp [] (TC-word\ wz))$

definition $Tword8 :: t$ **where**
 $Tword8 = (Tword\ W8)$

definition $Tword64 :: t$ **where**
 $Tword64 = (Tword\ W64)$

definition $Tword8array :: t$ **where**
 $Tword8array = (Tapp [] TC-word8array)$

definition $Tfn :: t \Rightarrow t \Rightarrow t$ **where**
 $Tfn\ t1\ t2 = (Tapp [t1,t2] TC-fn)$

definition $Texn :: t$ **where**
 $Texn = (Tapp [] TC-exn)$

— *Patterns*

datatype $pat =$
 $Pany$
| $Pvar\ varN$
| $Plit\ lit$
— *Constructor applications. A Nothing constructor indicates a tuple pattern.*
| $Pcon\ ((modN, conN)id0)option\ pat\ list$
| $Pref\ pat$

| *Ptannot pat t*

— *Expressions*

datatype *exp0* =

- | *Raise exp0*
- | *Handle exp0 (pat * exp0) list*
- | *Lit lit*
- *Constructor application. A Nothing constructor indicates a tuple pattern.*
- | *Con ((modN, conN)id0)option exp0 list*
- | *Var (modN, varN) id0*
- | *Fun varN exp0*
- *Application of a primitive operator to arguments. Includes function application.*
- | *App op0 exp0 list*
- *Logical operations (and, or)*
- | *Log lop exp0 exp0*
- | *If exp0 exp0 exp0*
- *Pattern matching*
- | *Mat exp0 (pat * exp0) list*
- *A let expression A Nothing value for the binding indicates that this is a sequencing expression, that is: (e1; e2).*
- | *Let varN option exp0 exp0*
- *Local definition of (potentially) mutually recursive functions. The first varN is the function's name, and the second varN is its parameter.*
- | *Letrec (varN * varN * exp0) list exp0*
- | *Tannot exp0 t*
- *Location annotated expressions, not expected in source programs*
- | *Lannot exp0 locs*

type-synonym *type-def* = (*tvarN list * typeN * (conN * t list) list*) *list*

— *Declarations*

datatype *dec* =

- *Top-level bindings * The pattern allows several names to be bound at once*
- | *Dlet locs pat exp0*
- *Mutually recursive function definition*
- | *Dletrec locs (varN * varN * exp0) list*
- *Type definition Defines several data types, each of which has several named variants, which can in turn have several arguments.*
- | *Dtype locs type-def*
- *Type abbreviations*
- | *Dabbrev locs tvarN list typeN t*
- *New exceptions*
- | *Dexn locs conN t list*

type-synonym *decs* = *dec list*

— *Specifications For giving the signature of a module*

datatype *spec* =

- | *Sval varN t*

```

| Stype type-def
| Stabbrev tvarN list typeN t
| Stype-opq tvarN list typeN
| Sern conN t list

type-synonym specs = spec list

datatype top0 =
  Tmod modN specs option decs
| Tdec dec

type-synonym prog = top0 list

— Accumulates the bindings of a pattern
— val pat-bindings : pat -> list varN -> list varN
function (sequential, domintros)
pat-bindings :: (pat)list =>(string)list =>(string)list
and
pat-bindings :: pat =>(string)list =>(string)list where

pat-bindings Pany already-bound = (
  already-bound )
|
pat-bindings (Pvar n) already-bound = (
  n # already-bound )
|
pat-bindings (Plit l) already-bound = (
  already-bound )
|
pat-bindings (Pcon - ps) already-bound = (
  pats-bindings ps already-bound )
|
pat-bindings (Pref p) already-bound = (
  pat-bindings p already-bound )
|
pat-bindings (Ptannot p -) already-bound = (
  pat-bindings p already-bound )
|
pats-bindings [] already-bound = (
  already-bound )
|
pats-bindings (p # ps) already-bound = (
  pats-bindings ps (pat-bindings p already-bound))
⟨proof⟩

end

```

Chapter 5

Generated by Lem from
semantics/ast.lem.

theory *AstAuxiliary*

imports

Main

HOL-Library.Datatype-Records

LEM.Lem-pervasives

Lib

Namespace

FpSem

Ast

begin

— *****

—

— *Termination Proofs*

—

— *****

termination *pat-bindings* *<proof>*

end

Chapter 6

Generated by Lem from *semantics/ffi/ffi.lem.*

theory *Ffi*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
LEM.Lem-pervasives-extra
Lib

begin

— *open import Pervasives*
— *open import Pervasives-extra*
— *open import Lib*

— *An oracle says how to perform an ffi call based on its internal state, * represented by the type variable 'ffi.*

datatype *'ffi oracle-result* = *Oracle-return 'ffi 8 word list | Oracle-diverge | Oracle-fail*

type-synonym *'ffi oracle-function* = *'ffi ⇒ 8 word list ⇒ 8 word list ⇒ 'ffi oracle-result*

type-synonym *'ffi oracle0* = *string ⇒ 'ffi oracle-function*

— *An I/O event, IO-event s bytes bytes2, represents the call of FFI function s with * immutable input bytes and mutable input map fst bytes2, * returning map snd bytes2 in the mutable array.*

datatype *io-event* = *IO-event string 8 word list ((8 word * 8 word)list)*

datatype *ffi-outcome* = *FFI-diverged | FFI-failed*

datatype *final-event* = *Final-event string 8 word list 8 word list ffi-outcome*

datatype-record 'ffi ffi-state =

oracle0 :: 'ffi oracle0

ffi-state :: 'ffi

final-event :: final-event option

io-events :: io-event list

— val initial-ffi-state : forall 'ffi. oracle 'ffi -> 'ffi -> ffi-state 'ffi

definition initial-ffi-state :: (string => 'ffi oracle-function) => 'ffi => 'ffi ffi-state
where

```
initial-ffi-state oc ffi1 = (  
  (| oracle0      = oc  
    , ffi-state   = ffi1  
    , final-event = None  
    , io-events   = ([])  
  |) )
```

— val call-FFI : forall 'ffi. ffi-state 'ffi -> string -> list word8 -> list word8
-> ffi-state 'ffi * list word8

definition call-FFI :: 'ffi ffi-state => string => (8 word)list => (8 word)list => 'ffi
ffi-state*(8 word)list **where**

```
call-FFI st s conf bytes = (  
  if ((final-event st) = None) ^ ¬ (s = ('')) then  
    (case (oracle0 st) s(ffi-state st) conf bytes of  
      Oracle-return ffi' bytes' =>  
        if List.length bytes' = List.length bytes then  
          (( st (| ffi-state := ffi'  
              , io-events :=  
                ((io-events st) @  
                  [IO-event s conf (zipSameLength bytes bytes')])  
            |)), bytes')  
        else (( st (| final-event := (Some (Final-event s conf bytes FFI-failed)) |)),  
bytes)  
      | Oracle-diverge =>  
        (( st (| final-event := (Some (Final-event s conf bytes FFI-diverged)) |)),  
bytes)  
      | Oracle-fail =>  
        (( st (| final-event := (Some (Final-event s conf bytes FFI-failed)) |)), bytes)  
    )  
  else (st, bytes)
```


datatype *outcome* = *Success* | *Resource-limit-hit* | *FFI-outcome* *final-event*

— *A program can Diverge, Terminate, or Fail. We prove that Fail is avoided. For Diverge and Terminate, we keep track of what I/O events are valid I/O events for this behaviour.*

datatype *behaviour* =

— *There cannot be any non-returning FFI calls in a diverging execution. The list of I/O events can be finite or infinite, hence the llist (lazy list) type.*

Diverge *io-event* *llist*

— *Terminating executions can only perform a finite number of FFI calls. The execution can be terminated by a non-returning FFI call.*

| *Terminate* *outcome* *io-event* *list*

— *Failure is a behaviour which we prove cannot occur for any well-typed program.*

| *Fail*

— *trace-based semantics can be recovered as an instance of oracle-based * semantics as follows.*

— *val trace-oracle : oracle (llist io-event)*

definition *trace-oracle* :: *string* \Rightarrow (*io-event*)*llist* \Rightarrow (*8 word*)*list* \Rightarrow (*8 word*)*list*

\Rightarrow ((*io-event*)*llist*)*oracle-result* **where**

trace-oracle *s* *io-trace* *conf* *input1* = (

(*case* *lhd'* *io-trace* of

Some (*IO-event* *s'* *conf'* *bytes2*) \Rightarrow

if (*s* = *s'*) \wedge ((*List.map* *fst* *bytes2* = *input1*) \wedge (*conf* = *conf'*)) *then*

Oracle-return (*Option.the* (*ltl'* *io-trace*)) (*List.map* *snd* *bytes2*)

else *Oracle-fail*

| - \Rightarrow *Oracle-fail*

))

end

Chapter 7

Generated by Lem from *semantics/semanticPrimitives.lem*.

theory *SemanticPrimitives*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
LEM.Lem-list-extra
LEM.Lem-string
Lib
Namespace
Ast
Ffi
FpSem
LEM.Lem-string-extra

begin

— *open import Pervasives*
— *open import Lib*
— *import List-extra*
— *import String*
— *import String-extra*
— *open import Ast*
— *open import Namespace*
— *open import Ffi*
— *open import FpSem*

— *The type that a constructor builds is either a named datatype or an exception. **
For exceptions, we also keep the module that the exception was declared in.

datatype *tid-or-exn* =
 TypeId (*modN*, *typeN*) *id0*
 | *TypeExn* (*modN*, *conN*) *id0*

— *val type-defs-to-new-tdecs : list modN -> type-def -> set tid-or-exn*
definition *type-defs-to-new-tdecs* :: (string)list =>((tvarN)list*string*(conN*(t)list)list)list
=>(tid-or-exn)set **where**
type-defs-to-new-tdecs mn tdefs = (
List.set (List.map (λx .
(case x of (tvs,tn,ctors) => TypeId (mk-id mn tn))) tdefs))

datatype-record 'v sem-env =

v :: (modN, varN, 'v) namespace

c :: (modN, conN, (nat * tid-or-exn)) namespace

— *Value forms*

datatype *v* =

| *Litv lit*

— *Constructor application.*

| *Conv (conN * tid-or-exn)option v list*

— *Function closures The environment is used for the free variables in the function*

| *Closure v sem-env varN exp0*

— *Function closure for recursive functions * See Closure and Letrec above * The last variable name indicates which function from the mutually * recursive bundle this closure value represents*

| *Recclosure v sem-env (varN * varN * exp0) list varN*

| *Loc nat*

| *Vectorv v list*

type-synonym *env-ctor* = (modN, conN, (nat * tid-or-exn)) namespace

type-synonym *env-val* = (modN, varN, v) namespace

definition *Bindv* :: v **where**

Bindv = (Conv (Some(("Bind"),TypeExn(Short("Bind")))) [])

— *The result of evaluation*

datatype *abort* =

| *Rtype-error*

| *Rtimeout-error*

datatype 'a *error-result* =

| *Rraise 'a* — *Should only be a value of type exn*

| *Rabort abort*

datatype('a, 'b) *result* =

| *Rval 'a*

```

| Rerr 'b error-result

— Stores
datatype 'a store-v =
  — A ref cell
  Refv 'a
  — A byte array
  | W8array 8 word list
  — An array of values
  | Varray 'a list

— val store-v-same-type : forall 'a. store-v 'a -> store-v 'a -> bool
definition store-v-same-type :: 'a store-v => 'a store-v => bool where
  store-v-same-type v1 v2 = (
    (case (v1,v2) of
      (Refv -, Refv -) => True
    | (W8array -, W8array -) => True
    | (Varray -, Varray -) => True
    | - => False
    ))

— The nth item in the list is the value at location n
type-synonym 'a store = ('a store-v) list

— val empty-store : forall 'a. store 'a
definition empty-store :: ('a store-v) list where
  empty-store = ( [])

— val store-lookup : forall 'a. nat -> store 'a -> maybe (store-v 'a)
definition store-lookup :: nat => ('a store-v) list => ('a store-v) option where
  store-lookup l st = (
    if l < List.length st then
      Some (List.nth st l)
    else
      None )

— val store-alloc : forall 'a. store-v 'a -> store 'a -> store 'a * nat
definition store-alloc :: 'a store-v => ('a store-v) list => ('a store-v) list * nat where

  store-alloc v2 st = (
    ((st @ [v2]), List.length st))

— val store-assign : forall 'a. nat -> store-v 'a -> store 'a -> maybe (store 'a)
definition store-assign :: nat => 'a store-v => ('a store-v) list => (('a store-v) list) option
where

```

```

    store-assign n v2 st = (
if (n < List.length st) ∧
    store-v-same-type (List.nth st n) v2
then
    Some (List.list-update st n v2)
else
    None )

```

datatype-record 'ffi state =

clock :: nat

refs :: v store

ffi :: 'ffi ffi-state

defined-types :: tid-or-exn set

defined-mods :: (modN list) set

— Other primitives

— Check that a constructor is properly applied

— val do-con-check : env-ctor -> maybe (id modN conN) -> nat -> bool

fun do-con-check :: ((string),(string),(nat*tid-or-exn))namespace =>(((string),(string))id0)option

=> nat => bool **where**

do-con-check envC None l = (True)

| do-con-check envC (Some n) l = (

(case nsLookup envC n of

None => False

| Some (l',ns) => l = l'

))

— val build-conv : env-ctor -> maybe (id modN conN) -> list v -> maybe v

fun build-conv :: ((string),(string),(nat*tid-or-exn))namespace =>(((string),(string))id0)option

=>(v)list =>(v)option **where**

build-conv envC None vs = (

Some (Conv None vs))

| build-conv envC (Some id1) vs = (

(case nsLookup envC id1 of

None => None

| Some (len,t1) => Some (Conv (Some (id-to-n id1, t1)) vs)

))

— val lit-same-type : lit -> lit -> bool

definition *lit-same-type* :: *lit* ⇒ *lit* ⇒ *bool* **where**

```
lit-same-type l1 l2 = (  
  (case (l1,l2) of  
    (IntLit -, IntLit -) => True  
  | (Char -, Char -) => True  
  | (StrLit -, StrLit -) => True  
  | (Word8 -, Word8 -) => True  
  | (Word64 -, Word64 -) => True  
  | - => False  
  ))
```

datatype *'a match-result* =

```
No-match  
| Match-type-error  
| Match 'a
```

— *val same-tid* : *tid-or-exn* -> *tid-or-exn* -> *bool*

fun *same-tid* :: *tid-or-exn* ⇒ *tid-or-exn* ⇒ *bool* **where**

```
same-tid (TypeId tn1) (TypeId tn2) = ( tn1 = tn2 )  
| same-tid (TypeExn -) (TypeExn -) = ( True )  
| same-tid - - = ( False )
```

— *val same-ctor* : *conN* * *tid-or-exn* -> *conN* * *tid-or-exn* -> *bool*

fun *same-ctor* :: *string*tid-or-exn* ⇒ *string*tid-or-exn* ⇒ *bool* **where**

```
same-ctor (cn1, TypeExn mn1) (cn2, TypeExn mn2) = ( (cn1 = cn2) ∧  
(mn1 = mn2))  
| same-ctor (cn1, -) (cn2, -) = ( cn1 = cn2 )
```

— *val ctor-same-type* : *maybe (conN * tid-or-exn)* -> *maybe (conN * tid-or-exn)*
-> *bool*

definition *ctor-same-type* :: (*string*tid-or-exn*)*option* ⇒ (*string*tid-or-exn*)*option*
⇒ *bool* **where**

```
ctor-same-type c1 c2 = (  
  (case (c1,c2) of  
    (None, None) => True  
  | (Some (-,t1), Some (-,t2)) => same-tid t1 t2  
  | - => False  
  ))
```

— *A big-step pattern matcher. If the value matches the pattern, return an * environment with the pattern variables bound to the corresponding sub-terms * of the value; this environment extends the environment given as an argument. * No-match is returned when there is no match, but any constructors * encountered in determining the match failure are applied to the correct * number of arguments, and constructors in corresponding positions in the * pattern and value come from*

the same type. Match-type-error is returned * when one of these conditions is violated

```

— val pmatch : env-ctor -> store v -> pat -> v -> alist varN v -> match-result
(alist varN v)
function (sequential,domintros)
pmatch-list :: ((string),(string),(nat*tid-or-exn))namespace =>((v)store-v)list =>(pat)list
=>(v)list =>(string*v)list =>((string*v)list)match-result
and
pmatch :: ((string),(string),(nat*tid-or-exn))namespace =>((v)store-v)list => pat
=> v =>(string*v)list =>((string*v)list)match-result where

pmatch envC s Pany v' env = ( Match env )
|
pmatch envC s (Pvar x) v' env = ( Match ((x,v')# env))
|
pmatch envC s (Plit l) (Litv l') env = (
  if l = l' then
    Match env
  else if lit-same-type l l' then
    No-match
  else
    Match-type-error )
|
pmatch envC s (Pcon (Some n) ps) (Conv (Some (n', t')) vs) env = (
  (case nsLookup envC n of
    Some (l, t1) =>
      if same-tid t1 t' ^ (List.length ps = l) then
        if same-ctor (id-to-n n, t1) (n',t') then
          if List.length vs = l then
            pmatch-list envC s ps vs env
          else
            Match-type-error
        else
          No-match
      else
        Match-type-error
    | - => Match-type-error
  ))
|
pmatch envC s (Pcon None ps) (Conv None vs) env = (
  if List.length ps = List.length vs then
    pmatch-list envC s ps vs env
  else
    Match-type-error )
|
pmatch envC s (Pref p) (Loc lnum) env = (
  (case store-lookup lnum s of
    Some (Refv v2) => pmatch envC s p v2 env
    | Some - => Match-type-error
  )

```

```

    | None => Match-type-error
  ))
|
pmatch envC s (Ptannot p t1) v2 env = (
  pmatch envC s p v2 env )
|
pmatch envC - - - env = ( Match-type-error )
|
pmatch-list envC s [] [] env = ( Match env )
|
pmatch-list envC s (p # ps) (v2 # vs) env = (
  (case pmatch envC s p v2 env of
    No-match => No-match
    | Match-type-error => Match-type-error
    | Match env' => pmatch-list envC s ps vs env'
  ))
|
pmatch-list envC s - - - env = ( Match-type-error )
⟨proof⟩
definition build-rec-env :: (varN*varN*exp0)list =>(v)sem-env =>((string),(string),(v))namespace
=>((string),(string),(v))namespace where
  build-rec-env funs cl-env add-to-env = (
    List.foldr ( λx .
      (case x of
        (f,x,e) => λ env' . nsBind f (Recclosure cl-env funs f) env'
      )) funs add-to-env )

```

— Lookup in the list of mutually recursive functions

— val find-recfun : forall 'a 'b. varN -> list (varN * 'a * 'b) -> maybe ('a * 'b)

```

fun find-recfun :: string =>(string*'a*'b)list =>('a*'b)option where
  find-recfun n ([]) = ( None )
| find-recfun n ((f,x,e) # funs) = (
  if f = n then
    Some (x,e)
  else
    find-recfun n funs )

```

```

datatype eq-result =
  Eq-val bool
| Eq-type-error

```

— val do-eq : v -> v -> eq-result

```

function (sequential,domintros)
do-eq-list :: (v)list =>(v)list => eq-result
and
do-eq :: v => v => eq-result where

```



```

do-eq (Litv l1) (Litv l2) = (
  if lit-same-type l1 l2 then Eq-val (l1 = l2)
  else Eq-type-error )
|
do-eq (Loc l1) (Loc l2) = ( Eq-val (l1 = l2))
|
do-eq (Conv cn1 vs1) (Conv cn2 vs2) = (
  if (cn1 = cn2) ∧ (List.length vs1 = List.length vs2) then
    do-eq-list vs1 vs2
  else if ctor-same-type cn1 cn2 then
    Eq-val False
  else
    Eq-type-error )
|
do-eq (Vectorv vs1) (Vectorv vs2) = (
  if List.length vs1 = List.length vs2 then
    do-eq-list vs1 vs2
  else
    Eq-val False )
|
do-eq (Closure - - -) (Closure - - -) = ( Eq-val True )
|
do-eq (Closure - - -) (Recclosure - - -) = ( Eq-val True )
|
do-eq (Recclosure - - -) (Closure - - -) = ( Eq-val True )
|
do-eq (Recclosure - - -) (Recclosure - - -) = ( Eq-val True )
|
do-eq - - = ( Eq-type-error )
|
do-eq-list [] [] = ( Eq-val True )
|
do-eq-list (v1 # vs1) (v2 # vs2) = (
  (case do-eq v1 v2 of
    Eq-type-error => Eq-type-error
  | Eq-val r =>
    if ¬ r then
      Eq-val False
    else
      do-eq-list vs1 vs2
  ))
|
do-eq-list - - = ( Eq-val False )
⟨proof⟩
definition prim-exn :: string ⇒ v where
  prim-exn cn = ( Conv (Some (cn, TypeExn (Short cn))) [] )

```

— Do an application

```

— val do-opapp : list v -> maybe (sem-env v * exp)
fun do-opapp :: (v)list =>((v)sem-env*exp0)option where
  do-opapp ([Closure env n e, v2]) = (
    Some (( env (| v := (nsBind n v2(v env)) |)), e))
| do-opapp ([Recclosure env funs n, v2]) = (
  if allDistinct (List.map ( λx .
    (case x of (f,x,e) => f )) funs) then
    (case find-recfun n funs of
      Some (n,e) => Some (( env (| v := (nsBind n v2 (build-rec-env funs
env(v env)))) |)), e)
    | None => None
  )
  else
    None )
| do-opapp - = ( None )

```

— If a value represents a list, get that list. Otherwise return Nothing

— val v-to-list : v -> maybe (list v)

function (sequential,domintros) v-to-list :: v =>((v)list)option **where**

```

  v-to-list (Conv (Some (cn, TypeId (Short tn))) []) = (
    if (cn = ("nil")) ∧ (tn = ("list")) then
      Some []
    else
      None )
| v-to-list (Conv (Some (cn, TypeId (Short tn))) [v1,v2]) = (
  if (cn = ("::")) ∧ (tn = ("list")) then
    (case v-to-list v2 of
      Some vs => Some (v1 # vs)
    | None => None
  )
  else
    None )
| v-to-list - = ( None )

```

<proof>

function (sequential,domintros) v-to-char-list :: v =>((char)list)option **where**

```

  v-to-char-list (Conv (Some (cn, TypeId (Short tn))) []) = (
    if (cn = ("nil")) ∧ (tn = ("list")) then
      Some []
    else
      None )
| v-to-char-list (Conv (Some (cn, TypeId (Short tn))) [Litv (Char c2),v2]) = (
  if (cn = ("::")) ∧ (tn = ("list")) then
    (case v-to-char-list v2 of
      Some cs => Some (c2 # cs)
    | None => None
  )
  else
    None )

```

```

    None )
| v-to-char-list - = ( None )
⟨proof⟩
function (sequential,domintros) vs-to-string :: (v)list ⇒(string)option where
    vs-to-string [] = ( Some (""))
| vs-to-string (Litv(StrLit s1)# vs) = (
    (case vs-to-string vs of
        Some s2 => Some (s1 @ s2)
    | - => None
    ))
| vs-to-string - = ( None )
⟨proof⟩
fun copy-array :: 'a list*int ⇒ int ⇒('a list*int)option ⇒('a list)option where

    copy-array (src,srcoff) len d = (
    if (srcoff <( 0 :: int)) ∨ ((len <( 0 :: int)) ∨ (List.length src < nat (abs ( srcoff
+ len)))) then None else
    (let copied = (List.take (nat (abs ( len))) (List.drop (nat (abs ( srcoff))) src))
    in
    (case d of
        Some (dst,dstoff) =>
            if (dstoff <( 0 :: int)) ∨ (List.length dst < nat (abs ( dstoff + len))) then
None else
                Some ((List.take (nat (abs ( dstoff))) dst @
                    copied) @
                    List.drop (nat (abs ( dstoff + len))) dst)
        | None => Some copied
    )))

— val ws-to-chars : list word8 -> list char
definition ws-to-chars :: (8 word)list ⇒(char)list where
    ws-to-chars ws = ( List.map (λ w . (%n. char-of (n::nat))(unat w)) ws )

— val chars-to-ws : list char -> list word8
definition chars-to-ws :: (char)list ⇒(8 word)list where
    chars-to-ws cs = ( List.map (λ c2 . word-of-int(int(of-char c2))) cs )

— val opn-lookup : opn -> integer -> integer -> integer
fun opn-lookup :: opn ⇒ int ⇒ int ⇒ int where
    opn-lookup Plus = ( (+))
| opn-lookup Minus = ( (-))
| opn-lookup Times = ( (*))
| opn-lookup Divide = ( (div))
| opn-lookup Modulo = ( (mod))

```

```

— val opb-lookup : opb -> integer -> integer -> bool
fun opb-lookup :: opb => int => int => bool where
    opb-lookup Lt = ( (<))
| opb-lookup Gt = ( (>))
| opb-lookup Leq = ( (<=))
| opb-lookup Geq = ( (>=))

— val opw8-lookup : opw -> word8 -> word8 -> word8
fun opw8-lookup :: opw => 8 word => 8 word => 8 word where
    opw8-lookup Andw = ( Bit-Operations.and )
| opw8-lookup Orw = ( Bit-Operations.or )
| opw8-lookup Xor = ( Bit-Operations.xor )
| opw8-lookup Add = ( Groups.plus )
| opw8-lookup Sub = ( Groups.minus )

— val opw64-lookup : opw -> word64 -> word64 -> word64
fun opw64-lookup :: opw => 64 word => 64 word => 64 word where
    opw64-lookup Andw = ( Bit-Operations.and )
| opw64-lookup Orw = ( Bit-Operations.or )
| opw64-lookup Xor = ( Bit-Operations.xor )
| opw64-lookup Add = ( Groups.plus )
| opw64-lookup Sub = ( Groups.minus )

— val shift8-lookup : shift -> word8 -> nat -> word8
fun shift8-lookup :: shift => 8 word => nat => 8 word where
    shift8-lookup Lsl = ( shifl )
| shift8-lookup Lsr = ( shiftr )
| shift8-lookup Asr = ( sshiftr )
| shift8-lookup Ror = ( (% a b. word-rotr b a ) )

— val shift64-lookup : shift -> word64 -> nat -> word64
fun shift64-lookup :: shift => 64 word => nat => 64 word where
    shift64-lookup Lsl = ( shifl )
| shift64-lookup Lsr = ( shiftr )
| shift64-lookup Asr = ( sshiftr )
| shift64-lookup Ror = ( (% a b. word-rotr b a ) )

— val Boolv : bool -> v
definition Boolv :: bool => v where
    Boolv b = ( if b
    then Conv (Some ("true"), TypeId (Short ("bool"))) []
    else Conv (Some ("false"), TypeId (Short ("bool"))) [] )

```

```

datatype exp-or-val =
  Exp exp0
| Val v

```

```

type-synonym( 'ffi, 'v) store-ffi = 'v store * 'ffi ffi-state

```

— *val do-app* : forall 'ffi. store-ffi 'ffi v -> op -> list v -> maybe (store-ffi 'ffi v * result v v)

```

fun do-app :: ((v)store-v)list*'ffi ffi-state => op0 =>(v)list =>(((v)store-v)list*'ffi
ffi-state)*(v),(v)result)option where

```

```

  do-app ((s:: v store),(t1:: 'ffi ffi-state)) op1 vs = (
    (case (op1, vs) of
      (Opn op1, [Litv (IntLit n1), Litv (IntLit n2)]) =>
        if ((op1 = Divide) ∨ (op1 = Modulo)) ∧ (n2 = ( 0 :: int)) then
          Some ((s,t1), Rerr (Rraise (prim-ern ("Div"))))
        else
          Some ((s,t1), Rval (Litv (IntLit (opn-lookup op1 n1 n2))))
    | (Opb op1, [Litv (IntLit n1), Litv (IntLit n2)]) =>
      Some ((s,t1), Rval (Boolv (opb-lookup op1 n1 n2)))
    | (Opw W8 op1, [Litv (Word8 w1), Litv (Word8 w2)]) =>
      Some ((s,t1), Rval (Litv (Word8 (opw8-lookup op1 w1 w2))))
    | (Opw W64 op1, [Litv (Word64 w1), Litv (Word64 w2)]) =>
      Some ((s,t1), Rval (Litv (Word64 (opw64-lookup op1 w1 w2))))
    | (FP-bop bop, [Litv (Word64 w1), Litv (Word64 w2)]) =>
      Some ((s,t1),Rval (Litv (Word64 (fp-bop bop w1 w2))))
    | (FP-uop uop, [Litv (Word64 w)]) =>
      Some ((s,t1),Rval (Litv (Word64 (fp-uop uop w))))
    | (FP-cmp cmp, [Litv (Word64 w1), Litv (Word64 w2)]) =>
      Some ((s,t1),Rval (Boolv (fp-cmp cmp w1 w2)))
    | (Shift W8 op1 n, [Litv (Word8 w)]) =>
      Some ((s,t1), Rval (Litv (Word8 (shift8-lookup op1 w n))))
    | (Shift W64 op1 n, [Litv (Word64 w)]) =>
      Some ((s,t1), Rval (Litv (Word64 (shift64-lookup op1 w n))))
    | (Equality, [v1, v2]) =>
      (case do-eq v1 v2 of
        Eq-type-error => None
        | Eq-val b => Some ((s,t1), Rval (Boolv b))
      )
    | (Opassign, [Loc lnum, v2]) =>
      (case store-assign lnum (Refv v2) s of
        Some s' => Some ((s',t1), Rval (Conv None []))
        | None => None
      )
    | (Opref, [v2]) =>
      (let (s',n) = (store-alloc (Refv v2) s) in
        Some ((s',t1), Rval (Loc n)))
    | (Opderefer, [Loc n]) =>
      (case store-lookup n s of
        Some (Refv v2) => Some ((s,t1),Rval v2)

```

```

    | - => None
  )
| (Aw8alloc, [Litv (IntLit n), Litv (Word8 w)]) =>
  if n < ( 0 :: int) then
    Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
  else
    (let (s',lnum) =
      (store-alloc (W8array (List.replicate (nat (abs ( n))) w)) s)
    in
      Some ((s',t1), Rval (Loc lnum)))
| (Aw8sub, [Loc lnum, Litv (IntLit i)]) =>
  (case store-lookup lnum s of
    Some (W8array ws) =>
      if i < ( 0 :: int) then
        Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
      else
        (let n = (nat (abs ( i))) in
          if n ≥ List.length ws then
            Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
          else
            Some ((s,t1), Rval (Litv (Word8 (List.nth ws n))))
        )
    | - => None
  )
| (Aw8length, [Loc n]) =>
  (case store-lookup n s of
    Some (W8array ws) =>
      Some ((s,t1), Rval (Litv (IntLit (int (List.length ws)))))
    | - => None
  )
| (Aw8update, [Loc lnum, Litv (IntLit i), Litv (Word8 w)]) =>
  (case store-lookup lnum s of
    Some (W8array ws) =>
      if i < ( 0 :: int) then
        Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
      else
        (let n = (nat (abs ( i))) in
          if n ≥ List.length ws then
            Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
          else
            (case store-assign lnum (W8array (List.list-update ws n w)) s of
              None => None
              | Some s' => Some ((s',t1), Rval (Conv None []))
            )
        )
    | - => None
  )
| (WordFromInt W8, [Litv (IntLit i)]) =>
  Some ((s,t1), Rval (Litv (Word8 (word-of-int i))))
| (WordFromInt W64, [Litv (IntLit i)]) =>
  Some ((s,t1), Rval (Litv (Word64 (word-of-int i))))

```

```

| (WordToInt W8, [Litv (Word8 w)]) =>
  Some ((s,t1), Rval (Litv (IntLit (int(unat w)))))
| (WordToInt W64, [Litv (Word64 w)]) =>
  Some ((s,t1), Rval (Litv (IntLit (int(unat w)))))
| (CopyStrStr, [Litv(StrLit str),Litv(IntLit off),Litv(IntLit len)]) =>
  Some ((s,t1),
    (case copy-array ( str,off) len None of
      None => Rerr (Rraise (prim-exn ("Subscript")))
    | Some cs => Rval (Litv(StrLit((cs))))
    ))
| (CopyStrAw8, [Litv(StrLit str),Litv(IntLit off),Litv(IntLit len),
  Loc dst,Litv(IntLit dstoff)]) =>
  (case store-lookup dst s of
    Some (W8array ws) =>
      (case copy-array ( str,off) len (Some(ws-to-chars ws,dstoffs)) of
        None => Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
      | Some cs =>
        (case store-assign dst (W8array (chars-to-ws cs)) s of
          Some s' => Some ((s',t1), Rval (Conv None []))
        | - => None
        ))
      )
    | - => None
  )
| (CopyAw8Str, [Loc src,Litv(IntLit off),Litv(IntLit len)]) =>
  (case store-lookup src s of
    Some (W8array ws) =>
      Some ((s,t1),
        (case copy-array (ws,off) len None of
          None => Rerr (Rraise (prim-exn ("Subscript")))
        | Some ws => Rval (Litv(StrLit((ws-to-chars ws))))
        ))
      )
    | - => None
  )
| (CopyAw8Aw8, [Loc src,Litv(IntLit off),Litv(IntLit len),
  Loc dst,Litv(IntLit dstoff)]) =>
  (case (store-lookup src s, store-lookup dst s) of
    (Some (W8array ws), Some (W8array ds)) =>
      (case copy-array (ws,off) len (Some(ds,dstoffs)) of
        None => Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
      | Some ws =>
        (case store-assign dst (W8array ws) s of
          Some s' => Some ((s',t1), Rval (Conv None []))
        | - => None
        ))
      )
    | - => None
  )
| (Ord, [Litv (Char c2)]) =>

```

```

    Some ((s,t1), Rval (Litv(IntLit(int(of-char c2))))))
| (Chr, [Litv (IntLit i)]) =>
    Some ((s,t1),
      (if (i < ( 0 :: int)) ∨ (i > ( 255 :: int)) then
        Rerr (Rraise (prim-exn ("Chr")))
      else
        Rval (Litv(Char((%n. char-of (n::nat))(nat (abs ( i)))))))
| (Chopb op1, [Litv (Char c1), Litv (Char c2)]) =>
    Some ((s,t1), Rval (Boolv (opb-lookup op1 (int(of-char c1)) (int(of-char
c2)))))
| (Implode, [v2]) =>
    (case v-to-char-list v2 of
      Some ls =>
        Some ((s,t1), Rval (Litv (StrLit ( ls))))
      | None => None
    )
| (Strsub, [Litv (StrLit str), Litv (IntLit i)]) =>
    if i < ( 0 :: int) then
      Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
    else
      (let n = (nat (abs ( i))) in
        if n ≥ List.length str then
          Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
        else
          Some ((s,t1), Rval (Litv (Char (List.nth ( str) n))))
      )
| (Strlen, [Litv (StrLit str)]) =>
    Some ((s,t1), Rval (Litv(IntLit(int(List.length str))))))
| (Strcat, [v2]) =>
    (case v-to-list v2 of
      Some vs =>
        (case vs-to-string vs of
          Some str =>
            Some ((s,t1), Rval (Litv(StrLit str)))
          | - => None
        )
      | - => None
    )
| (VfromList, [v2]) =>
    (case v-to-list v2 of
      Some vs =>
        Some ((s,t1), Rval (Vectorv vs))
      | None => None
    )
| (Vsub, [Vectorv vs, Litv (IntLit i)]) =>
    if i < ( 0 :: int) then
      Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
    else
      (let n = (nat (abs ( i))) in
        if n ≥ List.length vs then

```



```

        Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
      else
        Some ((s,t1), Rval (List.nth vs n))
    | (Vlength, [Vectorv vs]) =>
      Some ((s,t1), Rval (Litv (IntLit (int (List.length vs)))))
    | (Aalloc, [Litv (IntLit n), v2]) =>
      if n < ( 0 :: int) then
        Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
      else
        (let (s',lnum) =
           (store-alloc (Varray (List.replicate (nat (abs ( n))) v2)) s)
          in
          Some ((s',t1), Rval (Loc lnum)))
    | (AallocEmpty, [Conv None []]) =>
      (let (s',lnum) = (store-alloc (Varray [] s) s) in
       Some ((s',t1), Rval (Loc lnum)))
    | (Asub, [Loc lnum, Litv (IntLit i)]) =>
      (case store-lookup lnum s of
       Some (Varray vs) =>
         if i < ( 0 :: int) then
           Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
         else
           (let n = (nat (abs ( i))) in
            if n ≥ List.length vs then
              Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
            else
              Some ((s,t1), Rval (List.nth vs n)))
         | - => None
      )
    | (Alength, [Loc n]) =>
      (case store-lookup n s of
       Some (Varray vs) =>
         Some ((s,t1), Rval (Litv (IntLit (int (List.length vs)))))
       | - => None
      )
    | (Aupdate, [Loc lnum, Litv (IntLit i), v2]) =>
      (case store-lookup lnum s of
       Some (Varray vs) =>
         if i < ( 0 :: int) then
           Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
         else
           (let n = (nat (abs ( i))) in
            if n ≥ List.length vs then
              Some ((s,t1), Rerr (Rraise (prim-exn ("Subscript"))))
            else
              (case store-assign lnum (Varray (List.list-update vs n v2)) s of
               None => None
               | Some s' => Some ((s',t1), Rval (Conv None []))
              ))
         | - => None
      )
  ))

```

```

    | - => None
  )
| (ConfigGC, [Litv (IntLit i), Litv (IntLit j)]) =>
  Some ((s,t1), Rval (Conv None []))
| (FFI n, [Litv(StrLit conf), Loc lnum]) =>
  (case store-lookup lnum s of
    Some (W8array ws) =>
      (case call-FFI t1 n (List.map (λ c2 . of-nat(of-char c2)) ( conf)) ws of
        (t', ws') =>
          (case store-assign lnum (W8array ws') s of
            Some s' => Some ((s', t'), Rval (Conv None []))
            | None => None
          )
        )
    )
  )
| - => None
)
| - => None
))

```

— Do a logical operation

— val do-log : lop -> v -> exp -> maybe exp-or-val

fun do-log :: lop => v => exp0 =>(exp-or-val)option **where**

```

  do-log And v2 e = (
    (case v2 of
      Litv - => None
    | Conv m l2 => (case m of
        None => None
      | Some p => (case p of
          (s1,t1) =>
            if(s1 = ("true")) then
              ((case t1 of
                  TypeId i => (case i of
                      Short s2 =>
                        if(s2 = ("bool")) then
                          ((case l2 of
                              [] => Some (Exp e)
                              | - => None
                            )) else None
                        | Long - - => None
                    )
                | TypeExn - => None
              )) else
            (
              if(s1 = ("false")) then
                ((case t1 of
                    TypeId i2 => (case i2 of
                        Short s4 =>
                          if(s4 = ("bool")) then

```

```

((case l2 of
  [] => Some
    (Val v2)
  | - => None
)) else None
| Long - - =>
None
)
| TypeExn - => None
)) else None)
)
)
| Closure - - - => None
| Recclosure - - - => None
| Loc - => None
| Vectorv - => None
))
| do-log Or v2 e = (
(case v2 of
  Litv - => None
| Conv m0 l6 => (case m0 of
  None => None
| Some p0 => (case p0 of
  (s8,t0) =>
if(s8 = ("false")) then
((case t0 of
  TypeId i5 => (case i5 of
    Short s9 =>
if(s9 = ("bool")) then
((case l6 of
  [] => Some
    (Exp e)
  | - => None
)) else None
| Long - - =>
None
)
| TypeExn - => None
)) else
(
if(s8 = ("true")) then
((case t0 of
  TypeId i8 => (case i8 of
    Short s11 =>
if(s11 = ("bool")) then
((case l6 of
  [] =>
Some (Val v2)
| - =>

```

```

None
)) else None
| Long - - =>
None
)
| TypeExn - => None
)) else None)
)
)
| Closure - - - => None
| Recclosure - - - => None
| Loc - => None
| Vectorv - => None
))

```

— *Do an if-then-else*

— *val do-if : v -> exp -> exp -> maybe exp*

definition *do-if* :: v => exp0 => exp0 =>(exp0)option **where**

```

do-if v2 e1 e2 = (
  if v2 = (Boolv True) then
    Some e1
  else if v2 = (Boolv False) then
    Some e2
  else
    None )

```

— *Semantic helpers for definitions*

— *Build a constructor environment for the type definition tds*

— *val build-tdefs : list modN -> list (list tvarN * typeN * list (conN * list t)) -> env-ctor*

definition *build-tdefs* :: (string)list =>((tvarN)list*string*(string*(t)list)list)list =>((string),(string),(nat*tid-or-exn))namespace **where**

```

build-tdefs mn tds = (
  alist-to-ns
  (List.rev
   (List.concat
    (List.map
     ( λx .
       (case x of
        (tvs, tn, condefs) =>
List.map
  ( λx . (case x of
          (conN, ts) =>
            (conN, (List.length ts, TypeId (mk-id mn tn)))
          )) condefs
        ))
    ))

```

tds))))

— Checks that no constructor is defined twice in a type

— val check-dup-ctors : list (list tvarN * typeN * list (conN * list t)) -> bool

definition check-dup-ctors :: ((tvarN)list*string*(string*(t)list)list)list => bool
where

```

check-dup-ctors tds = (
  Lem-list.allDistinct ((let x2 =
    ([]) in List.foldr
    (λx . (case x of
      (tvs, tn, condefs) => λ x2 . List.foldr
        (λx .
          (case x of
            (n, ts) =>
              λ x2 .
                if True then
                  n # x2
                else
                  x2
            )) condefs
          x2
        )) tds x2))))

```

— val combine-dec-result : forall 'a. sem-env v -> result (sem-env v) 'a -> result (sem-env v) 'a

fun combine-dec-result :: (v)sem-env =>(((v)sem-env), 'a)result =>(((v)sem-env), 'a)result
where

```

combine-dec-result env (Rerr e) = ( Rerr e )
| combine-dec-result env (Rval env') = ( Rval (| v = (nsAppend(v env')(v env)),
c = (nsAppend(c env')(c env)) |) )

```

— val extend-dec-env : sem-env v -> sem-env v -> sem-env v

definition extend-dec-env :: (v)sem-env =>(v)sem-env =>(v)sem-env **where**

```

extend-dec-env new-env env = (
  (| v = (nsAppend(v new-env)(v env)), c = (nsAppend(c new-env)(c env))
  |) )

```

— val decs-to-types : list dec -> list typeN

definition decs-to-types :: (dec)list =>(string)list **where**

```

decs-to-types ds = (
  List.concat (List.map (λ d .
    (case d of
      Dtype locs tds => List.map ( λx .
        (case x of (tvs,tn,ctors) => tn )) tds
      | - => [] ))

```

ds))

— *val no-dup-types : list dec -> bool*

definition *no-dup-types* :: (*dec*)list \Rightarrow bool **where**

no-dup-types ds = (
 Lem-list.allDistinct (*decs-to-types ds*)

— *val prog-to-mods : list top -> list (list modN)*

definition *prog-to-mods* :: (*top0*)list \Rightarrow ((*string*)list)list **where**

prog-to-mods tops = (
 List.concat (*List.map* (λ *top1* .
 (case *top1* of
 Tmod mn - - \Rightarrow [[*mn*]]
 | - \Rightarrow []))
 tops))

— *val no-dup-mods : list top -> set (list modN) -> bool*

definition *no-dup-mods* :: (*top0*)list \Rightarrow ((*modN*)list)set \Rightarrow bool **where**

no-dup-mods tops defined-mods2 = (
 Lem-list.allDistinct (*prog-to-mods tops*) \wedge
 disjnt (*List.set* (*prog-to-mods tops*) *defined-mods2*)

— *val prog-to-top-types : list top -> list typeN*

definition *prog-to-top-types* :: (*top0*)list \Rightarrow (*string*)list **where**

prog-to-top-types tops = (
 List.concat (*List.map* (λ *top1* .
 (case *top1* of
 Tdec d \Rightarrow *decs-to-types* [*d*]
 | - \Rightarrow []))
 tops))

— *val no-dup-top-types : list top -> set tid-or-exn -> bool*

definition *no-dup-top-types* :: (*top0*)list \Rightarrow (*tid-or-exn*)set \Rightarrow bool **where**

no-dup-top-types tops defined-types2 = (
 Lem-list.allDistinct (*prog-to-top-types tops*) \wedge
 disjnt (*List.set* (*List.map* (λ *tn* . *TypeId* (*Short tn*)) (*prog-to-top-types tops*)))
 defined-types2)

end

Chapter 8

Generated by Lem from *seman- tics/alt-semantics/smallStep.lem.*

theory *SmallStep*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives-extra
Lib
Namespace
Ast
SemanticPrimitives
Ffi

begin

— *open import Pervasives-extra*
— *open import Lib*
— *open import Ast*
— *open import Namespace*
— *open import SemanticPrimitives*
— *open import Ffi*

— *Small-step semantics for expression only. Modules and definitions have * big-step semantics only*

— *Evaluation contexts * The hole is denoted by the unit type * The env argument contains bindings for the free variables of expressions in the context*

datatype *ctxt-frame* =

Craise unit
| *Chandle unit (pat * exp0) list*

| *Capp* *op0* *v list* *unit* *exp0 list*
 | *Clog* *lop* *unit* *exp0*
 | *Cif* *unit* *exp0* *exp0*
 — *The value is raised if none of the patterns match*
 | *Cmat* *unit* (*pat* * *exp0*) *list* *v*
 | *Clet* *varN* *option* *unit* *exp0*
 — *Evaluating a constructor's arguments* * *The v list should be in reverse order.*
 | *Ccon* (*(modN, conN)id0*)*option* *v list* *unit* *exp0 list*
 | *Ctannot* *unit* *t*
 | *Clannot* *unit* *locs*

type-synonym *ctxt* = *ctxt-frame* * *v sem-env*

— *State for CEK-style expression evaluation* * — *constructor data* * — *the store* *
 — *the environment for the free variables of the current expression* * — *the current*
expression to evaluate, or a value if finished * — *the context stack (continuation)*
of what to do once the current expression * *is finished.* Each entry has an
environment for it's free variables

type-synonym *'ffi small-state* = *v sem-env* * (*'ffi, v*) *store-ffi* * *exp-or-val* * *ctxt list*

datatype *'ffi e-step-result* =

Estep *'ffi small-state*
 | *Eabort* *abort*
 | *Estuck*

— *The semantics are deterministic, and presented functionally instead of* * *re-*
lationally for proof rather than readability; the steps are very small: we * *push*
individual frames onto the context stack instead of finding a redex in a * *single step*

— *val push* : forall *'ffi. sem-env v* -> *store-ffi 'ffi v* -> *exp* -> *ctxt-frame* ->
list ctxt -> *e-step-result 'ffi*

definition *push* :: (*v*)*sem-env* =>(*v*)*store***'ffi ffi-state* => *exp0* => *ctxt-frame* =>(*ctxt-frame**(*v*)*sem-env*)*list*
=> *'ffi e-step-result* **where**
push env s e c' cs = (*Estep* (*env, s, Exp e, ((c',env)# cs)*))

— *val return* : forall *'ffi. sem-env v* -> *store-ffi 'ffi v* -> *v* -> *list ctxt* ->
e-step-result 'ffi

definition *return* :: (*v*)*sem-env* =>(*v*)*store***'ffi ffi-state* => *v* =>(*ctxt*)*list* => *'ffi*
e-step-result **where**
return env s v2 c2 = (*Estep* (*env, s, Val v2, c2*))

— *val application* : forall *'ffi. op* -> *sem-env v* -> *store-ffi 'ffi v* -> *list v* ->
list ctxt -> *e-step-result 'ffi*

definition *application* :: *op0* =>(*v*)*sem-env* =>(*v*)*store***'ffi ffi-state* =>(*v*)*list* =>(*ctxt*)*list*
=> *'ffi e-step-result* **where**
application op1 env s vs c2 = (


```

(case op1 of
  Opapp =>
    (case do-opapp vs of
      Some (env,e) => Estep (env, s, Exp e, c2)
      | None => Eabort Rtype-error
    )
  | - =>
    (case do-app s op1 vs of
      Some (s',r) =>
        (case r of
          Rerr (Rraise v2) => Estep (env,s',Val v2,((Craise () ,env)# c2))
          | Rerr (Rabort a) => Eabort a
          | Rval v2 => return env s' v2 c2
        )
      | None => Eabort Rtype-error
    )
  )
))

```

— apply a context to a value

— val continue : forall 'ffi. store-ffi 'ffi v -> v -> list ctxt -> e-step-result 'ffi

fun continue :: (v)store*'ffi ffi-state => v =>(ctxt-frame*(v)sem-env)list => 'ffi
e-step-result **where**

```

  continue s v2 ([]) = ( Estuck )
| continue s v2 ((Craise -, env) # c2) = (
  (case c2 of
    [] => Estuck
    | ((Chandle - pes,env') # c2) =>
      Estep (env,s,Val v2,((Cmat () pes v2, env')# c2))
    | - # c2 => Estep (env,s,Val v2,((Craise () ,env)# c2))
  ))
| continue s v2 ((Chandle - pes, env) # c2) = (
  return env s v2 c2 )
| continue s v2 ((Capp op1 vs - [], env) # c2) = (
  application op1 env s (v2 # vs) c2 )
| continue s v2 ((Capp op1 vs - (e # es), env) # c2) = (
  push env s e (Capp op1 (v2 # vs) () es) c2 )
| continue s v2 ((Clog l - e, env) # c2) = (
  (case do-log l v2 e of
    Some (Exp e) => Estep (env, s, Exp e, c2)
    | Some (Val v2) => return env s v2 c2
    | None => Eabort Rtype-error
  ))
| continue s v2 ((Cif - e1 e2, env) # c2) = (
  (case do-if v2 e1 e2 of
    Some e => Estep (env, s, Exp e, c2)
    | None => Eabort Rtype-error
  ))
| continue s v2 ((Cmat - [] err-v, env) # c2) = (

```

```

      Estep (env, s, Val err-v, ((Craise () , env) # c2)))
| continue s v2 ((Cmat - ((p,e)# pes) err-v, env) # c2) = (
  if Lem-list.allDistinct (pat-bindings p []) then
    (case pmatch(c env) (fst s) p v2 [] of
      Match-type-error => Eabort Rtype-error
      | No-match => Estep (env, s, Val v2, ((Cmat () pes err-v,env)# c2))
      | Match env' => Estep (( env (| v := (nsAppend (alist-to-ns env')(v
env)) |)), s, Exp e, c2)
    )
  else
    Eabort Rtype-error )
| continue s v2 ((Clet n - e, env) # c2) = (
  Estep (( env (| v := (nsOptBind n v2(v env)) |)), s, Exp e, c2))
| continue s v2 ((Ccon n vs - [], env) # c2) = (
  if do-con-check(c env) n (List.length vs +( 1 :: nat)) then
    (case build-conv(c env) n (v2 # vs) of
      None => Eabort Rtype-error
      | Some v2 => return env s v2 c2
    )
  else
    Eabort Rtype-error )
| continue s v2 ((Ccon n vs - (e # es), env) # c2) = (
  if do-con-check(c env) n (((List.length vs +( 1 :: nat)) +( 1 :: nat)) +
List.length es) then
    push env s e (Ccon n (v2 # vs) () es) c2
  else
    Eabort Rtype-error )
| continue s v2 ((Ctannot - t1, env) # c2) = (
  return env s v2 c2 )
| continue s v2 ((Clannot - l, env) # c2) = (
  return env s v2 c2 )

```

— *The single step expression evaluator. Returns None if there is nothing to * do, but no type error. Returns Type-error on encountering free variables, * mis-applied (or non-existent) constructors, and when the wrong kind of value * is given to a primitive. Returns Bind-error when no pattern in a match * matches the value. Otherwise it returns the next state*

— *val e-step : forall 'ffi. small-state 'ffi -> e-step-result 'ffi*
fun e-step :: (v)sem-env*((v)store*'ffi ffi-state)*exp-or-val*(ctxt)list => 'ffi e-step-result
where

```

  e-step (env, s,(Val v2), c2) = (
    continue s v2 c2 )
| e-step (env, s,(Exp e), c2) = (
  (case e of
    Lit l => return env s (Litv l) c2
    | Raise e =>
      push env s e (Craise () ) c2
  )

```

```

| Handle e pes =>
  push env s e (Chandle () pes) c2
| Con n es =>
  if do-con-check(c env) n (List.length es) then
    (case List.rev es of
      [] =>
        (case build-conv(c env) n [] of
          None => Eabort Rtype-error
          | Some v2 => return env s v2 c2
        )
      | e # es =>
        push env s e (Ccon n [] () es) c2
    )
  else
    Eabort Rtype-error
| Var n =>
  (case nsLookup(v env) n of
    None => Eabort Rtype-error
    | Some v2 =>
      return env s v2 c2
  )
| Fun n e => return env s (Closure env n e) c2
| App op1 es =>
  (case List.rev es of
    [] => application op1 env s [] c2
    | (e # es) => push env s e (Capp op1 [] () es) c2
  )
| Log l e1 e2 => push env s e1 (Clog l () e2) c2
| If e1 e2 e3 => push env s e1 (Cif () e2 e3) c2
| Mat e pes => push env s e (Cmat () pes (Conv (Some ("Bind"),
TypeExpn (Short ("Bind")))) [])) c2
| Let n e1 e2 => push env s e1 (Clet n () e2) c2
| Letrec funs e =>
  if ¬ (allDistinct (List.map (λx .
(case x of (x,y,z) => x)) funs)) then
    Eabort Rtype-error
  else
    Estep (( env (| v := (build-rec-env funs env(v env)) |)),
      s, Exp e, c2)
| Tannot e t1 => push env s e (Ctannot () t1) c2
| Lannot e l => push env s e (Clannot () l) c2
))

```

— Define a semantic function using the steps

— val e-step-reln : forall 'ffi. small-state 'ffi -> small-state 'ffi -> bool
— val small-eval : forall 'ffi. sem-env v -> store-ffi 'ffi v -> exp -> list ctxt ->
store-ffi 'ffi v * result v v -> bool

definition $e\text{-step-reln} :: (v)\text{sem-env}*(\text{'ffi},(v))\text{store-ffi}*\text{exp-or-val}*(\text{ctxt})\text{list} \Rightarrow (v)\text{sem-env}*(\text{'ffi},(v))\text{store-ffi}*\text{exp} \Rightarrow \text{bool}$ **where**
 $e\text{-step-reln } st1 \ st2 = (
(e\text{-step } st1 = E\text{step } st2))$

fun

$small\text{-eval} :: (v)\text{sem-env} \Rightarrow (v)\text{store}*\text{'ffi } \text{ffi}\text{-state} \Rightarrow \text{exp0} \Rightarrow (\text{ctxt})\text{list} \Rightarrow ((v)\text{store}*\text{'ffi } \text{ffi}\text{-state})*((v),(v))\text{result} \Rightarrow \text{bool}$ **where**

$small\text{-eval } env \ s \ e \ c2 \ (s', \ Rval \ v2) = ((
\exists \ env'. \ (rtranclp \ (e\text{-step-reln})) \ (env,s,Exp \ e,c2) \ (env',s',Val \ v2,[]))$
|
 $small\text{-eval } env \ s \ e \ c2 \ (s', \ Rerr \ (Rraise \ v2)) = ((
\exists \ env'.
\exists \ env''. \ (rtranclp \ (e\text{-step-reln})) \ (env,s,Exp \ e,c2) \ (env',s',Val \ v2,[(Craise \ () \ ,
env'')]))$
|
 $small\text{-eval } env \ s \ e \ c2 \ (s', \ Rerr \ (Rabort \ a)) = ((
\exists \ env'.
\exists \ e'.
\exists \ c'.
(rtranclp \ (e\text{-step-reln})) \ (env,s,Exp \ e,c2) \ (env',s',e',c') \wedge
(e\text{-step} \ (env',s',e',c') = E\text{abort} \ a))$

— $val \ e\text{-diverges} : \text{forall } \text{'ffi}. \text{sem-env } v \ -> \ \text{store-ffi } \text{'ffi } v \ -> \ \text{exp} \ -> \ \text{bool}$

definition $e\text{-diverges} :: (v)\text{sem-env} \Rightarrow (v)\text{store}*\text{'ffi } \text{ffi}\text{-state} \Rightarrow \text{exp0} \Rightarrow \text{bool}$ **where**

$e\text{-diverges } env \ s \ e = ((
\forall \ env'.
\forall \ s'.
\forall \ e'.
\forall \ c'.
(rtranclp \ (e\text{-step-reln})) \ (env,s,Exp \ e,[]) \ (env',s',e',c')
\longrightarrow
((\exists \ env''. \ \exists \ s''. \ \exists \ e''. \ \exists \ c''.
e\text{-step-reln} \ (env',s',e',c') \ (env'',s'',e'',c''))))$

end

Chapter 9

Generated by Lem from *seman- tics/alt-semantics/bigStep.lem.*

theory *BigStep*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives-extra
Lib
Namespace
Ast
SemanticPrimitives
Ffi
SmallStep

begin

— *open import Pervasives-extra*
— *open import Lib*
— *open import Namespace*
— *open import Ast*
— *open import SemanticPrimitives*
— *open import Ffi*

— *To get the definition of expression divergence to use in defining definition *
divergence*
— *open import SmallStep*

----- *Big step semantics* -----

— *If the first argument is true, the big step semantics counts down how many*

functions applications have happened, and raises an exception when the counter runs out.

inductive

evaluate-match :: $bool \Rightarrow (v)sem\text{-}env \Rightarrow 'ffi\ state \Rightarrow v \Rightarrow (pat * exp0)list \Rightarrow v \Rightarrow 'ffi\ state * ((v),(v))result \Rightarrow bool$

and

evaluate-list :: $bool \Rightarrow (v)sem\text{-}env \Rightarrow 'ffi\ state \Rightarrow (exp0)list \Rightarrow 'ffi\ state * (((v)list),(v))result \Rightarrow bool$

and

evaluate :: $bool \Rightarrow (v)sem\text{-}env \Rightarrow 'ffi\ state \Rightarrow exp0 \Rightarrow 'ffi\ state * ((v),(v))result \Rightarrow bool$ **where**

lit : $\bigwedge ck\ env\ l\ s.$

evaluate ck env s (Lit l) (s, Rval (Litv l))

|

raise1 : $\bigwedge ck\ env\ e\ s1\ s2\ v1.$

evaluate ck s1 env e (s2, Rval v1)

\implies

evaluate ck s1 env (Raise e) (s2, Rerr (Rraise v1))

|

raise2 : $\bigwedge ck\ env\ e\ s1\ s2\ err.$

evaluate ck s1 env e (s2, Rerr err)

\implies

evaluate ck s1 env (Raise e) (s2, Rerr err)

|

handle1 : $\bigwedge ck\ s1\ s2\ env\ e\ v1\ pes.$

evaluate ck s1 env e (s2, Rval v1)

\implies

evaluate ck s1 env (Handle e pes) (s2, Rval v1)

|

handle2 : $\bigwedge ck\ s1\ s2\ env\ e\ pes\ v1\ bv.$

evaluate ck env s1 e (s2, Rerr (Rraise v1)) \wedge

evaluate-match ck env s2 v1 pes v1 bv

\implies

evaluate ck env s1 (Handle e pes) bv

|

handle3 : $\bigwedge ck\ s1\ s2\ env\ e\ pes\ a.$

$evaluate\ ck\ env\ s1\ e\ (s2,\ Rerr\ (Rabort\ a))$
 $==>$
 $evaluate\ ck\ env\ s1\ (Handle\ e\ pes)\ (s2,\ Rerr\ (Rabort\ a))$

|

$con1 : \bigwedge ck\ env\ cn\ es\ vs\ s\ s'\ v1.$
 $do-con-check(c\ env)\ cn\ (List.length\ es) \wedge$
 $((build-conv(c\ env)\ cn\ (List.rev\ vs) = Some\ v1) \wedge$
 $evaluate-list\ ck\ env\ s\ (List.rev\ es)\ (s',\ Rval\ vs))$
 $==>$
 $evaluate\ ck\ env\ s\ (Con\ cn\ es)\ (s',\ Rval\ v1)$

|

$con2 : \bigwedge ck\ env\ cn\ es\ s.$
 $\neg (do-con-check(c\ env)\ cn\ (List.length\ es))$
 $==>$
 $evaluate\ ck\ env\ s\ (Con\ cn\ es)\ (s,\ Rerr\ (Rabort\ Rtype-error))$

|

$con3 : \bigwedge ck\ env\ cn\ es\ err\ s\ s'.$
 $do-con-check(c\ env)\ cn\ (List.length\ es) \wedge$
 $evaluate-list\ ck\ env\ s\ (List.rev\ es)\ (s',\ Rerr\ err)$
 $==>$
 $evaluate\ ck\ env\ s\ (Con\ cn\ es)\ (s',\ Rerr\ err)$

|

$var1 : \bigwedge ck\ env\ n\ v1\ s.$
 $nsLookup(v\ env)\ n = Some\ v1$
 $==>$
 $evaluate\ ck\ env\ s\ (Var\ n)\ (s,\ Rval\ v1)$

|

$var2 : \bigwedge ck\ env\ n\ s.$
 $nsLookup(v\ env)\ n = None$
 $==>$
 $evaluate\ ck\ env\ s\ (Var\ n)\ (s,\ Rerr\ (Rabort\ Rtype-error))$

|

$fn : \bigwedge ck\ env\ n\ e\ s.$
 $evaluate\ ck\ env\ s\ (Fun\ n\ e)\ (s,\ Rval\ (Closure\ env\ n\ e))$

|

$app1 : \bigwedge ck\ env\ es\ vs\ env'\ e\ bv\ s1\ s2.$
 $evaluate_list\ ck\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \wedge$
 $((do_opapp\ (List.rev\ vs) = Some\ (env',\ e)) \wedge$
 $((ck \longrightarrow \neg ((clock\ s2) = (0 :: nat)))) \wedge$
 $evaluate\ ck\ env'\ (if\ ck\ then\ (s2\ |\ clock := ((clock\ s2) - (1 :: nat))\ |))\ else\ s2)$
 $e\ bv))$
 $==>$
 $evaluate\ ck\ env\ s1\ (App\ Opapp\ es)\ bv$

|

$app2 : \bigwedge ck\ env\ es\ vs\ env'\ e\ s1\ s2.$
 $evaluate_list\ ck\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \wedge$
 $((do_opapp\ (List.rev\ vs) = Some\ (env',\ e)) \wedge$
 $((clock\ s2) = (0 :: nat)) \wedge$
 $ck))$
 $==>$
 $evaluate\ ck\ env\ s1\ (App\ Opapp\ es)\ (s2,\ Rerr\ (Rabort\ Rtimeout-error))$

|

$app3 : \bigwedge ck\ env\ es\ vs\ s1\ s2.$
 $evaluate_list\ ck\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \wedge$
 $(do_opapp\ (List.rev\ vs) = None)$
 $==>$
 $evaluate\ ck\ env\ s1\ (App\ Opapp\ es)\ (s2,\ Rerr\ (Rabort\ Rtype-error))$

|

$app4 : \bigwedge ck\ env\ op0\ es\ vs\ res\ s1\ s2\ refs'\ ffi'.$
 $evaluate_list\ ck\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \wedge$
 $((do_app\ ((refs\ s2),\ (ffi\ s2))\ op0\ (List.rev\ vs) = Some\ ((refs',\ ffi'),\ res)) \wedge$
 $(op0 \neq Opapp))$
 $==>$
 $evaluate\ ck\ env\ s1\ (App\ op0\ es)\ ((s2\ |\ refs := refs',\ ffi := ffi'\ |)),\ res)$

|

$app5 : \bigwedge ck\ env\ op0\ es\ vs\ s1\ s2.$
 $evaluate_list\ ck\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \wedge$
 $((do_app\ ((refs\ s2),\ (ffi\ s2))\ op0\ (List.rev\ vs) = None) \wedge$
 $(op0 \neq Opapp))$
 $==>$
 $evaluate\ ck\ env\ s1\ (App\ op0\ es)\ (s2,\ Rerr\ (Rabort\ Rtype-error))$

|

$app6 : \bigwedge ck\ env\ op0\ es\ err\ s1\ s2.$

$evaluate_list\ ck\ env\ s1\ (List.rev\ es)\ (s2,\ Rerr\ err)$
 $==>$
 $evaluate\ ck\ env\ s1\ (App\ op0\ es)\ (s2,\ Rerr\ err)$

|

$log1 : \bigwedge ck\ env\ op0\ e1\ e2\ v1\ e'\ bv\ s1\ s2.$
 $evaluate\ ck\ env\ s1\ e1\ (s2,\ Rval\ v1) \wedge$
 $((do_log\ op0\ v1\ e2 = Some\ (Exp\ e')) \wedge$
 $evaluate\ ck\ env\ s2\ e'\ bv)$
 $==>$
 $evaluate\ ck\ env\ s1\ (Log\ op0\ e1\ e2)\ bv$

|

$log2 : \bigwedge ck\ env\ op0\ e1\ e2\ v1\ bv\ s1\ s2.$
 $evaluate\ ck\ env\ s1\ e1\ (s2,\ Rval\ v1) \wedge$
 $(do_log\ op0\ v1\ e2 = Some\ (Val\ bv))$
 $==>$
 $evaluate\ ck\ env\ s1\ (Log\ op0\ e1\ e2)\ (s2,\ Rval\ bv)$

|

$log3 : \bigwedge ck\ env\ op0\ e1\ e2\ v1\ s1\ s2.$
 $evaluate\ ck\ env\ s1\ e1\ (s2,\ Rval\ v1) \wedge$
 $(do_log\ op0\ v1\ e2 = None)$
 $==>$
 $evaluate\ ck\ env\ s1\ (Log\ op0\ e1\ e2)\ (s2,\ Rerr\ (Rabort\ Rtype-error))$

|

$log4 : \bigwedge ck\ env\ op0\ e1\ e2\ err\ s\ s'.$
 $evaluate\ ck\ env\ s\ e1\ (s',\ Rerr\ err)$
 $==>$
 $evaluate\ ck\ env\ s\ (Log\ op0\ e1\ e2)\ (s',\ Rerr\ err)$

|

$if1 : \bigwedge ck\ env\ e1\ e2\ e3\ v1\ e'\ bv\ s1\ s2.$
 $evaluate\ ck\ env\ s1\ e1\ (s2,\ Rval\ v1) \wedge$
 $((do_if\ v1\ e2\ e3 = Some\ e') \wedge$
 $evaluate\ ck\ env\ s2\ e'\ bv)$
 $==>$
 $evaluate\ ck\ env\ s1\ (If\ e1\ e2\ e3)\ bv$

|

$if2 : \bigwedge ck\ env\ e1\ e2\ e3\ v1\ s1\ s2.$
 $evaluate\ ck\ env\ s1\ e1\ (s2,\ Rval\ v1) \wedge$

$(do\text{-}if\ v1\ e2\ e3 = None)$
 \implies
 $evaluate\ ck\ env\ s1\ (If\ e1\ e2\ e3)\ (s2,\ Rerr\ (Rabort\ Rtype\text{-}error))$

|

$if3 : \bigwedge ck\ env\ e1\ e2\ e3\ err\ s\ s'$
 $evaluate\ ck\ env\ s\ e1\ (s',\ Rerr\ err)$
 \implies
 $evaluate\ ck\ env\ s\ (If\ e1\ e2\ e3)\ (s',\ Rerr\ err)$

|

$mat1 : \bigwedge ck\ env\ e\ pes\ v1\ bv\ s1\ s2.$
 $evaluate\ ck\ env\ s1\ e\ (s2,\ Rval\ v1) \wedge$
 $evaluate\text{-}match\ ck\ env\ s2\ v1\ pes\ (Conv\ (Some\ (("Bind"),\ TypeExpn\ (Short\ ("Bind"))))$
 $[]) \ bv$
 \implies
 $evaluate\ ck\ env\ s1\ (Mat\ e\ pes)\ bv$

|

$mat2 : \bigwedge ck\ env\ e\ pes\ err\ s\ s'$
 $evaluate\ ck\ env\ s\ e\ (s',\ Rerr\ err)$
 \implies
 $evaluate\ ck\ env\ s\ (Mat\ e\ pes)\ (s',\ Rerr\ err)$

|

$let1 : \bigwedge ck\ env\ n\ e1\ e2\ v1\ bv\ s1\ s2.$
 $evaluate\ ck\ env\ s1\ e1\ (s2,\ Rval\ v1) \wedge$
 $evaluate\ ck\ (env\ (| v := (nsOptBind\ n\ v1\ (v\ env)) |))\ s2\ e2\ bv$
 \implies
 $evaluate\ ck\ env\ s1\ (Let\ n\ e1\ e2)\ bv$

|

$let2 : \bigwedge ck\ env\ n\ e1\ e2\ err\ s\ s'$
 $evaluate\ ck\ env\ s\ e1\ (s',\ Rerr\ err)$
 \implies
 $evaluate\ ck\ env\ s\ (Let\ n\ e1\ e2)\ (s',\ Rerr\ err)$

|

$letrec1 : \bigwedge ck\ env\ funs\ e\ bv\ s.$
 $Lem\text{-}list.allDistinct\ (List.map\ (\lambda x .$
 $(case\ x\ of\ (x,y,z) \implies x))\ funs) \wedge$
 $evaluate\ ck\ (env\ (| v := (build\text{-}rec\text{-}env\ funs\ env\ (v\ env)) |))\ s\ e\ bv$
 \implies

evaluate ck env s (Letrec funs e) bv

|

letrec2 : \bigwedge ck env funs e s.

*\neg (Lem-list.allDistinct (List.map (λx .
(case x of (x,y,z) => x)) funs))*

==>

evaluate ck env s (Letrec funs e) (s, Rerr (Rabort Rtype-error))

|

tannot : \bigwedge ck env e t0 s bv.

evaluate ck env s e bv

==>

evaluate ck env s (Tannot e t0) bv

|

locannot : \bigwedge ck env e l s bv.

evaluate ck env s e bv

==>

evaluate ck env s (Lannot e l) bv

|

empty : \bigwedge ck env s.

evaluate-list ck env s [] (s, Rval [])

|

cons1 : \bigwedge ck env e es v1 vs s1 s2 s3.

evaluate ck env s1 e (s2, Rval v1) \wedge

evaluate-list ck env s2 es (s3, Rval vs)

==>

evaluate-list ck env s1 (e # es) (s3, Rval (v1 # vs))

|

cons2 : \bigwedge ck env e es err s s'.

evaluate ck env s e (s', Rerr err)

==>

evaluate-list ck env s (e # es) (s', Rerr err)

|

cons3 : \bigwedge ck env e es v1 err s1 s2 s3.

evaluate ck env s1 e (s2, Rval v1) \wedge

$evaluate_list\ ck\ env\ s2\ es\ (s3,\ Rerr\ err)$
 $==>$
 $evaluate_list\ ck\ env\ s1\ (e\ \# \ es)\ (s3,\ Rerr\ err)$

|

$mat_empty : \bigwedge ck\ env\ v1\ err\ v\ s.$

$evaluate_match\ ck\ env\ s\ v1\ []\ err\ v\ (s,\ Rerr\ (Rraise\ err\ v))$

|

$mat_cons1 : \bigwedge ck\ env\ env'\ v1\ p\ pes\ e\ bv\ err\ v\ s.$
 $Lem_list.allDistinct\ (pat_bindings\ p\ []) \wedge$
 $((pmatch(c\ env)(refs\ s)\ p\ v1\ [] = Match\ env') \wedge$
 $evaluate\ ck\ (env\ (| v := (nsAppend\ (alist\ to\ ns\ env')(v\ env))\ |))\ s\ e\ bv)$
 $==>$
 $evaluate_match\ ck\ env\ s\ v1\ ((p,e)\# \ pes)\ err\ v\ bv$

|

$mat_cons2 : \bigwedge ck\ env\ v1\ p\ e\ pes\ bv\ s\ err\ v.$
 $Lem_list.allDistinct\ (pat_bindings\ p\ []) \wedge$
 $((pmatch(c\ env)(refs\ s)\ p\ v1\ [] = No_match) \wedge$
 $evaluate_match\ ck\ env\ s\ v1\ pes\ err\ v\ bv)$
 $==>$
 $evaluate_match\ ck\ env\ s\ v1\ ((p,e)\# \ pes)\ err\ v\ bv$

|

$mat_cons3 : \bigwedge ck\ env\ v1\ p\ e\ pes\ s\ err\ v.$
 $pmatch(c\ env)(refs\ s)\ p\ v1\ [] = Match_type_error$
 $==>$
 $evaluate_match\ ck\ env\ s\ v1\ ((p,e)\# \ pes)\ err\ v\ (s,\ Rerr\ (Rabort\ Rtype_error))$

|

$mat_cons4 : \bigwedge ck\ env\ v1\ p\ e\ pes\ s\ err\ v.$
 $\neg (Lem_list.allDistinct\ (pat_bindings\ p\ []))$
 $==>$
 $evaluate_match\ ck\ env\ s\ v1\ ((p,e)\# \ pes)\ err\ v\ (s,\ Rerr\ (Rabort\ Rtype_error))$

— The set *tid-or-exn* part of the state tracks all of the types and exceptions * that have been declared

inductive

$evaluate_dec :: bool \Rightarrow (modN)list \Rightarrow (v)sem_env \Rightarrow 'ffi\ state \Rightarrow dec \Rightarrow 'ffi\ state * (((v)sem_env),(v))result$
 $\Rightarrow bool$ **where**

$dlet1 : \bigwedge ck\ mn\ env\ p\ e\ v1\ env'\ s1\ s2\ locs.$

evaluate ck env s1 e (s2, Rval v1) ∧
(Lem-list.allDistinct (pat-bindings p [])) ∧
(pmatch(c env)(refs s2) p v1 [] = Match env')
 \implies
evaluate-dec ck mn env s1 (Dlet locs p e) (s2, Rval (| v = (alist-to-ns env'), c =
nsEmpty |))

|

dlet2 : ∧ ck mn env p e v1 s1 s2 locs.
evaluate ck env s1 e (s2, Rval v1) ∧
(Lem-list.allDistinct (pat-bindings p [])) ∧
(pmatch(c env)(refs s2) p v1 [] = No-match))
 \implies
evaluate-dec ck mn env s1 (Dlet locs p e) (s2, Rerr (Rraise Bindv))

|

dlet3 : ∧ ck mn env p e v1 s1 s2 locs.
evaluate ck env s1 e (s2, Rval v1) ∧
(Lem-list.allDistinct (pat-bindings p [])) ∧
(pmatch(c env)(refs s2) p v1 [] = Match-type-error))
 \implies
evaluate-dec ck mn env s1 (Dlet locs p e) (s2, Rerr (Rabort Rtype-error))

|

dlet4 : ∧ ck mn env p e s locs.
 \neg *(Lem-list.allDistinct (pat-bindings p []))*
 \implies
evaluate-dec ck mn env s (Dlet locs p e) (s, Rerr (Rabort Rtype-error))

|

dlet5 : ∧ ck mn env p e err s' locs.
evaluate ck env s e (s', Rerr err) ∧
Lem-list.allDistinct (pat-bindings p [])
 \implies
evaluate-dec ck mn env s (Dlet locs p e) (s', Rerr err)

|

dletrec1 : ∧ ck mn env funs s locs.
Lem-list.allDistinct (List.map (λx .
(case x of (x,y,z) => x)) funs)
 \implies
evaluate-dec ck mn env s (Dletrec locs funs) (s, Rval (| v = (build-rec-env funs env
nsEmpty), c = nsEmpty |))

|

dletrec2 : $\bigwedge ck mn env funs s locs.$
 $\neg (Lem-list.allDistinct (List.map (\lambda x .$
 $(case x of (x,y,z) => x)) funs))$
 $==>$
evaluate-dec ck mn env s (Dletrec locs funs) (s, Rerr (Rabort Rtype-error))

|

dtype1 : $\bigwedge ck mn env tds s new-tdecs locs.$
check-dup-ctors tds \wedge
 $((new-tdecs = type-defs-to-new-tdecs mn tds) \wedge$
 $(disjnt new-tdecs(defined-types s) \wedge$
Lem-list.allDistinct (List.map (\lambda x .
 $(case x of (tvs,tn,ctors) => tn)) tds)))$
 $==>$
evaluate-dec ck mn env s (Dtype locs tds) ((s (| defined-types := (new-tdecs \cup (defined-types
s)) |)), Rval (| v = nsEmpty, c = (build-tdefs mn tds) |))

|

dtype2 : $\bigwedge ck mn env tds s locs.$
 $\neg (check-dup-ctors tds) \vee$
 $(\neg (disjnt (type-defs-to-new-tdecs mn tds)(defined-types s)) \vee$
 $\neg (Lem-list.allDistinct (List.map (\lambda x .$
 $(case x of (tvs,tn,ctors) => tn)) tds)))$
 $==>$
evaluate-dec ck mn env s (Dtype locs tds) (s, Rerr (Rabort Rtype-error))

|

dtabbrev : $\bigwedge ck mn env tvs tn t0 s locs.$
evaluate-dec ck mn env s (Dtabbrev locs tvs tn t0) (s, Rval (| v = nsEmpty, c =
nsEmpty |))

|

dexn1 : $\bigwedge ck mn env cn ts s locs.$
 $\neg (TypeExn (mk-id mn cn) \in (defined-types s))$
 $==>$
evaluate-dec ck mn env s (Dexn locs cn ts) ((s (| defined-types := ({TypeExn (mk-id
mn cn)}) \cup (defined-types s)) |)), Rval (| v = nsEmpty, c = (nsSing cn (List.length
ts, TypeExn (mk-id mn cn)) |))

|

dexn2 : $\bigwedge ck mn env cn ts s locs.$

$TypeExn (mk-id mn cn) \in (defined-types \ s)$
 \implies
 $evaluate-dec \ ck \ mn \ env \ s \ (Dexn \ locs \ cn \ ts) \ (s, \ Rerr \ (Rabort \ Rtype-error))$

inductive

$evaluate-decs \ :: \ bool \ \Rightarrow (modN)list \ \Rightarrow (v)sem-env \ \Rightarrow 'ffi \ state \ \Rightarrow (dec)list \ \Rightarrow 'ffi$
 $state*((v)sem-env),(v))result \ \Rightarrow bool \ \mathbf{where}$

$empty \ : \ \bigwedge \ ck \ mn \ env \ s.$

$evaluate-decs \ ck \ mn \ env \ s \ [] \ (s, \ Rval \ (| \ v = nsEmpty, \ c = nsEmpty \ |))$

|

$cons1 \ : \ \bigwedge \ ck \ mn \ s1 \ s2 \ env \ d \ ds \ e.$
 $evaluate-dec \ ck \ mn \ env \ s1 \ d \ (s2, \ Rerr \ e)$
 \implies
 $evaluate-decs \ ck \ mn \ env \ s1 \ (d \ \# \ ds) \ (s2, \ Rerr \ e)$

|

$cons2 \ : \ \bigwedge \ ck \ mn \ s1 \ s2 \ s3 \ env \ d \ ds \ new-env \ r.$
 $evaluate-dec \ ck \ mn \ env \ s1 \ d \ (s2, \ Rval \ new-env) \ \wedge$
 $evaluate-decs \ ck \ mn \ (extend-dec-env \ new-env \ env) \ s2 \ ds \ (s3, \ r)$
 \implies
 $evaluate-decs \ ck \ mn \ env \ s1 \ (d \ \# \ ds) \ (s3, \ combine-dec-result \ new-env \ r)$

inductive

$evaluate-top \ :: \ bool \ \Rightarrow (v)sem-env \ \Rightarrow 'ffi \ state \ \Rightarrow top0 \ \Rightarrow 'ffi \ state*((v)sem-env),(v))result$
 $\Rightarrow bool \ \mathbf{where}$

$tdec1 \ : \ \bigwedge \ ck \ s1 \ s2 \ env \ d \ new-env.$
 $evaluate-dec \ ck \ [] \ env \ s1 \ d \ (s2, \ Rval \ new-env)$
 \implies
 $evaluate-top \ ck \ env \ s1 \ (Tdec \ d) \ (s2, \ Rval \ new-env)$

|

$tdec2 \ : \ \bigwedge \ ck \ s1 \ s2 \ env \ d \ err.$
 $evaluate-dec \ ck \ [] \ env \ s1 \ d \ (s2, \ Rerr \ err)$
 \implies
 $evaluate-top \ ck \ env \ s1 \ (Tdec \ d) \ (s2, \ Rerr \ err)$

|

$tmod1 \ : \ \bigwedge \ ck \ s1 \ s2 \ env \ ds \ mn \ specs \ new-env.$
 $\neg ([mn] \in (defined-mods \ s1)) \ \wedge$
 $(no-dup-types \ ds \ \wedge$
 $evaluate-decs \ ck \ [mn] \ env \ s1 \ ds \ (s2, \ Rval \ new-env))$
 \implies

*evaluate-top ck env s1 (Tmod mn specs ds) ((s2 (| defined-mods := ({[mn]}
 $\cup(\text{defined-mods } s2))$ |)), Rval (| v = (nsLift mn(v new-env)), c = (nsLift mn(c
new-env)) |))*

|

*tmod2 : $\bigwedge ck s1 s2 env ds mn specs err.$
 $\neg ([mn] \in(\text{defined-mods } s1)) \wedge$
 $(\text{no-dup-types } ds \wedge$
 $\text{evaluate-decs } ck [mn] env s1 ds (s2, Rerr err))$
 \implies
 $\text{evaluate-top } ck env s1 (Tmod mn specs ds) ((s2 (| \text{defined-mods := } (\{[mn]\}$
 $\cup(\text{defined-mods } s2))$ |)), Rerr err)*

|

*tmod3 : $\bigwedge ck s1 env ds mn specs.$
 $\neg (\text{no-dup-types } ds)$
 \implies
 $\text{evaluate-top } ck env s1 (Tmod mn specs ds) (s1, Rerr (Rabort Rtype-error))$*

|

*tmod4 : $\bigwedge ck env s mn specs ds.$
 $[mn] \in(\text{defined-mods } s)$
 \implies
 $\text{evaluate-top } ck env s (Tmod mn specs ds) (s, Rerr (Rabort Rtype-error))$*

inductive

evaluate-prog :: bool \Rightarrow (v)sem-env \Rightarrow 'ffi state \Rightarrow prog \Rightarrow 'ffi state(((v)sem-env),(v))result
 \Rightarrow bool **where***

empty : $\bigwedge ck env s.$

evaluate-prog ck env s [] (s, Rval (| v = nsEmpty, c = nsEmpty |))

|

*cons1 : $\bigwedge ck s1 s2 s3 env top0 tops new-env r.$
 $\text{evaluate-top } ck env s1 top0 (s2, Rval new-env) \wedge$
 $\text{evaluate-prog } ck (\text{extend-dec-env new-env env}) s2 tops (s3,r)$
 \implies
 $\text{evaluate-prog } ck env s1 (top0 \# tops) (s3, \text{combine-dec-result new-env } r)$*

|

*cons2 : $\bigwedge ck s1 s2 env top0 tops err.$
 $\text{evaluate-top } ck env s1 top0 (s2, Rerr err)$
 \implies*

evaluate-prog ck env s1 (top0 # tops) (s2, Rerr err)

— *val evaluate-whole-prog : forall 'ffi. Eq 'ffi => bool -> sem-env v -> state 'ffi -> prog -> state 'ffi * result (sem-env v) v -> bool*

fun *evaluate-whole-prog* :: *bool =>(v)sem-env => 'ffi state =>(top0)list => 'ffi state*((v)sem-env),(v)result => bool* **where**

evaluate-whole-prog ck env s1 tops (s2, res) = (
if no-dup-mods tops(defined-mods s1) ^ no-dup-top-types tops(defined-types s1)
then

evaluate-prog ck env s1 tops (s2, res)

else

(s1 = s2) ^ (res = Rerr (Rabort Rtype-error)))

— *val dec-diverges : forall 'ffi. sem-env v -> state 'ffi -> dec -> bool*

fun *dec-diverges* :: *(v)sem-env => 'ffi state => dec => bool* **where**

dec-diverges env st (Dlet locs p e) = (Lem-list.allDistinct (pat-bindings p [])
^ e-diverges env ((refs st),(ffi st)) e)

| dec-diverges env st (Dletrec locs funs) = (False)

| dec-diverges env st (Dtype locs tds) = (False)

| dec-diverges env st (Dtabbrev locs tvs tn t1) = (False)

| dec-diverges env st (Dexn locs cn ts) = (False)

inductive

decs-diverges :: *(modN)list =>(v)sem-env => 'ffi state => decs => bool* **where**

cons1 : ^ mn st env d ds.

dec-diverges env st d

==>

decs-diverges mn env st (d # ds)

|

cons2 : ^ mn s1 s2 env d ds new-env.

evaluate-dec False mn env s1 d (s2, Rval new-env) ^

decs-diverges mn (extend-dec-env new-env env) s2 ds

==>

decs-diverges mn env s1 (d # ds)

inductive

top-diverges :: *(v)sem-env => 'ffi state => top0 => bool* **where**

tdec : ^ st env d.

dec-diverges env st d

==>

top-diverges env st (Tdec d)

|

$tmod : \bigwedge env\ s1\ ds\ mn\ specs.$
 $\neg ([mn] \in (defined-mods\ s1)) \wedge$
 $(no-dup-types\ ds \wedge$
 $decs-diverges\ [mn]\ env\ s1\ ds)$
 $==>$
 $top-diverges\ env\ s1\ (Tmod\ mn\ specs\ ds)$

inductive

$prog-diverges :: (v)sem-env \Rightarrow 'ffi\ state \Rightarrow prog \Rightarrow bool$ **where**

$cons1 : \bigwedge st\ env\ top0\ tops.$
 $top-diverges\ env\ st\ top0$
 $==>$
 $prog-diverges\ env\ st\ (top0\ \# \ tops)$

|

$cons2 : \bigwedge s1\ s2\ env\ top0\ tops\ new-env.$
 $evaluate-top\ False\ env\ s1\ top0\ (s2, Rval\ new-env) \wedge$
 $prog-diverges\ (extend-dec-env\ new-env\ env)\ s2\ tops$
 $==>$
 $prog-diverges\ env\ s1\ (top0\ \# \ tops)$
end

Chapter 10

Generated by Lem from

seman-

tics/alt-semantics/proofs/bigSmallInvariants

theory *BigSmallInvariants*

imports

Main

HOL-Library.Datatype-Records

LEM.Lem-pervasives

Lib

Namespace

Ast

SemanticPrimitives

SmallStep

BigStep

begin

— *open import Pervasives*

— *open import Lib*

— *open import Namespace*

— *open import Ast*

— *open import SemanticPrimitives*

— *open import SmallStep*

— *open import BigStep*

— ----- *Auxiliary relations for proving big/small step equivalence* -----

inductive

evaluate-ctxt :: (v) *sem-env* \Rightarrow *'ffi state* \Rightarrow *ctxt-frame* \Rightarrow $v \Rightarrow$ *'ffi state* * $((v), (v))$ *result*
 \Rightarrow *bool* **where**

$raise : \bigwedge env s v1.$

$evaluate-ctx env s (Craise ()) v1 (s, Rerr (Rraise v1))$

|

$handle : \bigwedge env s v1 pes.$

$evaluate-ctx env s (Chandle () pes) v1 (s, Rval v1)$

|

$app1 : \bigwedge env e v1 vs1 vs2 es env' bv s1 s2.$
 $evaluate-list False env s1 es (s2, Rval vs2) \wedge$
 $((do-opapp ((List.rev vs2 @ [v1]) @ vs1) = Some (env',e)) \wedge$
 $evaluate False env' s2 e bv)$

$==>$

$evaluate-ctx env s1 (Capp Opapp vs1 () es) v1 bv$

|

$app2 : \bigwedge env v1 vs1 vs2 es s1 s2.$
 $evaluate-list False env s1 es (s2, Rval vs2) \wedge$
 $(do-opapp ((List.rev vs2 @ [v1]) @ vs1) = None)$

$==>$

$evaluate-ctx env s1 (Capp Opapp vs1 () es) v1 (s2, Rerr (Rabort Rtype-error))$

|

$app3 : \bigwedge env op0 v1 vs1 vs2 es res s1 s2 new-refs new-ffi.$
 $(op0 \neq Opapp) \wedge$
 $(evaluate-list False env s1 es (s2, Rval vs2) \wedge$
 $(do-app ((refs s2),(ffi s2)) op0 ((List.rev vs2 @ [v1]) @ vs1) = Some ((new-refs,$
 $new-ffi),res)))$

$==>$

$evaluate-ctx env s1 (Capp op0 vs1 () es) v1 ((s2 (| ffi := new-ffi, refs := new-refs |)), res)$

|

$app4 : \bigwedge env op0 v1 vs1 vs2 es s1 s2.$
 $(op0 \neq Opapp) \wedge$
 $(evaluate-list False env s1 es (s2, Rval vs2) \wedge$
 $(do-app ((refs s2),(ffi s2)) op0 ((List.rev vs2 @ [v1]) @ vs1) = None))$

$==>$

$evaluate-ctx env s1 (Capp op0 vs1 () es) v1 (s2, Rerr (Rabort Rtype-error))$

|

$app5 : \bigwedge env\ op0\ es\ vs\ v1\ err\ s\ s'.$
 $evaluate-list\ False\ env\ s\ es\ (s',\ Rerr\ err)$
 $==>$
 $evaluate-ctxt\ env\ s\ (Capp\ op0\ vs\ ()\ es)\ v1\ (s',\ Rerr\ err)$

|

$log1 : \bigwedge env\ op0\ e2\ v1\ e'\ bv\ s.$
 $(do-log\ op0\ v1\ e2 = Some\ (Exp\ e')) \wedge$
 $evaluate\ False\ env\ s\ e'\ bv$
 $==>$
 $evaluate-ctxt\ env\ s\ (Clog\ op0\ ()\ e2)\ v1\ bv$

|

$log2 : \bigwedge env\ op0\ e2\ v1\ v'\ s.$
 $do-log\ op0\ v1\ e2 = Some\ (Val\ v')$
 $==>$
 $evaluate-ctxt\ env\ s\ (Clog\ op0\ ()\ e2)\ v1\ (s,\ Rval\ v')$

|

$log3 : \bigwedge env\ op0\ e2\ v1\ s.$
 $(do-log\ op0\ v1\ e2 = None)$
 $==>$
 $evaluate-ctxt\ env\ s\ (Clog\ op0\ ()\ e2)\ v1\ (s,\ Rerr\ (Rabort\ Rtype-error))$

|

$if1 : \bigwedge env\ e2\ e3\ v1\ e'\ bv\ s.$
 $(do-if\ v1\ e2\ e3 = Some\ e') \wedge$
 $evaluate\ False\ env\ s\ e'\ bv$
 $==>$
 $evaluate-ctxt\ env\ s\ (Cif\ ()\ e2\ e3)\ v1\ bv$

|

$if2 : \bigwedge env\ e2\ e3\ v1\ s.$
 $do-if\ v1\ e2\ e3 = None$
 $==>$
 $evaluate-ctxt\ env\ s\ (Cif\ ()\ e2\ e3)\ v1\ (s,\ Rerr\ (Rabort\ Rtype-error))$

|

$mat : \bigwedge env\ pes\ v1\ bv\ s\ err-v.$
 $evaluate-match\ False\ env\ s\ v1\ pes\ err-v\ bv$
 $==>$
 $evaluate-ctxt\ env\ s\ (Cmat\ ()\ pes\ err-v)\ v1\ bv$

|

$lt : \bigwedge env\ n\ e2\ v1\ bv\ s.$
 $evaluate\ False\ (\ | v := (nsOptBind\ n\ v1\ (v\ env))\ |))\ s\ e2\ bv$
 $==>$
 $evaluate-ctxt\ env\ s\ (Clet\ n\ ()\ e2)\ v1\ bv$

|

$con1 : \bigwedge env\ cn\ es\ vs\ v1\ vs'\ s1\ s2\ v'.$
 $do-con-check(c\ env)\ cn\ ((List.length\ vs + List.length\ es) + (1 :: nat)) \wedge$
 $((build-conv(c\ env)\ cn\ ((List.rev\ vs' @ [v1]) @ vs) = Some\ v') \wedge$
 $evaluate-list\ False\ env\ s1\ es\ (s2,\ Rval\ vs'))$
 $==>$
 $evaluate-ctxt\ env\ s1\ (Ccon\ cn\ vs\ ()\ es)\ v1\ (s2,\ Rval\ v')$

|

$con2 : \bigwedge env\ cn\ es\ vs\ v1\ s.$
 $\neg (do-con-check(c\ env)\ cn\ ((List.length\ vs + List.length\ es) + (1 :: nat)))$
 $==>$
 $evaluate-ctxt\ env\ s\ (Ccon\ cn\ vs\ ()\ es)\ v1\ (s,\ Rerr\ (Rabort\ Rtype-error))$

|

$con3 : \bigwedge env\ cn\ es\ vs\ v1\ err\ s\ s'.$
 $do-con-check(c\ env)\ cn\ ((List.length\ vs + List.length\ es) + (1 :: nat)) \wedge$
 $evaluate-list\ False\ env\ s\ es\ (s',\ Rerr\ err)$
 $==>$
 $evaluate-ctxt\ env\ s\ (Ccon\ cn\ vs\ ()\ es)\ v1\ (s',\ Rerr\ err)$

|

$tannot : \bigwedge env\ v1\ s\ t0.$
 $evaluate-ctxt\ env\ s\ (Ctannot\ ()\ t0)\ v1\ (s,\ Rval\ v1)$

|

$lannot : \bigwedge env\ v1\ s\ l.$
 $evaluate-ctxt\ env\ s\ (Clannot\ ()\ l)\ v1\ (s,\ Rval\ v1)$

inductive

$evaluate-ctxts :: 'ffi\ state \Rightarrow (ctxt)\ list \Rightarrow ((v),(v))\ result \Rightarrow 'ffi\ state * ((v),(v))\ result$
 $\Rightarrow bool$ **where**

$empty : \bigwedge res\ s.$

$evaluate-ctxts\ s\ []\ res\ (s,\ res)$

|

$cons-val : \bigwedge c1 cs env v1 res bv s1 s2.$
 $evaluate-ctxt env s1 c1 v1 (s2, res) \wedge$
 $evaluate-ctxts s2 cs res bv$
 $==>$
 $evaluate-ctxts s1 ((c1,env)\# cs) (Rval v1) bv$

|

$cons-err : \bigwedge c1 cs env err s bv.$
 $evaluate-ctxts s cs (Rerr err) bv \wedge$
 $((\forall pes. c1 \neq Chandle () pes)) \vee$
 $((\forall v1. err \neq Rraise v1)))$
 $==>$
 $evaluate-ctxts s ((c1,env)\# cs) (Rerr err) bv$

|

$cons-handle : \bigwedge cs env s s' res1 res2 pes v1.$
 $evaluate-match False env s v1 pes v1 (s', res1) \wedge$
 $evaluate-ctxts s' cs res1 res2$
 $==>$
 $evaluate-ctxts s ((Chandle () pes,env)\# cs) (Rerr (Rraise v1)) res2$

inductive

$evaluate-state :: 'ffi small-state \Rightarrow 'ffi state*((v),(v))result \Rightarrow bool$ **where**

$exp : \bigwedge env e c1 res bv ffi0 refs0 st.$
 $evaluate False env (| clock =((0 :: nat)), refs = refs0, ffi = ffi0, defined-types =$
 $(\{\}) , defined-mods =$
 $(\{\}) |) e (st, res) \wedge$
 $evaluate-ctxts st c1 res bv$
 $==>$
 $evaluate-state (env, (refs0, ffi0), Exp e, c1) bv$

|

$vl : \bigwedge env ffi0 refs0 v1 c1 bv.$
 $evaluate-ctxts (| clock =((0 :: nat)), refs = refs0, ffi = ffi0, defined-types = (\{\}),$
 $defined-mods =$
 $(\{\}) |) c1 (Rval v1) bv$
 $==>$
 $evaluate-state (env, (refs0, ffi0), Val v1, c1) bv$
end

Chapter 11

Generated by Lem from *semantics/evaluate.lem.*

theory *Evaluate*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives-extra
Lib
Namespace
Ast
SemanticPrimitives
Ffi

begin

— *open import Pervasives-extra*
— *open import Lib*
— *open import Ast*
— *open import Namespace*
— *open import SemanticPrimitives*
— *open import Ffi*

— *The semantics is defined here using fix-clock so that HOL4 generates * provable termination conditions. However, after termination is proved, we * clean up the definition (in HOL4) to remove occurrences of fix-clock.*

fun *fix-clock* :: 'a state \Rightarrow 'b state*'c \Rightarrow 'b state*'c **where**
 fix-clock s (s',res) = (
 ((s' (| *clock* := (if(*clock* s') \leq (*clock* s)
 then(*clock* s') else(*clock* s)) |)),res))

definition *dec-clock* :: 'a state \Rightarrow 'a state **where**

$dec-clock\ s = ((s (| clock := ((clock\ s) - (1 :: nat)))))$

— *list-result* is equivalent to *map-result* ($\backslash v. [v]$) *I*, where *map-result* is * defined in *evalPropsTheory*

fun
list-result :: ('a,'b)result \Rightarrow (('a list),'b)result **where**

list-result (Rval v2) = (Rval [v2])

|
list-result (Rerr e) = (Rerr e)

— *val evaluate* : forall 'ffi. state 'ffi \rightarrow sem-env v \rightarrow list exp \rightarrow state 'ffi * result (list v) v

— *val evaluate-match* : forall 'ffi. state 'ffi \rightarrow sem-env v \rightarrow v \rightarrow list (pat * exp) \rightarrow v \rightarrow state 'ffi * result (list v) v

function (*sequential,domintros*)

fun-evaluate-match :: 'ffi state \Rightarrow (v)sem-env \Rightarrow v \Rightarrow (pat*exp0)list \Rightarrow v \Rightarrow 'ffi state*((v)list),(v))result

and

fun-evaluate :: 'ffi state \Rightarrow (v)sem-env \Rightarrow (exp0)list \Rightarrow 'ffi state*((v)list),(v))result **where**

fun-evaluate st env [] = ((st, Rval []))

|
fun-evaluate st env (e1 # e2 # es) = (
 (case *fix-clock* st (*fun-evaluate* st env [e1]) of
 (st', Rval v1) =>
 (case *fun-evaluate* st' env (e2 # es) of
 (st'', Rval vs) => (st'', Rval (List.hd v1 # vs))
 | res => res
)
 | res => res
))

|
fun-evaluate st env [Lit l] = ((st, Rval [Litv l]))

|
fun-evaluate st env [Raise e] = (
 (case *fun-evaluate* st env [e] of
 (st', Rval v2) => (st', Rerr (Rraise (List.hd v2)))
 | res => res
))

|
fun-evaluate st env [Handle e pes] = (
 (case *fix-clock* st (*fun-evaluate* st env [e]) of
 (st', Rerr (Rraise v2)) => *fun-evaluate-match* st' env v2 pes v2
 | res => res
))

```

|
fun-evaluate st env [Con cn es] = (
  if do-con-check(c env) cn (List.length es) then
    (case fun-evaluate st env (List.rev es) of
      (st', Rval vs) =>
        (case build-conv(c env) cn (List.rev vs) of
          Some v2 => (st', Rval [v2])
          | None => (st', Rerr (Rabort Rtype-error))
        )
      | res => res
    )
  else (st, Rerr (Rabort Rtype-error)))
|
fun-evaluate st env [Var n] = (
  (case nsLookup(v env) n of
    Some v2 => (st, Rval [v2])
    | None => (st, Rerr (Rabort Rtype-error))
  ))
|
fun-evaluate st env [Fun x e] = ( (st, Rval [Closure env x e]) )
|
fun-evaluate st env [App op1 es] = (
  (case fix-clock st (fun-evaluate st env (List.rev es)) of
    (st', Rval vs) =>
      if op1 = Opapp then
        (case do-opapp (List.rev vs) of
          Some (env',e) =>
            if (clock st') = (0 :: nat) then
              (st', Rerr (Rabort Rtimeout-error))
            else
              fun-evaluate (dec-clock st') env' [e]
          | None => (st', Rerr (Rabort Rtype-error))
        )
      else
        (case do-app ((refs st'),(ffi st')) op1 (List.rev vs) of
          Some ((refs1,ffi1),r) => (( st' (| refs := refs1, ffi := ffi1 |)), list-result r)
          | None => (st', Rerr (Rabort Rtype-error))
        )
    | res => res
  ))
|
fun-evaluate st env [Log lop e1 e2] = (
  (case fix-clock st (fun-evaluate st env [e1]) of
    (st', Rval v1) =>
      (case do-log lop (List.hd v1) e2 of
        Some (Exp e) => fun-evaluate st' env [e]
        | Some (Val v2) => (st', Rval [v2])
        | None => (st', Rerr (Rabort Rtype-error))
      )
  )
)

```

```

| res => res
))
|
fun-evaluate st env [If e1 e2 e3] = (
  (case fix-clock st (fun-evaluate st env [e1]) of
    (st', Rval v2) =>
      (case do-if (List.hd v2) e2 e3 of
        Some e => fun-evaluate st' env [e]
        | None => (st', Rerr (Rabort Rtype-error))
      )
    )
  | res => res
))
|
fun-evaluate st env [Mat e pes] = (
  (case fix-clock st (fun-evaluate st env [e]) of
    (st', Rval v2) =>
      fun-evaluate-match st' env (List.hd v2) pes Bindv
    )
  | res => res
))
|
fun-evaluate st env [Let xo e1 e2] = (
  (case fix-clock st (fun-evaluate st env [e1]) of
    (st', Rval v2) => fun-evaluate st' ( env (| v := (nsOptBind xo (List.hd v2))(v
env)) |)) [e2]
  | res => res
))
|
fun-evaluate st env [Letrec funs e] = (
  if allDistinct (List.map ( λx .
    (case x of (x,y,z) => x )) funs) then
    fun-evaluate st ( env (| v := (build-rec-env funs env(v env)) |)) [e]
  else
    (st, Rerr (Rabort Rtype-error)))
|
fun-evaluate st env [Tannot e t1] = (
  fun-evaluate st env [e])
|
fun-evaluate st env [Lannot e l] = (
  fun-evaluate st env [e])
|
fun-evaluate-match st env v2 [] err-v = ( (st, Rerr (Rraise err-v)))
|
fun-evaluate-match st env v2 ((p,e)# pes) err-v = (
  if allDistinct (pat-bindings p []) then
    (case pmatch(c env)(refs st) p v2 [] of
      Match env-v' => fun-evaluate st ( env (| v := (nsAppend (alist-to-ns env-v')(v
env)) |)) [e]
      | No-match => fun-evaluate-match st env v2 pes err-v
      | Match-type-error => (st, Rerr (Rabort Rtype-error))
    )
  )

```

```

    )
    else (st, Rerr (Rabort Rtype-error)))
  <proof>
fun
fun-evaluate-decs :: (string)list => 'ffi state =>(v)sem-env =>(dec)list => 'ffi state*((v)sem-env),(v))result
where

fun-evaluate-decs mn st env [] = ( (st, Rval (| v = nsEmpty, c = nsEmpty |)))
|
fun-evaluate-decs mn st env (d1 # d2 # ds) = (
  (case fun-evaluate-decs mn st env [d1] of
    (st1, Rval env1) =>
      (case fun-evaluate-decs mn st1 (extend-dec-env env1 env) (d2 # ds) of
        (st2,r) => (st2, combine-dec-result env1 r)
      )
    | res => res
  ))
|
fun-evaluate-decs mn st env [Dlet locs p e] = (
  if allDistinct (pat-bindings p []) then
    (case fun-evaluate st env [e] of
      (st', Rval v2) =>
        (st',
          (case pmatch(c env)(refs st') p (List.hd v2) [] of
            Match new-vals => Rval (| v = (alist-to-ns new-vals), c = nsEmpty |)
            | No-match => Rerr (Rraise Bindv)
            | Match-type-error => Rerr (Rabort Rtype-error)
          ))
        | (st', Rerr err) => (st', Rerr err)
      )
    else
      (st, Rerr (Rabort Rtype-error)))
|
fun-evaluate-decs mn st env [Dletrec locs fns] = (
  (st,
    (if allDistinct (List.map (λx .
      (case x of (x,y,z) => x )) fns) then
      Rval (| v = (build-rec-env fns env nsEmpty), c = nsEmpty |)
    else
      Rerr (Rabort Rtype-error))))
|
fun-evaluate-decs mn st env [Dtype locs tds] = (
  (let new-tdecs = (type-defs-to-new-tdecs mn tds) in
    if check-dup-ctors tds ∧
      (disjnt new-tdecs(defined-types st) ∧
        allDistinct (List.map (λx .
          (case x of (tvs,tn,ctors) => tn )) tds))
    then
      (( st (| defined-types := (new-tdecs ∪(defined-types st)) |)),

```

```

      Rval (| v = nsEmpty, c = (build-tdefs mn tds) |))
    else
      (st, Rerr (Rabort Rtype-error)))
|
fun-evaluate-decs mn st env [Dabbrev locs tvs tn t1] = (
  (st, Rval (| v = nsEmpty, c = nsEmpty |)))
|
fun-evaluate-decs mn st env [Dexn locs cn ts] = (
  if TypeExn (mk-id mn cn) ∈ (defined-types st) then
    (st, Rerr (Rabort Rtype-error))
  else
    (( st (| defined-types := ({TypeExn (mk-id mn cn)} ∪ (defined-types st)) |)),
      Rval (| v = nsEmpty, c = (nsSing cn (List.length ts, TypeExn (mk-id mn cn)))
    |)))
)))

```

definition *envLift* :: *string* ⇒ *'a sem-env* ⇒ *'a sem-env* **where**
envLift mn env = (
 (| v = (nsLift mn(v env)), c = (nsLift mn(c env)) |))

— *val evaluate-tops* : forall *'ffi. state 'ffi* → *sem-env v* → *list top* → *state 'ffi*
 * *result (sem-env v) v*

fun
evaluate-tops :: *'ffi state* ⇒ *(v)sem-env* ⇒ *(top0)list* ⇒ *'ffi state* * *((v)sem-env), (v)result*
where

```

evaluate-tops st env [] = ( (st, Rval (| v = nsEmpty, c = nsEmpty |)))
|
evaluate-tops st env (top1 # top2 # tops) = (
  (case evaluate-tops st env [top1] of
    (st1, Rval env1) =>
      (case evaluate-tops st1 (extend-dec-env env1 env) (top2 # tops) of
        (st2, r) => (st2, combine-dec-result env1 r)
      )
  )
| res => res
))
|
evaluate-tops st env [Tdec d] = ( fun-evaluate-decs [] st env [d] )
|
evaluate-tops st env [Tmod mn specs ds] = (
  if ¬ ([mn] ∈ (defined-mods st)) ∧ no-dup-types ds
  then
    (case fun-evaluate-decs [mn] st env ds of
      (st', r) =>
        (( st' (| defined-mods := ({[mn]} ∪ (defined-mods st')) |)),
          (case r of
            Rval env' => Rval (| v = (nsLift mn(v env')), c = (nsLift mn(c env'))
          |)
        )
    )
  )
)

```

```

    | Rerr err => Rerr err
  ))
)
else
  (st, Rerr (Rabort Rtype-error))

```

— *val evaluate-prog : forall 'ffi. state 'ffi -> sem-env v -> prog -> state 'ffi * result (sem-env v) v*

definition

fun-evaluate-prog :: 'ffi state =>(v)sem-env =>(top0)list => 'ffi state((v)sem-env),(v))result*
where

```

fun-evaluate-prog st env prog = (
  if no-dup-mods prog(defined-mods st) ^ no-dup-top-types prog(defined-types st)
  then
    evaluate-tops st env prog
  else
    (st, Rerr (Rabort Rtype-error))

```

end

Chapter 12

Generated by Lem from
misc/lem-lib-stub/lib.lem.

theory *LibAuxiliary*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
LEM.Lem-list-extra
LEM.Lem-string
Coinductive.Coinductive-List
Lib

begin

— *****
—
— *Termination Proofs*
—
— *****

termination *lunion* *<proof>*

end

Chapter 13

Generated by Lem from
semantics/namespace.lem.

theory *NamespaceAuxiliary*

imports

Main

HOL-Library.Datatype-Records

LEM.Lem-pervasives

LEM.Lem-set-extra

Namespace

begin

— *****

—

— *Termination Proofs*

—

— *****

termination *nsMap* *(proof)*

end

Chapter 14

Generated by Lem from *semantics/primTypes.lem.*

theory *PrimTypes*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
Lib
Namespace
Ast
SemanticPrimitives
Ffi
Evaluate

begin

— *open import Pervasives*
— *open import Ast*
— *open import SemanticPrimitives*
— *open import Ffi*
— *open import Namespace*
— *open import Lib*
— *open import Evaluate*

— *val prim-types-program : prog*
definition *prim-types-program* :: (*top0*)*list* **where**
 prim-types-program = (
 [Tdec (Dexn ((| row = 0, col = 0, offset = 0 |), (| row = 0, col = 0, offset =
0 |)) ("Bind")) []],
 Tdec (Dexn ((| row = 0, col = 0, offset = 0 |), (| row = 0, col = 0, offset =
0 |)) ("Chr")) []],
 Tdec (Dexn ((| row = 0, col = 0, offset = 0 |), (| row = 0, col = 0, offset =
0 |)) ("Div")) []],

```

    Tdec (Dexn ((| row = 0, col = 0, offset = 0 |), (| row = 0, col = 0, offset =
0 |)) ("Subscript" []),
    Tdec (Dtype ((| row = 0, col = 0, offset = 0 |), (| row = 0, col = 0, offset =
0 |)) [(|, ("bool"), [(("false"), []), ((("true"), []))])],
    Tdec (Dtype ((| row = 0, col = 0, offset = 0 |), (| row = 0, col = 0, offset =
0 |)) [(|([[(CHR 0x27), (CHR "a")]), ("list"), [(("nil"), []), (":"), [Tvar ([[(CHR
0x27), (CHR "a")]), Tapp [Tvar ([[(CHR 0x27), (CHR "a")]) (TC-name (Short
("list"))])])])])],
    Tdec (Dtype ((| row = 0, col = 0, offset = 0 |), (| row = 0, col = 0, offset =
0 |)) [(|([[(CHR 0x27), (CHR "a")]), ("option"), [(("NONE"), []), ("SOME"),
[Tvar ([[(CHR 0x27), (CHR "a")])])])])]) ]

```

```

— val add-to-sem-env : forall 'ffi. Eq 'ffi => (state 'ffi * sem-env v) -> prog ->
maybe (state 'ffi * sem-env v)
fun add-to-sem-env :: 'ffi state*(v)sem-env =>(top0)list =>('ffi state*(v)sem-env)option
where
    add-to-sem-env (st, env) prog = (
    (case fun-evaluate-prog st env prog of
    (st', Rval env') => Some (st', extend-dec-env env' env)
    | - => None
    ))

```

```

— val prim-sem-env : forall 'ffi. Eq 'ffi => ffi-state 'ffi -> maybe (state 'ffi *
sem-env v)
definition prim-sem-env :: 'ffi ffi-state =>('ffi state*(v)sem-env)option where
    prim-sem-env ffi1 = (
    add-to-sem-env
    ((| clock =(( 0 :: nat)), refs = ([]), ffi = ffi1, defined-types = ({}), defined-mods
= ({}) |),
    (| v = nsEmpty, c = nsEmpty |))
    prim-types-program )

```

end

Chapter 15

Generated by Lem from *semantics/semanticPrimitives.lem*.

theory *SemanticPrimitivesAuxiliary*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
LEM.Lem-list-extra
LEM.Lem-string
Lib
Namespace
Ast
Ffi
FpSem
LEM.Lem-string-extra
SemanticPrimitives

begin

— *****
—
— *Termination Proofs*
—
— *****

termination *pmatch* *<proof>*

termination *do-eq* *<proof>*

termination *v-to-list* *<proof>*

termination *v-to-char-list* *<proof>*

termination *vs-to-string* $\langle proof \rangle$

end

Chapter 16

Generated by Lem from *semantics/ffi/simpleIO.lem.*

theory *SimpleIO*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives
LEM.Lem-pervasives-extra
Lib
Ffi

begin

— *open import Pervasives*
— *open import Pervasives-extra*
— *open import Lib*
— *open import Ffi*

datatype-record *simpleIO* =

input :: 8 word llist
output0 :: 8 word llist

— *val isEof* : oracle-function *simpleIO*

fun *isEof* :: *simpleIO* ⇒(8 word)list ⇒(8 word)list ⇒(*simpleIO*)oracle-result

where

isEof st conf ([]) = (*Oracle-fail*)
| *isEof st conf* (x # xs) = (*Oracle-return st* ((if(*input st*) = *LNil* then of-nat ((
1 :: nat)) else of-nat ((0 :: nat))))# xs))

— *val getChar* : oracle-function *simpleIO*

fun *getChar* :: *simpleIO* ⇒(8 word)list ⇒(8 word)list ⇒(*simpleIO*)oracle-result

where

```
  getChar st conf ([]) = ( Oracle-fail )
| getChar st conf (x # xs) = (
  (case lhd'(input st) of
    Some y => Oracle-return (( st (| input := (Option.the (lhd'(input st)))) |)))
(y # xs)
  | - => Oracle-fail
  ))
```

— *val putChar : oracle-function simpleIO*

definition *putChar* :: *simpleIO* \Rightarrow (8 word)list \Rightarrow (8 word)list \Rightarrow (*simpleIO*)oracle-result
where

```
  putChar st conf input1 = (
  (case input1 of
    [] => Oracle-fail
  | x # - => Oracle-return (( st (| output0 := (LCons x(output0 st)) |))) input1
  ))
```

— *val exit : oracle-function simpleIO*

definition *exit0* :: *simpleIO* \Rightarrow (8 word)list \Rightarrow (8 word)list \Rightarrow (*simpleIO*)oracle-result
where

```
  exit0 st conf input1 = ( Oracle-diverge )
```

— *val simpleIO-oracle : oracle simpleIO*

definition *simpleIO-oracle* :: *string* \Rightarrow *simpleIO* \Rightarrow (8 word)list \Rightarrow (8 word)list
 \Rightarrow (*simpleIO*)oracle-result **where**

```
  simpleIO-oracle s st conf input1 = (
  if s = ("isEof") then
    isEof st conf input1
  else if s = ("getChar") then
    getChar st conf input1
  else if s = ("putChar") then
    putChar st conf input1
  else if s = ("exit") then
    exit0 st conf input1
  else
    Oracle-fail )
```

end

Chapter 17

Generated by Lem from *semantics/tokens.lem.*

theory *Tokens*

imports

Main

HOL-Library.Datatype-Records

LEM.Lem-pervasives-extra

begin

— *open import Pervasives-extra*

— *Tokens for Standard ML. NB, not all of them are used in CakeML*

datatype *token* =

WhitespaceT nat | NewlineT | LexErrorT
| HashT | LparT | RparT | StarT | CommaT | ArrowT | DotsT | ColonT | SealT
| SemicolonT | EqualsT | DarrowT | LbrackT | RbrackT | UnderbarT | LbraceT
| BarT | RbraceT | AndT | AndalsoT | AsT | CaseT | DatatypeT
| ElseT | EndT | EqtypeT | ExceptionT | FnT | FunT | HandleT | IfT
| InT | IncludeT | LetT | LocalT | OfT | OpT
| OpenT | OrelseT | RaiseT | RecT | RefT | SharingT | SigT | SignatureT |
StructT
| StructureT | ThenT | TypeT | ValT | WhereT | WhileT | WithT | WithtypeT
| IntT int
| HexintT string
| WordT nat
| RealT string
| StringT string
| CharT char
| TyvarT string
| AlphaT string
| SymbolT string
| LongidT string string
| FFIT string

end

Chapter 18

Generated by Lem from *semantics/typeSystem.lem.*

theory *TypeSystem*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives-extra
Lib
Namespace
Ast
SemanticPrimitives

begin

— *open import Pervasives-extra*
— *open import Lib*
— *open import Ast*
— *open import Namespace*
— *open import SemanticPrimitives*

— *Check that the free type variables are in the given list. Every deBruijn * variable must be smaller than the first argument. So if it is 0, no deBruijn * indices are permitted.*

— *val check-freevars : nat -> list tvarN -> t -> bool*

function (*sequential,domintros*)

check-freevars :: *nat* =>(*string*)*list* => *t* => *bool* **where**

*check-freevars dbmax tvs (Tvar tv) = (
 Set.member tv (set tvs))*

|
*check-freevars dbmax tvs (Tapp ts tn) = (
 (($\forall x \in (\text{set } ts).$ (*check-freevars dbmax tvs* *x*)))*
|

```

check-freevars dbmax tvs (Tvar-db n) = ( n < dbmax )
⟨proof⟩
function (sequential,domintros)
type-subst :: ((string),(t))Map.map ⇒ t ⇒ t where

type-subst s (Tvar tv) = (
  (case s tv of
    None => Tvar tv
  | Some(t1) => t1
  ))
|
type-subst s (Tapp ts tn) = (
  Tapp (List.map (type-subst s) ts) tn )
|
type-subst s (Tvar-db n) = ( Tvar-db n )
⟨proof⟩
function (sequential,domintros)
deBruijn-inc :: nat ⇒ nat ⇒ t ⇒ t where

deBruijn-inc skip n (Tvar tv) = ( Tvar tv )
|
deBruijn-inc skip n (Tvar-db m) = (
  if m < skip then
    Tvar-db m
  else
    Tvar-db (m + n))
|
deBruijn-inc skip n (Tapp ts tn) = ( Tapp (List.map (deBruijn-inc skip n) ts) tn
)
⟨proof⟩
function (sequential,domintros)
deBruijn-subst :: nat ⇒(t)list ⇒ t ⇒ t where

deBruijn-subst skip ts (Tvar tv) = ( Tvar tv )
|
deBruijn-subst skip ts (Tvar-db n) = (
  if ¬ (n < skip) ∧ (n < (List.length ts + skip)) then
    List.nth ts (n - skip)
  else if ¬ (n < skip) then
    Tvar-db (n - List.length ts)
  else
    Tvar-db n )
|
deBruijn-subst skip ts (Tapp ts' tn) = (
  Tapp (List.map (deBruijn-subst skip ts) ts') tn )
⟨proof⟩
datatype tenv-val-exp =
  Empty
  — Binds several de Bruijn type variables

```

```

| Bind-tvar nat tenv-val-exp
— The number is how many de Bruijn type variables the typescheme binds
| Bind-name varN nat t tenv-val-exp

— val bind-tvar : nat -> tenv-val-exp -> tenv-val-exp
definition bind-tvar :: nat  $\Rightarrow$  tenv-val-exp  $\Rightarrow$  tenv-val-exp where
    bind-tvar tv tenvE = ( if tv = ( 0 :: nat ) then tenvE else Bind-tvar tv tenvE
)

— val opt-bind-name : maybe varN -> nat -> t -> tenv-val-exp -> tenv-val-exp
fun opt-bind-name :: (string)option  $\Rightarrow$  nat  $\Rightarrow$  t  $\Rightarrow$  tenv-val-exp  $\Rightarrow$  tenv-val-exp
where
    opt-bind-name None tv t1 tenvE = ( tenvE )
| opt-bind-name (Some n^) tv t1 tenvE = ( Bind-name n' tv t1 tenvE )

— val tveLookup : varN -> nat -> tenv-val-exp -> maybe (nat * t)
fun
tveLookup :: string  $\Rightarrow$  nat  $\Rightarrow$  tenv-val-exp  $\Rightarrow$  (nat*t)option where

tveLookup n inc Empty = ( None )
|
tveLookup n inc (Bind-tvar tv tenvE) = ( tveLookup n (inc + tv) tenvE )
|
tveLookup n inc (Bind-name n' tv t1 tenvE) = (
    if n' = n then
        Some (tv, deBruijn-inc tv inc t1)
    else
        tveLookup n inc tenvE )

type-synonym tenv-abbrev = (modN, typeN, ( tvarN list * t )) namespace
type-synonym tenv-ctor = (modN, conN, ( tvarN list * t list * tid-or-ern ))
namespace
type-synonym tenv-val = (modN, varN, (nat * t)) namespace

datatype-record type-env =

    v0 :: tenv-val

    c0 :: tenv-ctor

    t :: tenv-abbrev

— val extend-dec-tenv : type-env -> type-env -> type-env
definition extend-dec-tenv :: type-env  $\Rightarrow$  type-env  $\Rightarrow$  type-env where

```

```

    extend-dec-tenv tenv' tenv = (
  (| v0 = (nsAppend(v0 tenv')(v0 tenv)),
    c0 = (nsAppend(c0 tenv')(c0 tenv)),
    t = (nsAppend(t tenv')(t tenv)) |) )

— val lookup-varE : id modN varN -> tenv-val-exp -> maybe (nat * t)
fun lookup-varE :: ((string),(string))id0 => tenv-val-exp =>(nat*t)option where

    lookup-varE (Short x) tenvE = ( tveLookup x(( 0 :: nat)) tenvE )
  | lookup-varE - tenvE = ( None )

— val lookup-var : id modN varN -> tenv-val-exp -> type-env -> maybe (nat *
t)
definition lookup-var :: ((modN),(varN))id0 => tenv-val-exp => type-env =>(nat*t)option
where
    lookup-var id1 tenvE tenv = (
  (case lookup-varE id1 tenvE of
    Some x => Some x
  | None => nsLookup(v0 tenv) id1
  ))

— val num-tvs : tenv-val-exp -> nat
fun
num-tvs :: tenv-val-exp => nat where

num-tvs Empty = (( 0 :: nat))
|
num-tvs (Bind-tvar tvs tenvE) = ( tvs + num-tvs tenvE )
|
num-tvs (Bind-name n tvs t1 tenvE) = ( num-tvs tenvE )

— val bind-var-list : nat -> list (varN * t) -> tenv-val-exp -> tenv-val-exp
fun
bind-var-list :: nat =>(string*t)list => tenv-val-exp => tenv-val-exp where

bind-var-list tvs [] tenvE = ( tenvE )
|
bind-var-list tvs ((n,t1)# binds) tenvE = (
  Bind-name n tvs t1 (bind-var-list tvs binds tenvE))

— A pattern matches values of a certain type and extends the type environment *
with the pattern's binders. The number is the maximum deBruijn type variable *
allowed.
— val type-p : nat -> type-env -> pat -> t -> list (varN * t) -> bool

```

- An expression has a type
- $\text{val type-e} : \text{type-env} \rightarrow \text{tenv-val-exp} \rightarrow \text{exp} \rightarrow t \rightarrow \text{bool}$
- A list of expressions has a list of types
- $\text{val type-es} : \text{type-env} \rightarrow \text{tenv-val-exp} \rightarrow \text{list exp} \rightarrow \text{list } t \rightarrow \text{bool}$
- Type a mutually recursive bundle of functions. Unlike pattern typing, the * resulting environment does not extend the input environment, but just * represents the functions
- $\text{val type-funs} : \text{type-env} \rightarrow \text{tenv-val-exp} \rightarrow \text{list (varN * varN * exp)} \rightarrow \text{list (varN * t)} \rightarrow \text{bool}$

datatype-record *decls* =

defined-mods0 :: (*modN list*) set

defined-types0 :: ((*modN*, *typeN*) *id0*) set

defined-exns :: ((*modN*, *conN*) *id0*) set

- $\text{val empty-decls} : \text{decls}$

definition *empty-decls* :: *decls* **where**

$\text{empty-decls} = ((| \text{defined-mods0} = (\{\}), \text{defined-types0} = (\{\}), \text{defined-exns} = (\{\}) |))$

- $\text{val union-decls} : \text{decls} \rightarrow \text{decls} \rightarrow \text{decls}$

definition *union-decls* :: *decls* \Rightarrow *decls* \Rightarrow *decls* **where**

$\text{union-decls } d1 \ d2 = ($
 $(| \text{defined-mods0} = ((\text{defined-mods0 } d1) \cup (\text{defined-mods0 } d2)),$
 $\text{defined-types0} = ((\text{defined-types0 } d1) \cup (\text{defined-types0 } d2)),$
 $\text{defined-exns} = ((\text{defined-exns } d1) \cup (\text{defined-exns } d2)) |))$

- Check a declaration and update the top-level environments * The arguments are in order: * — the module that the declaration is in * — the set of all modules, and types, and exceptions that have been previously declared * — the type environment * — the declaration * — the set of all modules, and types, and exceptions that are declared here * — the environment of new stuff declared here

- $\text{val type-d} : \text{bool} \rightarrow \text{list modN} \rightarrow \text{decls} \rightarrow \text{type-env} \rightarrow \text{dec} \rightarrow \text{decls} \rightarrow \text{type-env} \rightarrow \text{bool}$

- $\text{val type-ds} : \text{bool} \rightarrow \text{list modN} \rightarrow \text{decls} \rightarrow \text{type-env} \rightarrow \text{list dec} \rightarrow \text{decls} \rightarrow \text{type-env} \rightarrow \text{bool}$

- $\text{val check-signature} : \text{list modN} \rightarrow \text{tenv-abbrev} \rightarrow \text{decls} \rightarrow \text{type-env} \rightarrow \text{maybe specs} \rightarrow \text{decls} \rightarrow \text{type-env} \rightarrow \text{bool}$

```

— val type-specs : list modN -> tenv-abbrev -> specs -> decls -> type-env ->
bool
— val type-prog : bool -> decls -> type-env -> list top -> decls -> type-env
-> bool

— Check that the operator can have type (t1 -> ... -> tn -> t)
— val type-op : op -> list t -> t -> bool
fun type-op :: op0 =>(t)list => t => bool where
  type-op (Opn o0) ts t1 = (
    (case (o0,ts) of
      ( -, [Tapp [] TC-int, Tapp [] TC-int]) => (t1 = Tint)
    | (-,-) => False
    )
  )
| type-op (Opb o1) ts t1 = (
  (case (o1,ts) of
    ( -, [Tapp [] TC-int, Tapp [] TC-int]) => (t1 =
      Tapp []
      (TC-name
      (Short ("bool"))))
    | (-,-) => False
  )
)
| type-op (Opw w o2) ts t1 = (
  (case (w,o2,ts) of
    ( W8, -, [Tapp [] TC-word8, Tapp [] TC-word8]) => (t1 =
      Tapp [] TC-word8)
    | ( W64, -, [Tapp [] TC-word64, Tapp [] TC-word64]) => (t1 =
      Tapp []
      TC-word64)
    | (-,-,-) => False
  )
)
| type-op (Shift w0 s n0) ts t1 = (
  (case (w0,s,n0,ts) of
    ( W8, -, -, [Tapp [] TC-word8]) => (t1 = Tapp [] TC-word8)
    | ( W64, -, -, [Tapp [] TC-word64]) => (t1 = Tapp [] TC-word64)
    | (-,-,-,-) => False
  )
)
| type-op Equality ts t1 = (
  (case ts of
    [t11, t2] => (t11 = t2) ∧
      (t1 = Tapp [] (TC-name (Short ("bool"))))
    | - => False
  )
)
| type-op (FP-cmp f) ts t1 = (
  (case (f,ts) of
    ( -, [Tapp [] TC-word64, Tapp [] TC-word64]) => (t1 =
      Tapp []
      (TC-name
      (Short
      ("bool"))))

```

```

    | (-,-) => False
  ) )
| type-op (FP-uop f0) ts t1 = (
  (case (f0,ts) of
    ( -, [Tapp [] TC-word64]) => (t1 = Tapp [] TC-word64)
    | (-,-) => False
  ) )
| type-op (FP-bop f1) ts t1 = (
  (case (f1,ts) of
    ( -, [Tapp [] TC-word64, Tapp [] TC-word64]) => (t1 = Tapp [] TC-word64)
    | (-,-) => False
  ) )
| type-op Opapp ts t1 = (
  (case ts of
    [Tapp [t2', t3'] TC-fn, t2] => (t2 = t2') ∧ (t1 = t3')
    | - => False
  ) )
| type-op Opassign ts t1 = (
  (case ts of
    [Tapp [t11] TC-ref, t2] => (t11 = t2) ∧ (t1 = Tapp [] TC-tup)
    | - => False
  ) )
| type-op Opref ts t1 = (
  (case ts of [t11] => (t1 = Tapp [t11] TC-ref) | - => False ) )
| type-op Opderef ts t1 = (
  (case ts of [Tapp [t11] TC-ref] => (t1 = t11) | - => False ) )
| type-op Aw8alloc ts t1 = (
  (case ts of
    [Tapp [] TC-int, Tapp [] TC-word8] => (t1 = Tapp [] TC-word8array)
    | - => False
  ) )
| type-op Aw8sub ts t1 = (
  (case ts of
    [Tapp [] TC-word8array, Tapp [] TC-int] => (t1 = Tapp [] TC-word8)
    | - => False
  ) )
| type-op Aw8length ts t1 = (
  (case ts of [Tapp [] TC-word8array] => (t1 = Tapp [] TC-int) | - => False ) )
| type-op Aw8update ts t1 = (
  (case ts of
    [Tapp [] TC-word8array, Tapp [] TC-int, Tapp [] TC-word8] => t1 =
      Tapp
      []
      TC-tup
    | - => False
  ) )
| type-op (WordFromInt w1) ts t1 = (
  (case (w1,ts) of
    ( W8, [Tapp [] TC-int]) => t1 = Tapp [] TC-word8
  ) )

```

```

    | ( W64, [Tapp [] TC-int]) => t1 = Tapp [] TC-word64
    | (-,-) => False
  ) )
| type-op (WordToInt w2) ts t1 = (
  (case (w2,ts) of
    ( W8, [Tapp [] TC-word8]) => t1 = Tapp [] TC-int
    | ( W64, [Tapp [] TC-word64]) => t1 = Tapp [] TC-int
    | (-,-) => False
  ) )
| type-op CopyStrStr ts t1 = (
  (case ts of
    [Tapp [] TC-string, Tapp [] TC-int, Tapp [] TC-int] => t1 =
      Tapp []
      TC-string
    | - => False
  ) )
| type-op CopyStrAw8 ts t1 = (
  (case ts of
    [Tapp [] TC-string, Tapp [] TC-int, Tapp [] TC-int, Tapp [] TC-word8array,
    Tapp [] TC-int] =>
    t1 = Tapp [] TC-tup
    | - => False
  ) )
| type-op CopyAw8Str ts t1 = (
  (case ts of
    [Tapp [] TC-word8array, Tapp [] TC-int, Tapp [] TC-int] => t1 =
      Tapp
      []
      TC-string
    | - => False
  ) )
| type-op CopyAw8Aw8 ts t1 = (
  (case ts of
    [Tapp [] TC-word8array, Tapp [] TC-int, Tapp [] TC-int, Tapp [] TC-word8array,
    Tapp [] TC-int] =>
    t1 = Tapp [] TC-tup
    | - => False
  ) )
| type-op Ord ts t1 = (
  (case ts of [Tapp [] TC-char] => (t1 = Tint) | - => False ) )
| type-op Chr ts t1 = (
  (case ts of [Tapp [] TC-int] => (t1 = Tchar) | - => False ) )
| type-op (Chopb o3) ts t1 = (
  (case (o3,ts) of
    ( -, [Tapp [] TC-char, Tapp [] TC-char]) => (t1 =
      Tapp []
      (TC-name
      (Short ("bool"))))
    | (-,-) => False
  ) )

```



```

))
| type-op Implode ts t1 = (
  (case ts of
    [] => False
  | t0 # l0 => (case t0 of
    Tvar - => False
  | Tvar-db - => False
  | Tapp l1 t4 => (case l1 of
    [] => False
  | t5 # l2 => (case t5 of
    Tvar - => False
  | Tvar-db - => False
  | Tapp l3 t7 => (case l3 of
    [] =>
      (case t7 of
        TC-name - =>
          False
        | TC-int =>
          False
        | TC-char =>
          (case l2 of
            [] =>
              (case t4 of
                TC-name i0 =>
                  (case i0 of
                    Short s1 =>
                      if
                        (
                          s1 =
                            "list") then
                            (
                              (case l0 of
                                [] =>
                                  t1 =
                                    Tapp
                                      []
                                      TC-string
                                | - =>
                                  False
                              )) else
                                  False
                            | Long - - =>
                                  False
                            )
                                | TC-int =>
                                  False
                                | TC-char =>
                                  False
                                | TC-string =>

```



```

    )
  )
| type-op Strsub ts t1 = (
  (case ts of
    [Tapp [] TC-string, Tapp [] TC-int] => t1 = Tchar
    | - => False
  )
)
| type-op Strlen ts t1 = (
  (case ts of [Tapp [] TC-string] => t1 = Tint | - => False ) )
| type-op Strcat ts t1 = (
  (case ts of
    [] => False
    | t10 # l6 => (case t10 of
      Tvar - => False
      | Tvar-db - => False
      | Tapp l7 t12 => (case l7 of
        [] => False
        | t13 # l8 => (case t13 of
          Tvar - => False
          | Tvar-db - =>
            False
          | Tapp l9 t15 =>
            (case l9 of
              [] => (case t15 of
                TC-name - =>
                  False
                | TC-int =>
                  False
                | TC-char =>
                  False
                | TC-string =>
                  (case l8 of
                    [] =>
                      (case t12 of
                        TC-name i3 =>
                          (case i3 of
                            Short s3 =>
                              if(s3 =
                                ("list")) then
                                  ((case l6 of
                                    [] =>
                                      t1 =
                                        Tapp
                                        []
                                        TC-string
                                      | - =>
                                        False
                                    )) else
                                      False
                                  )
                                )
          )
        )
      )
    )
  )
)

```

```

    | Long - - =>
False
)
    | TC-int =>
False
    | TC-char =>
False
    | TC-string =>
False
    | TC-ref =>
False
    | TC-word8 =>
False
    | TC-word64 =>
False
    | TC-word8array =>
False
    | TC-fn =>
False
    | TC-tup =>
False
    | TC-exn =>
False
    | TC-vector =>
False
    | TC-array =>
False
)
    | - # - =>
False
)
    | TC-ref =>
False
    | TC-word8 =>
False
    | TC-word64 =>
False
    | TC-word8array =>
False
    | TC-fn =>
False
    | TC-tup =>
False
    | TC-exn =>
False
    | TC-vector =>
False
    | TC-array =>
False

```



```

False
| TC-word8array =>
False
| TC-fn =>
False
| TC-tup =>
False
| TC-exn =>
False
| TC-vector =>
False
| TC-array =>
False
)
| - # - =>
False
)
)
)
)
| type-op Vsub ts t1 = (
(case ts of
[Tapp [t11] TC-vector, Tapp [] TC-int] => t1 = t11
| - => False
))
| type-op Vlength ts t1 = (
(case ts of [Tapp [t11] TC-vector] => (t1 = Tapp [] TC-int) | - => False ) )
| type-op Aalloc ts t1 = (
(case ts of
[Tapp [] TC-int, t11] => t1 = Tapp [t11] TC-array
| - => False
))
| type-op AallocEmpty ts t1 = (
(case ts of
[Tapp [] TC-tup] =>( ∃ t10. t1 = Tapp [t10] TC-array)
| - => False
))
| type-op Asub ts t1 = (
(case ts of
[Tapp [t11] TC-array, Tapp [] TC-int] => t1 = t11
| - => False
))
| type-op Alength ts t1 = (
(case ts of [Tapp [t11] TC-array] => t1 = Tapp [] TC-int | - => False ) )
| type-op Aupdate ts t1 = (
(case ts of
[Tapp [t11] TC-array, Tapp [] TC-int, t2] => (t11 = t2) ∧
(t1 = Tapp [] TC-tup)
| - => False
)
)

```

```

    ) )
| type-op ConfigGC ts t1 = (
  (case ts of
    [Tapp [] TC-int, Tapp [] TC-int] => t1 = Tapp [] TC-tup
  | - => False
  ) )
| type-op (FFI s0) ts t1 = (
  (case (s0,ts) of
    (-, [Tapp [] TC-string, Tapp [] TC-word8array]) => t1 = Tapp [] TC-tup
  | (-,-) => False
  ) )

— val check-type-names : tenv-abbrev -> t -> bool
function (sequential,domintros)
check-type-names :: ((string),(string),((string)list*t))namespace => t => bool where

check-type-names tenvT (Tvar tv) = (
  True )
|
check-type-names tenvT (Tapp ts tn) = (
  (case tn of
    TC-name tn =>
      (case nsLookup tenvT tn of
        Some (tvs, t1) => List.length tvs = List.length ts
      | None => False
      )
  | - => True
  ) ^
  ((∀ x ∈ (set ts). (check-type-names tenvT) x)))
|
check-type-names tenvT (Tvar-db n) = (
  True )
⟨proof⟩
function (sequential,domintros)
type-name-subst :: ((string),(string),((string)list*t))namespace => t => t where

type-name-subst tenvT (Tvar tv) = ( Tvar tv )
|
type-name-subst tenvT (Tapp ts tc) = (
  (let args = (List.map (type-name-subst tenvT) ts) in
  (case tc of
    TC-name tn =>
      (case nsLookup tenvT tn of
        Some (tvs, t1) => type-subst (map-of (Lem-list-extra.zipSameLength
tvs args)) t1
      | None => Tapp args tc
      )
  )
  )

```

```

    | - => Tapp args tc
  )))
|
type-name-subst tenvT (Tvar-db n) = ( Tvar-db n )
⟨proof⟩
definition check-ctor-tenv :: ((modN),(typeN),((tvarN)list*t))namespace =>((tvarN)list*typeN*(conN*(t)list)
=> bool where
  check-ctor-tenv tenvT tds = (
  check-dup-ctors tds ∧
  ((∀ x ∈ (set tds). ( λx .
  (case x of
    (tvs,tn,ctors) =>
  Lem-list.allDistinct tvs ∧
  ((∀ x ∈ (set ctors).
    ( λx . (case x of
      (cn,ts) => ((∀ x ∈ (set ts).
        (check-freevars (( 0 :: nat)) tvs) x))
        ∧
        ((∀ x ∈ (set ts).
          (check-type-names tenvT) x))
      )) x))
  )) x)) ∧
  Lem-list.allDistinct (List.map ( λx .
  (case x of (-,tn,-) => tn )) tds)))

```

— *val build-ctor-tenv : list modN -> tenv-abbrev -> list (list tvarN * typeN * list (conN * list t)) -> tenv-ctor*

definition build-ctor-tenv :: (string)list =>((modN),(typeN),((tvarN)list*t))namespace
=>((tvarN)list*string*(string*(t)list)list)list =>((string),(string),((tvarN)list*(t)list*tid-or-exn))namespace
where

```

  build-ctor-tenv mn tenvT tds = (
  alist-to-ns
  (List.rev
  (List.concat
  (List.map
  ( λx .
  (case x of
    (tvs,tn,ctors) =>
  List.map
  ( λx . (case x of
    (cn,ts) => (cn,(tvs,List.map (type-name-subst tenvT)
      ts, TypeId (mk-id mn tn)))
    )) ctors
  ))
  tds))))

```

— *Check that an exception definition defines no already defined (or duplicate) **

constructors, and that the arguments have no free type variables.

— *val* *check-exn-tenv* : *list modN* → *conN* → *list t* → *bool*

definition *check-exn-tenv* :: (*modN*)*list* ⇒ *string* ⇒ (*t*)*list* ⇒ *bool* **where**

check-exn-tenv *mn cn ts* = (
 ((∀ *x* ∈ (*set ts*). (*check-freevars*((0 :: *nat*)) [] *x*)))

— *For the value restriction on let-based polymorphism*

— *val is-value* : *exp* → *bool*

function (*sequential, domintros*)

is-value :: *exp0* ⇒ *bool* **where**

is-value (*Lit* -) = (*True*)

|
is-value (*Con* - *es*) = ((∀ *x* ∈ (*set es*). *is-value* *x*))

|
is-value (*Var* -) = (*True*)

|
is-value (*Fun* - -) = (*True*)

|
is-value (*Tannot* *e* -) = (*is-value* *e*)

|
is-value (*Lannot* *e* -) = (*is-value* *e*)

|
is-value - = (*False*)

⟨*proof*⟩

fun *tid-exn-to-tc* :: *tid-or-exn* ⇒ *tctor* **where**

tid-exn-to-tc (*TypeId* *tid*) = (*TC-name* *tid*)

| *tid-exn-to-tc* (*TypeExn* -) = (*TC-exn*)

inductive

type-ps :: *nat* ⇒ *type-env* ⇒ (*pat*)*list* ⇒ (*t*)*list* ⇒ (*varN*t*)*list* ⇒ *bool*

and

type-p :: *nat* ⇒ *type-env* ⇒ *pat* ⇒ *t* ⇒ (*varN*t*)*list* ⇒ *bool* **where**

pany : ∧ *tvs tenv t0*.

check-freevars *tvs* [] *t0*

==>

type-p *tvs tenv Pany* *t0* []

|

pvar : ∧ *tvs tenv n t0*.

check-freevars *tvs* [] *t0*

==>

type-p *tvs tenv (Pvar* *n)* *t0* [(*n,t0*)]

|

plit-int : $\bigwedge tvs\ tenv\ n.$

type-p *tvs tenv* (*Plit* (*IntLit* *n*)) *Tint* []

|

plit-char : $\bigwedge tvs\ tenv\ c1.$

type-p *tvs tenv* (*Plit* (*Char* *c1*)) *Tchar* []

|

plit-string : $\bigwedge tvs\ tenv\ s.$

type-p *tvs tenv* (*Plit* (*StrLit* *s*)) *Tstring* []

|

plit-word8 : $\bigwedge tvs\ tenv\ w.$

type-p *tvs tenv* (*Plit* (*Word8* *w*)) *Tword8* []

|

plit-word64 : $\bigwedge tvs\ tenv\ w.$

type-p *tvs tenv* (*Plit* (*Word64* *w*)) *Tword64* []

|

pcon-some : $\bigwedge tvs\ tenv\ cn\ ps\ ts\ tvs'\ tn\ ts'\ bindings.$

$((\forall x \in (set\ ts').\ (check-freevars\ tvs\ [])\ x)) \wedge$

$((List.length\ ts' = List.length\ tvs') \wedge$

$(type-ps\ tvs\ tenv\ ps\ (List.map\ (type-subst\ (map-of\ (Lem-list-extra.zipSameLength\ tvs'\ ts'))\ ts)\ bindings) \wedge$

$(nsLookup(c0\ tenv)\ cn = Some\ (tvs',\ ts,\ tn))))$

\implies

type-p *tvs tenv* (*Pcon* (*Some* *cn*) *ps*) (*Tapp* *ts'* (*tid-exn-to-tc* *tn*)) *bindings*

|

pcon-none : $\bigwedge tvs\ tenv\ ps\ ts\ bindings.$

type-ps *tvs tenv* *ps* *ts* *bindings*

\implies

type-p *tvs tenv* (*Pcon* *None* *ps*) (*Tapp* *ts* *TC-tup*) *bindings*

|

$pref : \bigwedge tvs\ tenv\ p\ t0\ bindings.$
 $type-p\ tvs\ tenv\ p\ t0\ bindings$
 $==>$
 $type-p\ tvs\ tenv\ (Pref\ p)\ (Tref\ t0)\ bindings$

|

$ptypeannot : \bigwedge tvs\ tenv\ p\ t0\ bindings.$
 $check-freevars((\ 0 :: nat))\ []\ t0 \wedge$
 $(check-type-names(t\ tenv)\ t0 \wedge$
 $type-p\ tvs\ tenv\ p\ (type-name-subst(t\ tenv)\ t0)\ bindings)$
 $==>$
 $type-p\ tvs\ tenv\ (Pannot\ p\ t0)\ (type-name-subst(t\ tenv)\ t0)\ bindings$

|

$empty : \bigwedge tvs\ tenv.$

$type-ps\ tvs\ tenv\ []\ []\ []$

|

$cons : \bigwedge tvs\ tenv\ p\ ps\ t0\ ts\ bindings\ bindings'.$
 $type-p\ tvs\ tenv\ p\ t0\ bindings \wedge$
 $type-ps\ tvs\ tenv\ ps\ ts\ bindings'$
 $==>$
 $type-ps\ tvs\ tenv\ (p\ \# \ ps)\ (t0\ \# \ ts)\ (bindings'\@bindings)$

inductive

$type-funs :: type-env \Rightarrow tenv-val-exp \Rightarrow (varN*varN*exp0)list \Rightarrow (varN*t)list \Rightarrow$
 $bool$

and

$type-es :: type-env \Rightarrow tenv-val-exp \Rightarrow (exp0)list \Rightarrow (t)list \Rightarrow bool$

and

$type-e :: type-env \Rightarrow tenv-val-exp \Rightarrow exp0 \Rightarrow t \Rightarrow bool$ **where**

$lit-int : \bigwedge tenv\ tenvE\ n.$

$type-e\ tenv\ tenvE\ (Lit\ (IntLit\ n))\ Tint$

|

$lit-char : \bigwedge tenv\ tenvE\ c1.$

$type-e\ tenv\ tenvE\ (Lit\ (Char\ c1))\ Tchar$

|

$lit-string : \bigwedge tenv\ tenvE\ s.$

$type\text{-}e\ tenv\ tenvE\ (Lit\ (StrLit\ s))\ Tstring$

|

$lit\text{-}word8 : \bigwedge\ tenv\ tenvE\ w.$

$type\text{-}e\ tenv\ tenvE\ (Lit\ (Word8\ w))\ Tword8$

|

$lit\text{-}word64 : \bigwedge\ tenv\ tenvE\ w.$

$type\text{-}e\ tenv\ tenvE\ (Lit\ (Word64\ w))\ Tword64$

|

$raise : \bigwedge\ tenv\ tenvE\ e\ t0.$

$check\text{-}freevars\ (num\text{-}tvs\ tenvE)\ []\ t0 \wedge$

$type\text{-}e\ tenv\ tenvE\ e\ Texn$

$==>$

$type\text{-}e\ tenv\ tenvE\ (Raise\ e)\ t0$

|

$handle : \bigwedge\ tenv\ tenvE\ e\ pes\ t0.$

$type\text{-}e\ tenv\ tenvE\ e\ t0 \wedge (\neg\ (pes = [])) \wedge$

$((\forall\ (p,e) \in$

$List.set\ pes.\ (\exists\ bindings.$

$Lem\text{-}list.allDistinct\ (pat\text{-}bindings\ p\ []) \wedge$

$(type\text{-}p\ (num\text{-}tvs\ tenvE)\ tenv\ p\ Texn\ bindings \wedge$

$type\text{-}e\ tenv\ (bind\text{-}var\text{-}list\ (0 :: nat)\ bindings\ tenvE)\ e\ t0))))))$

$==>$

$type\text{-}e\ tenv\ tenvE\ (Handle\ e\ pes)\ t0$

|

$con\text{-}some : \bigwedge\ tenv\ tenvE\ cn\ es\ tvs\ tn\ ts'\ ts.$

$((\forall\ x \in (set\ ts').\ (check\text{-}freevars\ (num\text{-}tvs\ tenvE)\ []\ x)) \wedge$

$((List.length\ tvs = List.length\ ts') \wedge$

$(type\text{-}es\ tenv\ tenvE\ es\ (List.map\ (type\text{-}subst\ (map\text{-}of\ (Lem\text{-}list\text{-}extra.zipSameLength\ tvs\ ts'))\ ts) \wedge$

$(nsLookup\ (c0\ tenv)\ cn = Some\ (tvs,\ ts,\ tn))))$

$==>$

$type\text{-}e\ tenv\ tenvE\ (Con\ (Some\ cn)\ es)\ (Tapp\ ts'\ (tid\text{-}exn\text{-}to\text{-}tc\ tn))$

|

con-none : \bigwedge *tenv* *tenvE* *es* *ts*.
type-es *tenv* *tenvE* *es* *ts*
 \implies
type-e *tenv* *tenvE* (*Con* *None* *es*) (*Tapp* *ts* *TC-tup*)

|

var : \bigwedge *tenv* *tenvE* *n* *t0* *targs* *tvs*.
(*tvs* = *List.length* *targs*) \wedge
($(\forall x \in (\text{set } \textit{targs}). (\textit{check-freevars} (\textit{num-tvs} \textit{tenvE}) [] x)) \wedge$
(*lookup-var* *n* *tenvE* *tenv* = *Some* (*tvs*,*t0*)))
 \implies
type-e *tenv* *tenvE* (*Var* *n*) (*deBruijn-subst*((*0* :: *nat*)) *targs* *t0*)

|

fn : \bigwedge *tenv* *tenvE* *n* *e* *t1* *t2*.
check-freevars (*num-tvs* *tenvE*) [] *t1* \wedge
type-e *tenv* (*Bind-name* *n*((*0* :: *nat*)) *t1* *tenvE*) *e* *t2*
 \implies
type-e *tenv* *tenvE* (*Fun* *n* *e*) (*Tfn* *t1* *t2*)

|

app : \bigwedge *tenv* *tenvE* *op0* *es* *ts* *t0*.
type-es *tenv* *tenvE* *es* *ts* \wedge
(*type-op* *op0* *ts* *t0* \wedge
check-freevars (*num-tvs* *tenvE*) [] *t0*)
 \implies
type-e *tenv* *tenvE* (*App* *op0* *es*) *t0*

|

log : \bigwedge *tenv* *tenvE* *l* *e1* *e2*.
type-e *tenv* *tenvE* *e1* (*Tapp* [] (*TC-name* (*Short* ("bool")))) \wedge
type-e *tenv* *tenvE* *e2* (*Tapp* [] (*TC-name* (*Short* ("bool"))))
 \implies
type-e *tenv* *tenvE* (*Log* *l* *e1* *e2*) (*Tapp* [] (*TC-name* (*Short* ("bool"))))

|

if' : \bigwedge *tenv* *tenvE* *e1* *e2* *e3* *t0*.
type-e *tenv* *tenvE* *e1* (*Tapp* [] (*TC-name* (*Short* ("bool")))) \wedge
(*type-e* *tenv* *tenvE* *e2* *t0* \wedge
type-e *tenv* *tenvE* *e3* *t0*)
 \implies
type-e *tenv* *tenvE* (*If* *e1* *e2* *e3*) *t0*

|

$mat : \bigwedge \text{tenv } \text{tenvE } e \text{ pes } t1 \ t2.$
 $type\text{-}e \ \text{tenv } \text{tenvE } e \ t1 \wedge (\neg (\text{pes} = [])) \wedge$
 $((\forall (p,e) \in$
 $\quad List.set \ \text{pes}. \ (\exists \ \text{bindings}.$
 $\quad Lem\text{-}list.allDistinct \ (\text{pat}\text{-}bindings \ p \ []) \wedge$
 $\quad (type\text{-}p \ (\text{num}\text{-}tvs \ \text{tenvE}) \ \text{tenv } p \ t1 \ \text{bindings} \wedge$
 $\quad type\text{-}e \ \text{tenv} \ (\text{bind}\text{-}var\text{-}list((0 :: nat)) \ \text{bindings} \ \text{tenvE}) \ e \ t2))))$
 $==>$
 $type\text{-}e \ \text{tenv } \text{tenvE} \ (\text{Mat } e \ \text{pes}) \ t2$

|

$— \ \text{let}\text{-}poly : \text{forall } \text{tenv } \text{tenvE } n \ e1 \ e2 \ t1 \ t2 \ \text{tvs}. \ \text{is}\text{-}value \ e1 \ \&\& \ type\text{-}e \ \text{tenv}$
 $(\text{bind}\text{-}tvar \ \text{tvs} \ \text{tenvE}) \ e1 \ t1 \ \&\& \ type\text{-}e \ \text{tenv} \ (\text{opt}\text{-}bind\text{-}name \ n \ \text{tvs} \ t1 \ \text{tenvE}) \ e2$
 $t2 ==> type\text{-}e \ \text{tenv } \text{tenvE} \ (\text{Let } n \ e1 \ e2) \ t2 \ \text{and}$

$let\text{-}mono : \bigwedge \text{tenv } \text{tenvE } n \ e1 \ e2 \ t1 \ t2.$
 $type\text{-}e \ \text{tenv } \text{tenvE} \ e1 \ t1 \wedge$
 $type\text{-}e \ \text{tenv} \ (\text{opt}\text{-}bind\text{-}name \ n((0 :: nat)) \ t1 \ \text{tenvE}) \ e2 \ t2$
 $==>$
 $type\text{-}e \ \text{tenv } \text{tenvE} \ (\text{Let } n \ e1 \ e2) \ t2$

$— \ \text{and } \text{letrec} : \text{forall } \text{tenv } \text{tenvE} \ \text{funs } e \ t \ \text{tenv}' \ \text{tvs}. \ \text{type}\text{-}\text{funs} \ \text{tenv} \ (\text{bind}\text{-}var\text{-}list$
 $0 \ \text{tenv}' \ (\text{bind}\text{-}tvar \ \text{tvs} \ \text{tenvE})) \ \text{funs} \ \text{tenv}' \ \&\& \ type\text{-}e \ \text{tenv} \ (\text{bind}\text{-}var\text{-}list \ \text{tvs} \ \text{tenv}'$
 $\text{tenvE}) \ e \ t ==> type\text{-}e \ \text{tenv } \text{tenvE} \ (\text{Letrec} \ \text{funs} \ e) \ t$

|

$letrec : \bigwedge \text{tenv } \text{tenvE} \ \text{funs } e \ t0 \ \text{bindings}.$
 $type\text{-}\text{funs} \ \text{tenv} \ (\text{bind}\text{-}var\text{-}list((0 :: nat)) \ \text{bindings} \ \text{tenvE}) \ \text{funs} \ \text{bindings} \wedge$
 $type\text{-}e \ \text{tenv} \ (\text{bind}\text{-}var\text{-}list((0 :: nat)) \ \text{bindings} \ \text{tenvE}) \ e \ t0$
 $==>$
 $type\text{-}e \ \text{tenv } \text{tenvE} \ (\text{Letrec} \ \text{funs} \ e) \ t0$

|

$typeannot : \bigwedge \text{tenv } \text{tenvE} \ e \ t0.$
 $check\text{-}freevars((0 :: nat)) \ [] \ t0 \wedge$
 $(check\text{-}type\text{-}names(t \ \text{tenv}) \ t0 \wedge$
 $type\text{-}e \ \text{tenv } \text{tenvE} \ e \ (\text{type}\text{-}name\text{-}subst(t \ \text{tenv}) \ t0))$
 $==>$
 $type\text{-}e \ \text{tenv } \text{tenvE} \ (\text{Tannot } e \ t0) \ (\text{type}\text{-}name\text{-}subst(t \ \text{tenv}) \ t0)$

|

$locannot : \bigwedge \text{tenv } \text{tenvE} \ e \ l \ t0.$
 $type\text{-}e \ \text{tenv } \text{tenvE} \ e \ t0$
 $==>$

type-e *tenv* *tenvE* (*Lannot* *e* *l*) *t0*

|

empty : \bigwedge *tenv* *tenvE*.

type-es *tenv* *tenvE* [] []

|

cons : \bigwedge *tenv* *tenvE* *e* *es* *t0* *ts*.
type-e *tenv* *tenvE* *e* *t0* \wedge
type-es *tenv* *tenvE* *es* *ts*
 \implies
type-es *tenv* *tenvE* (*e* # *es*) (*t0* # *ts*)

|

no-funs : \bigwedge *tenv* *tenvE*.

type-funs *tenv* *tenvE* [] []

|

funs : \bigwedge *tenv* *tenvE* *fn* *n* *e* *funs* *bindings* *t1* *t2*.
check-freevars (*num-tvs* *tenvE*) [] (*Tfn* *t1* *t2*) \wedge
(*type-e* *tenv* (*Bind-name* *n*((*0* :: *nat*)) *t1* *tenvE*) *e* *t2* \wedge
(*type-funs* *tenv* *tenvE* *funs* *bindings* \wedge
(*Map.map-of* *bindings* *fn* = *None*)))
 \implies
type-funs *tenv* *tenvE* ((*fn*, *n*, *e*)# *funs*) ((*fn*, *Tfn* *t1* *t2*)# *bindings*)

— *val* *tenv-add-tvs* : *nat* \rightarrow *alist* *varN* *t* \rightarrow *alist* *varN* (*nat* * *t*)

definition *tenv-add-tvs* :: *nat* \Rightarrow (*string***t*)*list* \Rightarrow (*string**(*nat***t*))*list* **where**
tenv-add-tvs *tvs* *bindings* = (
List.map (λx .
(*case* *x* of (*n*,*t1*) \Rightarrow (*n*,(*tvs*,*t1*)))) *bindings*)

— *val* *type-pe-determ* : *type-env* \rightarrow *tenv-val-exp* \rightarrow *pat* \rightarrow *exp* \rightarrow *bool*

definition *type-pe-determ* :: *type-env* \Rightarrow *tenv-val-exp* \Rightarrow *pat* \Rightarrow *exp0* \Rightarrow *bool*
where

type-pe-determ *tenv* *tenvE* *p* *e* = ((
 \forall *t1*.
 \forall *tenv1*.
 \forall *t2*.
 \forall *tenv2*.
(*type-p*((*0* :: *nat*)) *tenv* *p* *t1* *tenv1* \wedge (*type-e* *tenv* *tenvE* *e* *t1* \wedge
(*type-p*((*0* :: *nat*)) *tenv* *p* *t2* *tenv2* \wedge *type-e* *tenv* *tenvE* *e* *t2*)))

→
 (tenv1 = tenv2)))

— *val tscheme-inst* : (nat * t) -> (nat * t) -> bool
fun *tscheme-inst* :: nat*t => nat*t => bool **where**
 tscheme-inst (*tv*s-spec, *t*-spec) (*tv*s-impl, *t*-impl) = ((
 ∃ *subst*.
 (List.length *subst* = *tv*s-impl) ∧
 (check-freevars *tv*s-impl [] *t*-impl ∧
 ((∀ *x* ∈ (set *subst*). (check-freevars *tv*s-spec [] *x*)) ∧
 (deBruijn-subst((0 :: nat)) *subst* *t*-impl = *t*-spec))))))

inductive

type-d :: bool =>(modN)list => decls => type-env => dec => decls => type-env =>
 bool **where**

dlet-poly : ∧ extra-checks *tv*s *mn* *tenv* *p* *e* *t0* *bindings* *decls* *locs*.
is-value *e* ∧
 (Lem-list.allDistinct (*pat*-bindings *p* [])) ∧
 (type-p *tv*s *tenv* *p* *t0* *bindings* ∧
 (type-e *tenv* (bind-tvar *tv*s Empty) *e* *t0* ∧
 (extra-checks →
 ((∀ *tv*s'. ∀ *bindings*'. ∀ *t*'.
 (type-p *tv*s' *tenv* *p* *t'* *bindings*' ∧
 type-e *tenv* (bind-tvar *tv*s' Empty) *e* *t'*) →
 list-all2 *tscheme-inst* (List.map snd (tenv-add-tvs *tv*s' *bindings*')) (List.map
 snd (tenv-add-tvs *tv*s *bindings*)))))))))
 ==>
type-d extra-checks *mn* *decls* *tenv* (Dlet *locs* *p* *e*)
 empty-decls (| *v0* = (alist-to-ns (tenv-add-tvs *tv*s *bindings*)), *c0* = nsEmpty, *t* =
 nsEmpty |)

|

dlet-mono : ∧ extra-checks *mn* *tenv* *p* *e* *t0* *bindings* *decls* *locs*.
 — The following line makes sure that when the value restriction prohibits generalisation, a type error is given rather than picking an arbitrary instantiation. However, we should only do the check when the extra-checks argument tells us to.
 (extra-checks → (¬ (is-value *e*) ∧ type-pe-determ *tenv* Empty *p* *e*)) ∧
 (Lem-list.allDistinct (*pat*-bindings *p* [])) ∧
 (type-p((0 :: nat)) *tenv* *p* *t0* *bindings* ∧
 type-e *tenv* Empty *e* *t0*)
 ==>
type-d extra-checks *mn* *decls* *tenv* (Dlet *locs* *p* *e*)
 empty-decls (| *v0* = (alist-to-ns (tenv-add-tvs((0 :: nat)) *bindings*)), *c0* =
 nsEmpty, *t* = nsEmpty |)

|

dletrec : \bigwedge *extra-checks mn tenv funs bindings tvs decls locs*.
type-funs tenv (*bind-var-list*((0 :: nat)) *bindings* (*bind-tvar tvs Empty*)) *funs bindings* \wedge
(*extra-checks* \longrightarrow
((\forall *tvs'*. \forall *bindings'*.
 type-funs tenv (*bind-var-list*((0 :: nat)) *bindings'* (*bind-tvar tvs' Empty*)) *funs bindings'* \longrightarrow
 list-all2 tscheme-inst (*List.map snd* (*tenv-add-tvs tvs' bindings'*)) (*List.map snd* (*tenv-add-tvs tvs bindings*))))))
 \impl
type-d extra-checks mn decls tenv (*Dletrec locs funs*)
 empty-decls (| *v0* = (*alist-to-ns* (*tenv-add-tvs tvs bindings*)), *c0* = *nsEmpty*, *t* = *nsEmpty* |)

|

dtype : \bigwedge *extra-checks mn tenv tdefs decls defined-types' decls' tenvT locs*.
check-ctor-tenv (*nsAppend tenvT*(*t tenv*)) *tdefs* \wedge
(*defined-types'* = *List.set* (*List.map* (λx .
 (*case x of* (*tvs,tn,ctors*) \impl (*mk-id mn tn*))) *tdefs*)) \wedge
(*disjnt defined-types'*(*defined-types0 decls*) \wedge
(*tenvT* = *alist-to-ns* (*List.map* (λx .
 (*case x of*
 (*tvs,tn,ctors*) \impl (*tn*, (*tvs*, *Tapp* (*List.map Tvar tvs*)
 (*TC-name* (*mk-id mn tn*))))))
)) *tdefs*)) \wedge
(*decls'* = (| *defined-mods0* = ({}), *defined-types0* = *defined-types'*, *defined-exns* = ({} |))))))
 \impl
type-d extra-checks mn decls tenv (*Dtype locs tdefs*)
 decls' (| *v0* = *nsEmpty*, *c0* = (*build-ctor-tenv mn* (*nsAppend tenvT*(*t tenv*)) *tdefs*), *t* = *tenvT* |)

|

dtabbrev : \bigwedge *extra-checks mn decls tenv tvs tn t0 locs*.
check-freevars((0 :: nat)) *tvs t0* \wedge
(*check-type-names*(*t tenv*) *t0* \wedge
Lem-list.allDistinct tvs)
 \impl
type-d extra-checks mn decls tenv (*Dtabbrev locs tvs tn t0*)
 empty-decls (| *v0* = *nsEmpty*, *c0* = *nsEmpty*,
 t = (*nsSing tn* (*tvs,type-name-subst*(*t tenv*) *t0*)) |)

|

dexn : \bigwedge *extra-checks mn tenv cn ts decls decls' locs*.

$check\text{-}env\text{-}tenv\ mn\ cn\ ts \wedge$
 $(\neg (mk\text{-}id\ mn\ cn \in (defined\text{-}exns\ decls)) \wedge$
 $((\forall x \in (set\ ts). (check\text{-}type\text{-}names(t\ tenv))\ x)) \wedge$
 $(decls' = (|\ defined\text{-}mods0 = (\{\}),\ defined\text{-}types0 = (\{\}),\ defined\text{-}exns = (\{mk\text{-}id$
 $mn\ cn\})\ |))))$
 \implies
 $type\text{-}d\ extra\text{-}checks\ mn\ decls\ tenv\ (Dexn\ locs\ cn\ ts)$
 $\quad decls' (|\ v0 = nsEmpty,$
 $\quad\quad c0 = (nsSing\ cn\ [],\ List.map\ (type\text{-}name\text{-}subst(t\ tenv))\ ts,\ TypeExn$
 $(mk\text{-}id\ mn\ cn))),$
 $\quad\quad t = nsEmpty\ |)$

inductive

$type\text{-}ds :: bool \Rightarrow (modN)list \Rightarrow decls \Rightarrow type\text{-}env \Rightarrow (dec)list \Rightarrow decls \Rightarrow type\text{-}env$
 $\Rightarrow bool$ **where**

$empty : \wedge extra\text{-}checks\ mn\ tenv\ decls.$

$type\text{-}ds\ extra\text{-}checks\ mn\ decls\ tenv\ []$
 $\quad empty\text{-}decls\ (|\ v0 = nsEmpty,\ c0 = nsEmpty,\ t = nsEmpty\ |)$

|

$cons : \wedge extra\text{-}checks\ mn\ tenv\ d\ ds\ tenv1\ tenv2\ decls\ decls1\ decls2.$
 $type\text{-}d\ extra\text{-}checks\ mn\ decls\ tenv\ d\ decls1\ tenv1 \wedge$
 $type\text{-}ds\ extra\text{-}checks\ mn\ (union\text{-}decls\ decls1\ decls)\ (extend\text{-}dec\text{-}tenv\ tenv1\ tenv)\ ds$
 $decls2\ tenv2$
 \implies
 $type\text{-}ds\ extra\text{-}checks\ mn\ decls\ tenv\ (d\ \# ds)$
 $\quad (union\text{-}decls\ decls2\ decls1)\ (extend\text{-}dec\text{-}tenv\ tenv2\ tenv1)$

inductive

$type\text{-}specs :: (modN)list \Rightarrow tenv\text{-}abbrev \Rightarrow specs \Rightarrow decls \Rightarrow type\text{-}env \Rightarrow bool$
where

$empty : \wedge mn\ tenvT.$

$type\text{-}specs\ mn\ tenvT\ []$
 $\quad empty\text{-}decls\ (|\ v0 = nsEmpty,\ c0 = nsEmpty,\ t = nsEmpty\ |)$

|

$sval : \wedge mn\ tenvT\ x\ t0\ specs\ tenv\ fvs\ decls\ subst.$
 $check\text{-}freevars((\ 0 :: nat))\ fvs\ t0 \wedge$
 $(check\text{-}type\text{-}names\ tenvT\ t0 \wedge$
 $(type\text{-}specs\ mn\ tenvT\ specs\ decls\ tenv \wedge$
 $(subst = map\text{-}of\ (Lem\text{-}list\text{-}extra.zipSameLength\ fvs\ (List.map\ Tvar\text{-}db\ (genlist\ (\lambda$
 $x . x)\ (List.length\ fvs))))))$
 \implies

$type\text{-}specs\ mn\ tenvT\ (Sval\ x\ t0\ \# \ specs)$
 $decls$
 $(extend\text{-}dec\text{-}tenv\ tenv$
 $(\mid v0 = (nsSing\ x\ (List.length\ fvs,\ type\text{-}subst\ subst\ (type\text{-}name\text{-}subst\ tenvT\ t0))),$
 $c0 = nsEmpty,$
 $t = nsEmpty\ \mid))$

|

$stype : \bigwedge mn\ tenvT\ tenv\ td\ specs\ decls'\ decls\ tenvT'$
 $(tenvT' = alist\text{-}to\text{-}ns\ (List.map\ (\lambda x .$
 $(case\ x\ of$
 $(tvs,tn,ctors) ==> (tn,\ (tvs,\ Tapp\ (List.map\ Tvar\ tvs$
 $(TC\text{-}name\ (mk\text{-}id\ mn\ tn))))$
 $))\ td)) \wedge$
 $(check\text{-}ctor\text{-}tenv\ (nsAppend\ tenvT'\ tenvT)\ td \wedge$
 $(type\text{-}specs\ mn\ (nsAppend\ tenvT'\ tenvT)\ specs\ decls\ tenv \wedge$
 $(decls' = (\mid defined\text{-}mods0 = (\{\}),$
 $defined\text{-}types0 = (List.set\ (List.map\ (\lambda x .$
 $(case\ x\ of\ (tvs,tn,ctors) ==> (mk\text{-}id\ mn\ tn)\ \mid))\ td),$
 $defined\text{-}exns = (\{\})\ \mid)))$

==>

$type\text{-}specs\ mn\ tenvT\ (Stype\ td\ \# \ specs)$
 $(union\text{-}decls\ decls\ decls')$
 $(extend\text{-}dec\text{-}tenv\ tenv$
 $(\mid v0 = nsEmpty,$
 $c0 = (build\text{-}ctor\text{-}tenv\ mn\ (nsAppend\ tenvT'\ tenvT)\ td),$
 $t = tenvT'\ \mid))$

|

$stabbrev : \bigwedge mn\ tenvT\ tenvT'\ tvs\ tn\ t0\ specs\ decls\ tenv.$
 $Lem\text{-}list.allDistinct\ tvs \wedge$
 $(check\text{-}freevars((\ 0 :: nat))\ tvs\ t0 \wedge$
 $(check\text{-}type\text{-}names\ tenvT\ t0 \wedge$
 $((tenvT' = nsSing\ tn\ (tvs,type\text{-}name\text{-}subst\ tenvT\ t0)) \wedge$
 $type\text{-}specs\ mn\ (nsAppend\ tenvT'\ tenvT)\ specs\ decls\ tenv)))$
 $==>$
 $type\text{-}specs\ mn\ tenvT\ (Stabbrev\ tvs\ tn\ t0\ \# \ specs)$
 $decls\ (extend\text{-}dec\text{-}tenv\ tenv\ (\mid v0 = nsEmpty,\ c0 = nsEmpty,\ t = tenvT'\ \mid))$

|

$sexn : \bigwedge mn\ tenvT\ tenv\ cn\ ts\ specs\ decls.$
 $check\text{-}exn\text{-}tenv\ mn\ cn\ ts \wedge$
 $(type\text{-}specs\ mn\ tenvT\ specs\ decls\ tenv \wedge$
 $((\forall x \in (set\ ts). (check\text{-}type\text{-}names\ tenvT)\ x)))$
 $==>$
 $type\text{-}specs\ mn\ tenvT\ (Sexn\ cn\ ts\ \# \ specs)$

```

    (union-decls decls (| defined-mods0 = ({}), defined-types0 = ({}), defined-exns =
    ({mk-id mn cn} |))
    (extend-dec-tenv tenv
    (| v0 = nsEmpty,
    c0 = (nsSing cn (|, List.map (type-name-subst tenvT) ts, TypeExn (mk-id
    mn cn))),
    t = nsEmpty |))

```

|

```

stype-opq :  $\bigwedge$  mn tenvT tenv tn specs tvs decls tenvT'.
Lem-list.allDistinct tvs  $\wedge$ 
((tenvT' = nsSing tn (tvs, Tapp (List.map Tvar tvs) (TC-name (mk-id mn tn))))
 $\wedge$ 
type-specs mn (nsAppend tenvT' tenvT) specs decls tenv)
==>
type-specs mn tenvT (Stype-opq tvs tn # specs)
(union-decls decls (| defined-mods0 = ({}), defined-types0 = ({mk-id mn tn}),
defined-exns = ({} |))
(extend-dec-tenv tenv (| v0 = nsEmpty, c0 = nsEmpty, t = tenvT' |))

```

— val weak-decls : decls \rightarrow decls \rightarrow bool

definition weak-decls :: decls \Rightarrow decls \Rightarrow bool **where**

```

    weak-decls decls-impl decls-spec = (
    ((defined-mods0 decls-impl) = (defined-mods0 decls-spec))  $\wedge$ 
    (((defined-types0 decls-spec)  $\subseteq$  (defined-types0 decls-impl))  $\wedge$ 
    ((defined-exns decls-spec)  $\subseteq$  (defined-exns decls-impl)))

```

— val weak-tenvT : id modN typeN \rightarrow (list tvarN * t) \rightarrow (list tvarN * t) \rightarrow bool

fun weak-tenvT :: ((modN),(typeN))id0 \Rightarrow (string)list*t \Rightarrow (string)list*t \Rightarrow bool **where**

```

    weak-tenvT n (tvs-spec, t-spec) (tvs-impl, t-impl) = (
    (
    — For simplicity, we reject matches that differ only by renaming of bound type
    variablestvs-spec = tvs-impl)  $\wedge$ 
    ((t-spec = t-impl)  $\vee$ 
    (
    — The specified type is opaquet-spec = Tapp (List.map Tvar tvs-spec) (TC-name
    n))))

```

definition tscheme-inst2 :: 'a \Rightarrow nat*t \Rightarrow nat*t \Rightarrow bool **where**

```

    tscheme-inst2 - ts1 ts2 = ( tscheme-inst ts1 ts2 )

```

— val weak-tenv : type-env \rightarrow type-env \rightarrow bool

definition weak-tenv :: type-env \Rightarrow type-env \Rightarrow bool **where**

$weak\text{-}tenv\ tenv\text{-}impl\ tenv\text{-}spec = ($
 $nsSub\ tscheme\text{-}inst2(v0\ tenv\text{-}spec)(v0\ tenv\text{-}impl) \wedge$
 $(nsSub\ (\lambda x .$
 $(case\ x\ of\ - \Rightarrow \lambda x\ y . x = y))(c0\ tenv\text{-}spec)(c0\ tenv\text{-}impl) \wedge$
 $nsSub\ weak\text{-}tenvT(t\ tenv\text{-}spec)(t\ tenv\text{-}impl))$

inductive

$check\text{-}signature :: (modN)list \Rightarrow tenv\text{-}abbrev \Rightarrow decls \Rightarrow type\text{-}env \Rightarrow (specs)option$
 $\Rightarrow decls \Rightarrow type\text{-}env \Rightarrow bool$ **where**

$none : \bigwedge mn\ tenvT\ decls\ tenv.$

$check\text{-}signature\ mn\ tenvT\ decls\ tenv\ None\ decls\ tenv$

|

$some : \bigwedge mn\ specs\ tenv\text{-}impl\ tenv\text{-}spec\ decls\text{-}impl\ decls\text{-}spec\ tenvT.$

$weak\text{-}tenv\ tenv\text{-}impl\ tenv\text{-}spec \wedge$
 $(weak\text{-}decls\ decls\text{-}impl\ decls\text{-}spec \wedge$
 $type\text{-}specs\ mn\ tenvT\ specs\ decls\text{-}spec\ tenv\text{-}spec)$

\Rightarrow

$check\text{-}signature\ mn\ tenvT\ decls\text{-}impl\ tenv\text{-}impl\ (Some\ specs)\ decls\text{-}spec\ tenv\text{-}spec$

definition $tenvLift :: string \Rightarrow type\text{-}env \Rightarrow type\text{-}env$ **where**

$tenvLift\ mn\ tenv = ($
 $(\mid v0 = (nsLift\ mn(v0\ tenv)),\ c0 = (nsLift\ mn(c0\ tenv)),\ t = (nsLift\ mn(t$
 $tenv))\ \mid))$

inductive

$type\text{-}top :: bool \Rightarrow decls \Rightarrow type\text{-}env \Rightarrow top0 \Rightarrow decls \Rightarrow type\text{-}env \Rightarrow bool$ **where**

$tdec : \bigwedge extra\text{-}checks\ tenv\ d\ tenv'\ decls\ decls'.$

$type\text{-}d\ extra\text{-}checks\ []\ decls\ tenv\ d\ decls'\ tenv'$

\Rightarrow

$type\text{-}top\ extra\text{-}checks\ decls\ tenv\ (Tdec\ d)\ decls'\ tenv'$

|

$tmod : \bigwedge extra\text{-}checks\ tenv\ mn\ spec\ ds\ tenv\text{-}impl\ tenv\text{-}spec\ decls\ decls\text{-}impl\ de-$
 $cls\text{-}spec.$

$\neg ([mn] \in (defined\text{-}mods0\ decls)) \wedge$

$(type\text{-}ds\ extra\text{-}checks\ [mn]\ decls\ tenv\ ds\ decls\text{-}impl\ tenv\text{-}impl \wedge$

$check\text{-}signature\ [mn](t\ tenv)\ decls\text{-}impl\ tenv\text{-}impl\ spec\ decls\text{-}spec\ tenv\text{-}spec)$

\Rightarrow

$type\text{-}top\ extra\text{-}checks\ decls\ tenv\ (Tmod\ mn\ spec\ ds)$

$(union\text{-}decls\ (\mid defined\text{-}mods0 = (\{[mn]\}),\ defined\text{-}types0 = (\{\}),\ defined\text{-}exns =$
 $(\{\})\ \mid)\ decls\text{-}spec)$

(tenvLift mn tenv-spec)

inductive

type-prog :: *bool* ⇒ *decls* ⇒ *type-env* ⇒ (*top0*)*list* ⇒ *decls* ⇒ *type-env* ⇒ *bool*

where

empty : ∧ *extra-checks* *tenv* *decls*.

type-prog *extra-checks* *decls* *tenv* [] *empty-decls* (| *v0* = *nsEmpty*, *c0* = *nsEmpty*, *t*
= *nsEmpty* |)

|

cons : ∧ *extra-checks* *tenv* *top0* *tops* *tenv1* *tenv2* *decls* *decls1* *decls2*.

type-top *extra-checks* *decls* *tenv* *top0* *decls1* *tenv1* ∧

type-prog *extra-checks* (*union-decls* *decls1* *decls*) (*extend-dec-tenv* *tenv1* *tenv*) *tops*
decls2 *tenv2*

==>

type-prog *extra-checks* *decls* *tenv* (*top0* # *tops*)

(*union-decls* *decls2* *decls1*) (*extend-dec-tenv* *tenv2* *tenv1*)

end

Chapter 19

Generated by Lem from *semantics/typeSystem.lem.*

theory *TypeSystemAuxiliary*

imports

Main
HOL-Library.Datatype-Records
LEM.Lem-pervasives-extra
Lib
Namespace
Ast
SemanticPrimitives
TypeSystem

begin

— *****
—
— *Termination Proofs*
—
— *****

termination *check-freevars* *<proof>*

termination *type-subst* *<proof>*

termination *deBruijn-inc* *<proof>*

termination *deBruijn-subst* *<proof>*

termination *check-type-names* *<proof>*

termination *type-name-subst* *<proof>*

termination *is-value* \langle *proof* \rangle

end

Part II

Proofs ported from HOL4

Chapter 20

Adaptations for Isabelle

```
theory Semantic-Extras
imports
  generated/CakeML/BigStep
  generated/CakeML/SemanticPrimitivesAuxiliary
  generated/CakeML/AstAuxiliary
  generated/CakeML/Evaluate
  HOL-Library.Simps-Case-Conv
begin

type-synonym exp = exp0

hide-const (open) sem-env.v

code-pred
  (modes: evaluate: i ⇒ i ⇒ i ⇒ i ⇒ o ⇒ bool as compute
   and evaluate-list: i ⇒ i ⇒ i ⇒ i ⇒ o ⇒ bool
   and evaluate-match: i ⇒ i ⇒ i ⇒ i ⇒ i ⇒ i ⇒ o ⇒ bool) evaluate <proof>

code-pred (modes: i ⇒ i ⇒ i ⇒ i ⇒ i ⇒ o ⇒ bool) evaluate-dec <proof>
code-pred (modes: i ⇒ i ⇒ i ⇒ i ⇒ i ⇒ o ⇒ bool) evaluate-decs <proof>
code-pred (modes: i ⇒ i ⇒ i ⇒ i ⇒ o ⇒ bool) evaluate-top <proof>
code-pred (modes: i ⇒ i ⇒ i ⇒ i ⇒ o ⇒ bool as compute-prog) evaluate-prog
  <proof>

termination pmatch-list <proof>
termination do-eq-list <proof>

lemma all-distinct-alt-def: allDistinct = distinct
  <proof>

lemma find-recfun-someD:
  assumes find-recfun n funs = Some (x, e)
  shows  $(n, x, e) \in \text{set funs}$ 
  <proof>
```

lemma *find-recfun-alt-def[simp]*: *find-recfun n funs = map-of funs n*
⟨*proof*⟩

lemma *size-list-rev[simp]*: *size-list f (rev xs) = size-list f xs*
⟨*proof*⟩

lemma *do-if-cases*:

obtains

(*none*) *do-if v e1 e2 = None*
| (*true*) *do-if v e1 e2 = Some e1*
| (*false*) *do-if v e1 e2 = Some e2*

⟨*proof*⟩

case-of-simps *do-log-alt-def*: *do-log.simps*

case-of-simps *do-con-check-alt-def*: *do-con-check.simps*

case-of-simps *list-result-alt-def*: *list-result.simps*

context begin

private fun-cases *do-logE*: *do-log op v e = res*

lemma *do-log-exp*: *do-log op v e = Some (Exp e') ⟹ e = e'*
⟨*proof*⟩

end

lemma *c-of-merge[simp]*: *c (extend-dec-env env2 env1) = nsAppend (c env2) (c env1)*
⟨*proof*⟩

lemma *v-of-merge[simp]*: *sem-env.v (extend-dec-env env2 env1) = nsAppend (sem-env.v env2) (sem-env.v env1)*
⟨*proof*⟩

lemma *nsEmpty-nsAppend[simp]*: *nsAppend e nsEmpty = e nsAppend nsEmpty e*
= *e*
⟨*proof*⟩

lemma *do-log-cases*:

obtains

(*none*) *do-log op v e = None*
| (*val*) *v' where do-log op v e = Some (Val v')*
| (*exp*) *do-log op v e = Some (Exp e)*

⟨*proof*⟩

context begin

private fun-cases *do-opappE*: *do-opapp vs = Some res*

lemma *do-opapp-cases*:
assumes *do-opapp vs = Some (env', exp')*
obtains *(closure) env n v0*
 where *vs = [Closure env n exp', v0]*
 env' = (env (| sem-env.v := nsBind n v0 (sem-env.v env) |))
| *(recclosure) env funs name n v0*
 where *vs = [Recclosure env funs name, v0]*
 and *allDistinct (map (λ(f, -, -). f) funs)*
 and *find-recfun name funs = Some (n, exp')*
 and *env' = (env (| sem-env.v := nsBind n v0 (build-rec-env funs env*
(sem-env.v env)) |))
<proof>

end

lemmas *evaluate-induct =*
evaluate-match-evaluate-list-evaluate.inducts[split-format(complete)]

lemma *evaluate-clock-mono*:
evaluate-match ck env s v pes v' (s', r1) ⇒ clock s' ≤ clock s
evaluate-list ck env s es (s', r2) ⇒ clock s' ≤ clock s
evaluate ck env s e (s', r3) ⇒ clock s' ≤ clock s
<proof>

lemma *evaluate-list-singleton-valE*:
assumes *evaluate-list ck env s [e] (s', Rval vs)*
obtains *v where vs = [v] evaluate ck env s e (s', Rval v)*
<proof>

lemma *evaluate-list-singleton-errD*:
assumes *evaluate-list ck env s [e] (s', Rerr err)*
shows *evaluate ck env s e (s', Rerr err)*
<proof>

lemma *evaluate-list-singleton-cases*:
assumes *evaluate-list ck env s [e] res*
obtains *(val) s' v where res = (s', Rval [v]) evaluate ck env s e (s', Rval v)*
| *(err) s' err where res = (s', Rerr err) evaluate ck env s e (s', Rerr err)*
<proof>

lemma *evaluate-list-singletonI*:
assumes *evaluate ck env s e (s', r)*
shows *evaluate-list ck env s [e] (s', list-result r)*
<proof>

lemma *prod-result-cases*:
obtains *(val) s v where r = (s, Rval v)*
| *(err) s err where r = (s, Rerr err)*

<proof>

lemma *do-con-check-build-conv*: *do-con-check (c env) cn (length es) ==> build-conv (c env) cn vs ≠ None*
<proof>

fun *match-result* :: *(v)sem-env => 'ffi state => v =>(pat*exp)list => v => (exp × (char list × v) list, v)result where*
match-result - - - [] err-v = Rerr (Rraise err-v) |
match-result env s v0 ((p, e) # pes) err-v =
(if Lem-list.allDistinct (pat-bindings p []) then
(case pmatch (sem-env.c env) (refs s) p v0 [] of
Match env' => Rval (e, env') |
No-match => match-result env s v0 pes err-v |
Match-type-error => Rerr (Rabort Rtype-error))
else
Rerr (Rabort Rtype-error))

case-of-simps *match-result-alt-def*: *match-result.simps*

lemma *match-result-sound*:

case match-result env s v0 pes err-v of
Rerr err => evaluate-match ck env s v0 pes err-v (s, Rerr err)
| Rval (e, env') =>
∃ bv.
evaluate ck (env [] sem-env.v := nsAppend (alist-to-ns env')(sem-env.v env)
) s e bv ->
evaluate-match ck env s v0 pes err-v bv
<proof>

lemma *match-result-sound-val*:

assumes *match-result env s v0 pes err-v = Rval (e, env')*
assumes *evaluate ck (env [] sem-env.v := nsAppend (alist-to-ns env')(sem-env.v env) [])* *s e bv*
shows *evaluate-match ck env s v0 pes err-v bv*
<proof>

lemma *match-result-sound-err*:

assumes *match-result env s v0 pes err-v = Rerr err*
shows *evaluate-match ck env s v0 pes err-v (s, Rerr err)*
<proof>

lemma *match-result-correct*:

assumes *evaluate-match ck env s v0 pes err-v (s', bv)*
shows *case bv of*
Rval v =>
∃ e env'. match-result env s v0 pes err-v = Rval (e, env') ∧ evaluate ck
(env [] sem-env.v := nsAppend (alist-to-ns env')(sem-env.v env) []) s e (s', Rval
v)

$| Rerr\ err \Rightarrow$
 $(match\ result\ env\ s\ v0\ pes\ err\ v = Rerr\ err) \vee$
 $(\exists e\ env'.\ match\ result\ env\ s\ v0\ pes\ err\ v = Rval\ (e,\ env') \wedge evaluate\ ck$
 $(env\ ()\ sem\ env.v := nsAppend\ (alist\ to\ ns\ env')\ (sem\ env.v\ env)\ ())\ s\ e\ (s',\ Rerr$
 $err))$
 $\langle proof \rangle$

end

Chapter 21

Functional big-step semantics

21.1 Termination proof

```
theory Evaluate-Termination
imports Semantic-Extras
begin
```

```
case-of-simps fix-clock-alt-def: fix-clock.simps
```

```
primrec size-exp' :: exp ⇒ nat where
size-exp' (Raise e) = Suc (size-exp' e) |
[simp del]: size-exp' (Handle e pes) = Suc (size-exp' e + size-list (λ(p, es). Suc
(size p + es)) (map (map-prod id size-exp') pes)) |
size-exp' (Con - es) = Suc (size-list id (map size-exp' es)) |
size-exp' (Fun - e) = Suc (size-exp' e) |
size-exp' (App - es) = Suc (size-list id (map size-exp' es)) |
size-exp' (Log - e f) = Suc (size-exp' e + size-exp' f) |
size-exp' (If e f g) = Suc (size-exp' e + size-exp' f + size-exp' g) |
[simp del]: size-exp' (Mat e pes) = Suc (size-exp' e + size-list (λ(p, es). Suc (size
p + es)) (map (map-prod id size-exp') pes)) |
size-exp' (Let - e f) = Suc (size-exp' e + size-exp' f) |
[simp del]: size-exp' (Letretec defs e) = Suc (size-exp' e + size-list (λ(-, -, es). Suc
(Suc es)) (map (map-prod id (map-prod id size-exp')) defs)) |
size-exp' (Tannot e -) = Suc (size-exp' e) |
size-exp' (Lannot e -) = Suc (size-exp' e) |
size-exp' (Lit -) = 0 |
size-exp' (Var -) = 0
```

```
lemma [simp]:
size-exp' (Mat e pes) = Suc (size-exp' e + size-list (size-prod size size-exp') pes)
⟨proof⟩
```

```
lemma [simp]:
size-exp' (Handle e pes) = Suc (size-exp' e + size-list (size-prod size size-exp')
pes)
```

<proof>

lemma *[simp]*:

$size-exp' (Letrech\ defs\ e) = Suc\ (size-exp'\ e + size-list\ (size-prod\ (\lambda-. 0)\ (size-prod\ (\lambda-. 0)\ size-exp'))\ defs)$

<proof>

context begin

private definition *fun-evaluate-relation* **where**

*fun-evaluate-relation = inv-image (less-than <*lex*> less-than) ($\lambda x.$*

case x of

Inr (s, -, es) \Rightarrow (clock s, size-list size-exp' es)

| Inl (s,-,pes,-) \Rightarrow (clock s, size-list (size-prod size size-exp') pes))

termination *fun-evaluate*

<proof>

end

end

21.2 Simplifying the definition

theory *Evaluate-Clock*

imports *Evaluate-Termination*

begin

hide-const (open) *sem-env.v*

lemma *fix-clock*:

$fix-clock\ s1\ (s2, x) = (s, x) \implies clock\ s \leq clock\ s1$

$fix-clock\ s1\ (s2, x) = (s, x) \implies clock\ s \leq clock\ s2$

<proof>

lemma *dec-clock[simp]*: $clock\ (dec-clock\ st) = clock\ st - 1$

<proof>

context begin

private lemma *fun-evaluate-clock0*:

$clock\ (fst\ (fun-evaluate-match\ s1\ env\ v\ p\ v')) \leq clock\ s1$

$clock\ (fst\ (fun-evaluate\ s1\ env\ e)) \leq clock\ s1$

<proof>

lemma *fun-evaluate-clock*:

$fun-evaluate-match\ s1\ env\ v\ p\ v' = (s2, r) \implies clock\ s2 \leq clock\ s1$

$fun-evaluate\ s1\ env\ e = (s2, r) \implies clock\ s2 \leq clock\ s1$

<proof>

end

lemma *fix-clock-evaluate*[simp]:

fix-clock s1 (fun-evaluate s1 env e) = fun-evaluate s1 env e
⟨proof⟩

declare *fun-evaluate.simps*[simp del]

declare *fun-evaluate-match.simps*[simp del]

lemmas *fun-evaluate-simps*[simp] =

fun-evaluate.simps[unfolded *fix-clock-evaluate*]

fun-evaluate-match.simps[unfolded *fix-clock-evaluate*]

lemmas *fun-evaluate-induct* =

fun-evaluate-match-fun-evaluate.induct[unfolded *fix-clock-evaluate*]

lemma *fun-evaluate-length*:

fun-evaluate-match s env v pes err-v = (s', res) ⇒ (case res of Rval vs ⇒ length vs = 1 | - ⇒ True)

fun-evaluate s env es = (s', res) ⇒ (case res of Rval vs ⇒ length vs = length es | - ⇒ True)

⟨proof⟩

lemma *fun-evaluate-matchE*:

assumes *fun-evaluate-match s env v pes err-v = (s', Rval vs)*

obtains *v where vs = [v]*

⟨proof⟩

end

21.3 Simplifying the definition: no mutual recursion

theory *Evaluate-Single*

imports *Evaluate-Clock*

begin

fun *evaluate-list* ::

('ffi state ⇒ exp ⇒ 'ffi state(v, v) result) ⇒*

'ffi state ⇒ exp list ⇒ 'ffi state(v list, v) result where*

Nil:

evaluate-list eval s [] = (s, Rval []) |

Cons:

evaluate-list eval s (e#es) =

(case fix-clock s (eval s e) of

$$\begin{aligned}
& (s', Rval v) \Rightarrow \\
& \quad (case\ evaluate-list\ eval\ s'\ es\ of \\
& \quad \quad (s'', Rval vs) \Rightarrow (s'', Rval (v\#\vs)) \\
& \quad \quad | res \Rightarrow res) \\
& | (s', Rerr err) \Rightarrow (s', Rerr err)
\end{aligned}$$

lemma *evaluate-list-cong[fundef-cong]*:

assumes $\bigwedge e\ s.\ e \in set\ es1 \implies clock\ s \leq clock\ s1 \implies eval1\ s\ e = eval2\ s\ e\ s1 = s2\ es1 = es2$

shows *evaluate-list eval1 s1 es1 = evaluate-list eval2 s2 es2*

<proof>

function (*sequential*)

evaluate :: *v sem-env* \Rightarrow *'ffi state* \Rightarrow *exp* \Rightarrow *'ffi state*(v,v)* **result where**

Lit:

evaluate env s (Lit l) = (s, Rval (Litv l)) |

Raise:

evaluate env s (Raise e) =
(case evaluate env s e of
(s', Rval v) \Rightarrow (s', Rerr (Rraise (v)))
| res \Rightarrow res) |

Handle:

evaluate env s (Handle e pes) =
(case evaluate env s e of
(s', Rerr (Rraise v)) \Rightarrow
(case match-result env s' v pes v of
(Rval (e', env')) \Rightarrow
evaluate (env (| sem-env.v := nsAppend (alist-to-ns env') (sem-env.v env)
)) s' e'
| (Rerr err) \Rightarrow (s', Rerr err))
| res \Rightarrow res) |

Con:

evaluate env s (Con cn es) =
(if do-con-check (c env) cn (length es) then
(case evaluate-list (evaluate env) s (rev es) of
(s', Rval vs) \Rightarrow
(case build-conv (c env) cn (rev vs) of
Some v \Rightarrow (s', Rval v)
| None \Rightarrow (s', Rerr (Rabort Rtype-error)))
| (s', Rerr err) \Rightarrow (s', Rerr err))
else (s, Rerr (Rabort Rtype-error))) |

Var:

evaluate env s (Var n) =
(case nsLookup (sem-env.v env) n of

$Some\ v \Rightarrow (s, Rval\ v)$
 $| None \Rightarrow (s, Rerr\ (Rabort\ Rtype-error)) |$

Fun:

$evaluate\ env\ s\ (Fun\ n\ e) = (s, Rval\ (Closure\ env\ n\ e)) |$

App:

$evaluate\ env\ s\ (App\ op0\ es) =$
 $(case\ evaluate-list\ (evaluate\ env)\ s\ (rev\ es)\ of$
 $(s', Rval\ vs) \Rightarrow$
 $(if\ op0 = Opapp\ then$
 $(case\ do-opapp\ (rev\ vs)\ of$
 $Some\ (env', e) \Rightarrow$
 $(if\ (clock\ s' = 0)\ then$
 $(s', Rerr\ (Rabort\ Rtimeout-error))$
 $else$
 $evaluate\ env'\ (dec-clock\ s')\ e)$
 $| None \Rightarrow (s', Rerr\ (Rabort\ Rtype-error))$)
 $else$
 $(case\ do-app\ (refs\ s', ffi\ s')\ op0\ (rev\ vs)\ of$
 $Some\ ((refs', ffi'), res) \Rightarrow (s'\ (refs:=refs', ffi:=ffi'), res)$
 $| None \Rightarrow (s', Rerr\ (Rabort\ Rtype-error))$)
 $| (s', Rerr\ err) \Rightarrow (s', Rerr\ err) |$

Log:

$evaluate\ env\ s\ (Log\ op0\ e1\ e2) =$
 $(case\ evaluate\ env\ s\ e1\ of$
 $(s', Rval\ v) \Rightarrow$
 $(case\ do-log\ op0\ v\ e2\ of$
 $Some\ (Exp\ e') \Rightarrow evaluate\ env\ s'\ e'$
 $| Some\ (Val\ bv) \Rightarrow (s', Rval\ bv)$
 $| None \Rightarrow (s', Rerr\ (Rabort\ Rtype-error))$)
 $| res \Rightarrow res) |$

If:

$evaluate\ env\ s\ (If\ e1\ e2\ e3) =$
 $(case\ evaluate\ env\ s\ e1\ of$
 $(s', Rval\ v) \Rightarrow$
 $(case\ do-if\ v\ e2\ e3\ of$
 $Some\ e' \Rightarrow evaluate\ env\ s'\ e'$
 $| None \Rightarrow (s', Rerr\ (Rabort\ Rtype-error))$)
 $| res \Rightarrow res) |$

Mat:

$evaluate\ env\ s\ (Mat\ e\ pes) =$
 $(case\ evaluate\ env\ s\ e\ of$
 $(s', Rval\ v) \Rightarrow$
 $(case\ match-result\ env\ s'\ v\ pes\ Bindv\ of$
 $Rval\ (e', env') \Rightarrow$

$$\text{evaluate } (\text{env } \langle \text{sem-env.v} := \text{nsAppend } (\text{alist-to-ns } \text{env}') (\text{sem-env.v } \text{env}) \rangle) \text{ s' e'}$$

$$| \text{Rerr } \text{err} \Rightarrow (\text{s}', \text{Rerr } \text{err})$$

$$| \text{res} \Rightarrow \text{res} |$$

Let:

$$\text{evaluate } \text{env } \text{s } (\text{Let } \text{n } \text{e1 } \text{e2}) =$$

$$\langle \text{case } \text{evaluate } \text{env } \text{s } \text{e1} \text{ of}$$

$$(\text{s}', \text{Rval } \text{v}) \Rightarrow$$

$$\text{evaluate } (\text{env } \langle \text{sem-env.v} := (\text{nsOptBind } \text{n } \text{v} (\text{sem-env.v } \text{env})) \rangle) \text{ s' e2}$$

$$| \text{res} \Rightarrow \text{res} |$$

Letrec:

$$\text{evaluate } \text{env } \text{s } (\text{Letrec } \text{funs } \text{e}) =$$

$$\langle \text{if } \text{distinct } (\text{List.map } (\lambda x. (\text{case } \text{x of } (\text{x,y,z}) \Rightarrow \text{x})) \text{funs}) \text{ then}$$

$$\text{evaluate } (\text{env } \langle \text{sem-env.v} := (\text{build-rec-env } \text{funs } \text{env} (\text{sem-env.v } \text{env})) \rangle) \text{ s e}$$

$$\text{else}$$

$$(\text{s}, \text{Rerr } (\text{Rabort } \text{Rtype-error})) |$$

Tannot:

$$\text{evaluate } \text{env } \text{s } (\text{Tannot } \text{e } \text{t0}) = \text{evaluate } \text{env } \text{s } \text{e} |$$

Lannot:

$$\text{evaluate } \text{env } \text{s } (\text{Lannot } \text{e } \text{l}) = \text{evaluate } \text{env } \text{s } \text{e}$$

$$\langle \text{proof} \rangle$$

context

notes *do-app.simps[simp del]*

begin

lemma *match-result-elim:*

assumes *match-result* $\text{env } \text{s } \text{v0 } \text{pes } \text{err-v} = \text{Rval } (\text{e}, \text{env}')$
shows $\exists \text{pat. } (\text{pat}, \text{e}) \in \text{set } \text{pes}$
 $\langle \text{proof} \rangle$ **lemma** *evaluate-list-clock-monotone:* $\text{clock } (\text{fst } (\text{evaluate-list } \text{eval } \text{s } \text{es}))$
 $\leq \text{clock } \text{s}$
 $\langle \text{proof} \rangle$

lemma *i-hate-words-helper:*

$i \leq (j - k :: \text{nat}) \implies i \leq j$
 $\langle \text{proof} \rangle$

thm *i-hate-words-helper* [THEN *le-trans*, *no-vars*]

private lemma *evaluate-clock-monotone:*

$\langle \text{clock } (\text{fst } (\text{evaluate } \text{env } \text{s } \text{e})) \leq \text{clock } \text{s} \rangle$
if $\langle \text{evaluate-dom } (\text{env}, \text{s}, \text{e}) \rangle$
 $\langle \text{proof} \rangle$ **definition** *fun-evaluate-single-relation* **where**
fun-evaluate-single-relation = *inv-image* (*less-than* $\langle * \text{lex} * \rangle$ *less-than*) $(\lambda x.$
 $\text{case } \text{x of } (\text{-}, \text{s}, \text{e}) \Rightarrow (\text{clock } \text{s}, \text{size-exp' } \text{e}))$

private lemma *pat-lem-less-size*:

$(pat, e) \in set\ pes \implies size\text{-}exp' e < (size\text{-}list (size\text{-}prod\ size\ size\text{-}exp') pes)$
 $\langle proof \rangle$ **lemma** *elem-less-size*: $e \in set\ es \implies size\text{-}exp' e \leq size\text{-}list\ size\text{-}exp' es$
 $\langle proof \rangle$

lemma *evaluate-total*: All evaluate-dom

$\langle proof \rangle$

termination *evaluate* $\langle proof \rangle$

lemma *evaluate-clock-monotone'*: $evaluate\ eval\ s\ e = (s', r) \implies clock\ s' \leq clock\ s$

$\langle proof \rangle$

fun *evaluate-list'* :: $v\ sem\text{-}env \Rightarrow 'ffi\ state \Rightarrow exp\ list \Rightarrow 'ffi\ state*(v\ list, v)\ result$
where

$evaluate\text{-}list'\ env\ s\ [] = (s, Rval\ [])$ |

$evaluate\text{-}list'\ env\ s\ (e\#\ es) =$

(case *evaluate env s e* of

$(s', Rval\ v) \Rightarrow$

(case *evaluate-list' env s' es* of

$(s'', Rval\ vs) \Rightarrow (s'', Rval\ (v\#\ vs))$

| *res* $\Rightarrow res$)

| $(s', Rerr\ err) \Rightarrow (s', Rerr\ err)$)

lemma *fix-clock-evaluate[simp]*: $fix\text{-}clock\ s\ (evaluate\ eval\ s\ e) = evaluate\ eval\ s\ e$

$\langle proof \rangle$

lemma *evaluate-list-eq[simp]*: $evaluate\text{-}list\ (evaluate\ env) = evaluate\text{-}list'\ env$

$\langle proof \rangle$

declare *evaluate-list.simps[simp del]*

lemma *fun-evaluate-equiv*:

$fun\text{-}evaluate\text{-}match\ s\ env\ v\ pes\ err\text{-}v = (case\ match\text{-}result\ env\ s\ v\ pes\ err\text{-}v\ of$

$Rerr\ err \Rightarrow (s, Rerr\ err)$

| $Rval\ (e, env') \Rightarrow evaluate\text{-}list\ (evaluate\ (env\ []\ sem\text{-}env.v := (nsAppend\ (alist\text{-}to\text{-}ns\ env')\ (sem\text{-}env.v\ env))\ []))\ s\ [e]$)

$fun\text{-}evaluate\ s\ env\ es = evaluate\text{-}list\ (evaluate\ env)\ s\ es$

$\langle proof \rangle$

corollary *fun-evaluate-equiv'*:

$evaluate\ env\ s\ e = map\text{-}prod\ id\ (map\text{-}result\ hd\ id)\ (fun\text{-}evaluate\ s\ env\ [e])$

$\langle proof \rangle$

end

end

Chapter 22

Relational big-step semantics

22.1 Determinism

```
theory Big-Step-Determ
imports Semantic-Extras
begin
```

```
lemma evaluate-determ:
```

```
  evaluate-match ck env s v pes v' r1a  $\implies$  evaluate-match ck env s v pes v' r1b  $\implies$ 
  r1a = r1b
```

```
  evaluate-list ck env s es r2a  $\implies$  evaluate-list ck env s es r2b  $\implies$  r2a = r2b
```

```
  evaluate ck env s e r3a  $\implies$  evaluate ck env s e r3b  $\implies$  r3a = r3b
```

```
<proof>
```

```
end
```

22.2 Totality

```
theory Big-Step-Total
imports Semantic-Extras
begin
```

```
context begin
```

```
private lemma evaluate-list-total0:
```

```
  fixes s :: 'a state
```

```
  assumes  $\bigwedge e \text{ env } s'::'a \text{ state. } e \in \text{set } es \implies \text{clock } s' \leq \text{clock } s \implies \exists s'' r. \text{evaluate}$ 
  True env s' e (s'', r)
```

```
  shows  $\exists s' r. \text{evaluate-list True env s es (s', r)}$ 
```

```
<proof> lemma evaluate-match-total0:
```

```
  fixes s :: 'a state
```

```
  assumes  $\bigwedge p e \text{ env } s'::'a \text{ state. } (p, e) \in \text{set } pes \implies \text{clock } s' \leq \text{clock } s \implies \exists s'' r. \text{evaluate}$ 
  True env s' e (s'', r)
```

```
  shows  $\exists s' r. \text{evaluate-match True env s v pes v' (s', r)}$ 
```

```
<proof>
```

lemma *evaluate-total*: $\exists s' r. \text{evaluate True env s e (s', r)}$
 <proof>

end

The following are pretty much the same proofs as above, but without additional assumptions; instead using *evaluate-total* directly.

lemma *evaluate-list-total*: $\exists s' r. \text{evaluate-list True env s es (s', r)}$
 <proof>

lemma *evaluate-match-total*: $\exists s' r. \text{evaluate-match True env s v pes v' (s', r)}$
 <proof>

end

22.3 Equivalence to the functional semantics

theory *Big-Step-Fun-Equiv*

imports

Big-Step-Determ

Big-Step-Total

Evaluate-Clock

begin

locale *eval* =

fixes

eval :: $v \text{ sem-env} \Rightarrow \text{exp} \Rightarrow 'a \text{ state} \Rightarrow 'a \text{ state} \times (v, v) \text{ result}$ **and**

eval-list :: $v \text{ sem-env} \Rightarrow \text{exp list} \Rightarrow 'a \text{ state} \Rightarrow 'a \text{ state} \times (v \text{ list}, v) \text{ result}$ **and**

eval-match :: $v \text{ sem-env} \Rightarrow v \Rightarrow (\text{pat} \times \text{exp}) \text{ list} \Rightarrow v \Rightarrow 'a \text{ state} \Rightarrow 'a \text{ state} \times (v, v) \text{ result}$

assumes

valid-eval: $\text{evaluate True env s e (eval env e s)}$ **and**

valid-eval-list: $\text{evaluate-list True env s es (eval-list env es s)}$ **and**

valid-eval-match: $\text{evaluate-match True env s v pes err-v (eval-match env v pes err-v s)}$

begin

lemmas *eval-all* = *valid-eval valid-eval-list valid-eval-match*

lemma *evaluate-iff*:

$\text{evaluate True env st e r} \longleftrightarrow (r = \text{eval env e st})$

$\text{evaluate-list True env st es r'} \longleftrightarrow (r' = \text{eval-list env es st})$

$\text{evaluate-match True env st v pes v' r} \longleftrightarrow (r = \text{eval-match env v pes v' st})$

<proof>

lemma *evaluate-iff-sym*:

$\text{evaluate True env st e r} \longleftrightarrow (\text{eval env e st} = r)$

$evaluate-list\ True\ env\ st\ es\ r' \longleftrightarrow (eval-list\ env\ es\ st = r')$
 $evaluate-match\ True\ env\ st\ v\ pes\ v'\ r \longleftrightarrow (eval-match\ env\ v\ pes\ v'\ st = r)$
 <proof>

lemma *other-eval-eq*:

assumes *Big-Step-Fun-Equiv.eval eval' eval-list' eval-match'*
shows $eval' = eval\ eval-list' = eval-list\ eval-match' = eval-match$
 <proof>

lemma *eval-list-singleton*:

$eval-list\ env\ [e]\ st = map-prod\ id\ list-result\ (eval\ env\ e\ st)$
 <proof>

lemma *eval-eqI*:

assumes $\bigwedge r. evaluate\ True\ env\ st1\ e1\ r \longleftrightarrow evaluate\ True\ env\ st2\ e2\ r$
shows $eval\ env\ e1\ st1 = eval\ env\ e2\ st2$
 <proof>

lemma *eval-match-eqI*:

assumes $\bigwedge r. evaluate-match\ True\ env1\ st1\ v1\ pes1\ err-v1\ r \longleftrightarrow evaluate-match\ True\ env2\ st2\ v2\ pes2\ err-v2\ r$
shows $eval-match\ env1\ v1\ pes1\ err-v1\ st1 = eval-match\ env2\ v2\ pes2\ err-v2\ st2$
 <proof>

lemma *eval-tannot[simp]*: $eval\ env\ (Tannot\ e\ t1)\ st = eval\ env\ e\ st$
 <proof>

lemma *eval-lannot[simp]*: $eval\ env\ (Lannot\ e\ t1)\ st = eval\ env\ e\ st$
 <proof>

lemma *eval-match[simp]*:

$eval\ env\ (Mat\ e\ pes)\ st =$
 (case $eval\ env\ e\ st$ of
 (st', Rval v) $\Rightarrow eval-match\ env\ v\ pes\ Bindv\ st'$
 | (st', Rerr err) $\Rightarrow (st', Rerr\ err)$)
 <proof>

lemma *eval-match-empty[simp]*: $eval-match\ env\ v2\ []\ err-v\ st = (st, Rerr\ (Rraise\ err-v))$
 <proof>

end

lemma *run-eval*: $\exists run-eval. \forall env\ e\ s. evaluate\ True\ env\ s\ e\ (run-eval\ env\ e\ s)$
 <proof>

lemma *run-eval-list*: $\exists run-eval-list. \forall env\ es\ s. evaluate-list\ True\ env\ s\ es\ (run-eval-list\ env\ es\ s)$
 <proof>

lemma *run-eval-match*: \exists *run-eval-match*. \forall *env v pes err-v s*. *evaluate-match True env s v pes err-v (run-eval-match env v pes err-v s)*
 ⟨*proof*⟩

global-interpretation *run: eval*

SOME f. \forall env e s. evaluate True env s e (f env e s)

SOME f. \forall env es s. evaluate-list True env s es (f env es s)

SOME f. \forall env v pes err-v s. evaluate-match True env s v pes err-v (f env v pes err-v s)

defines

run-eval = SOME f. \forall env e s. evaluate True env s e (f env e s) and

run-eval-list = SOME f. \forall env es s. evaluate-list True env s es (f env es s) and

run-eval-match = SOME f. \forall env v pes err-v s. evaluate-match True env s v pes err-v (f env v pes err-v s)

⟨*proof*⟩

hide-fact *run-eval*

hide-fact *run-eval-list*

hide-fact *run-eval-match*

lemma *fun-evaluate*:

evaluate-match True env s v pes err-v (map-prod id (map-result hd id) (fun-evaluate-match s env v pes err-v))

evaluate-list True env s es (fun-evaluate s env es)

⟨*proof*⟩

global-interpretation *fun: eval*

λ env e s. map-prod id (map-result hd id) (fun-evaluate s env [e])

λ env es s. fun-evaluate s env es

λ env v pes err-v s. map-prod id (map-result hd id) (fun-evaluate-match s env v pes err-v)

⟨*proof*⟩

lemmas *big-fun-equivalence =*

fun.other-eval-eq[OF run.eval-axioms]

—

run-eval =

(λ env e s. map-prod id (map-result hd id) (fun-evaluate s env [e]))

run-eval-list = (λ env es s. fun-evaluate s env es)

run-eval-match =

(λ env v pes err-v s.

map-prod id (map-result hd id) (fun-evaluate-match s env v pes err-v))

end

22.4 A simpler version with no clock parameter and factored-out matching

```

theory Big-Step-Unclocked
imports
  Semantic-Extras
  Big-Step-Determ
begin

inductive

evaluate-list :: (v)sem-env  $\Rightarrow$  'ffi state  $\Rightarrow$  (exp)list  $\Rightarrow$  'ffi state*((v)list),(v))result
 $\Rightarrow$  bool
  and
evaluate :: (v)sem-env  $\Rightarrow$  'ffi state  $\Rightarrow$  exp  $\Rightarrow$  'ffi state*((v),(v))result  $\Rightarrow$  bool
where

lit :  $\bigwedge$  env l s.

evaluate env s (Lit l) (s, Rval (Litv l))

|

raise1 :  $\bigwedge$  env e s1 s2 v1.
evaluate s1 env e (s2, Rval v1)
 $\implies$ 
evaluate s1 env (Raise e) (s2, Rerr (Rraise v1))

|

raise2 :  $\bigwedge$  env e s1 s2 err.
evaluate s1 env e (s2, Rerr err)
 $\implies$ 
evaluate s1 env (Raise e) (s2, Rerr err)

|

handle1 :  $\bigwedge$  s1 s2 env e v1 pes.
evaluate s1 env e (s2, Rval v1)
 $\implies$ 
evaluate s1 env (Handle e pes) (s2, Rval v1)

|

handle2 :  $\bigwedge$  s1 s2 env e pes v1 bv.
evaluate env s1 e (s2, Rerr (Rraise v1))  $\implies$ 
match-result env s2 v1 pes v1 = Rval (e', env')  $\implies$ 
evaluate (env  $\Downarrow$  sem-env.v := nsAppend (alist-to-ns env') (sem-env.v env)  $\Downarrow$ ) s2 e'
bv

```

\implies
evaluate env s1 (Handle e pes) bv

|

handle2b : $\bigwedge s1 s2 env e pes v1$.
evaluate env s1 e (s2, Rerr (Rraise v1)) \implies
match-result env s2 v1 pes v1 = Rerr err
 \implies
evaluate env s1 (Handle e pes) (s2, Rerr err)

|

handle3 : $\bigwedge s1 s2 env e pes a$.
evaluate env s1 e (s2, Rerr (Rabort a))
 \implies
evaluate env s1 (Handle e pes) (s2, Rerr (Rabort a))

|

con1 : $\bigwedge env cn es vs s s' v1$.
do-con-check(c env) cn (List.length es) \implies
build-conv(c env) cn (List.rev vs) = Some v1 \implies
evaluate-list env s (List.rev es) (s', Rval vs)
 \implies
evaluate env s (Con cn es) (s', Rval v1)

|

con2 : $\bigwedge env cn es s$.
 \neg (do-con-check(c env) cn (List.length es))
 \implies
evaluate env s (Con cn es) (s, Rerr (Rabort Rtype-error))

|

con3 : $\bigwedge env cn es err s s'$.
do-con-check(c env) cn (List.length es) \implies
evaluate-list env s (List.rev es) (s', Rerr err)
 \implies
evaluate env s (Con cn es) (s', Rerr err)

|

var1 : $\bigwedge env n v1 s$.
nsLookup(sem-env.v env) n = Some v1
 \implies
evaluate env s (Var n) (s, Rval v1)

|

$var2 : \bigwedge env\ n\ s.$
 $nsLookup(sem-env.v\ env)\ n = None$
 \implies
 $evaluate\ env\ s\ (Var\ n)\ (s,\ Rerr\ (Rabort\ Rtype-error))$

|

$fn : \bigwedge env\ n\ e\ s.$
 $evaluate\ env\ s\ (Fun\ n\ e)\ (s,\ Rval\ (Closure\ env\ n\ e))$

|

$app1 : \bigwedge env\ es\ vs\ env'\ e\ bv\ s1\ s2.$
 $evaluate-list\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \implies$
 $do-opapp\ (List.rev\ vs) = Some\ (env',\ e) \implies$
 $evaluate\ env'\ s2\ e\ bv$
 \implies
 $evaluate\ env\ s1\ (App\ Opapp\ es)\ bv$

|

$app3 : \bigwedge env\ es\ vs\ s1\ s2.$
 $evaluate-list\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \implies$
 $(do-opapp\ (List.rev\ vs) = None)$
 \implies
 $evaluate\ env\ s1\ (App\ Opapp\ es)\ (s2,\ Rerr\ (Rabort\ Rtype-error))$

|

$app4 : \bigwedge env\ op0\ es\ vs\ res\ s1\ s2\ refs'\ ffi'.$
 $evaluate-list\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \implies$
 $do-app\ ((refs\ s2),(ffi\ s2))\ op0\ (List.rev\ vs) = Some\ ((refs',ffi'),\ res) \implies$
 $op0 \neq Opapp$
 \implies
 $evaluate\ env\ s1\ (App\ op0\ es)\ ((s2\ (| refs := refs', ffi := ffi' |)),\ res)$

|

$app5 : \bigwedge env\ op0\ es\ vs\ s1\ s2.$
 $evaluate-list\ env\ s1\ (List.rev\ es)\ (s2,\ Rval\ vs) \implies$
 $do-app\ ((refs\ s2),(ffi\ s2))\ op0\ (List.rev\ vs) = None \implies$
 $op0 \neq Opapp$
 \implies
 $evaluate\ env\ s1\ (App\ op0\ es)\ (s2,\ Rerr\ (Rabort\ Rtype-error))$

|

$app6 : \bigwedge env\ op0\ es\ err\ s1\ s2.$
 $evaluate-list\ env\ s1\ (List.rev\ es)\ (s2,\ Rerr\ err)$
 \implies
 $evaluate\ env\ s1\ (App\ op0\ es)\ (s2,\ Rerr\ err)$

|

$log1 : \bigwedge env\ op0\ e1\ e2\ v1\ e'\ bv\ s1\ s2.$
 $evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1) \implies$
 $do-log\ op0\ v1\ e2 = Some\ (Exp\ e') \implies$
 $evaluate\ env\ s2\ e'\ bv$
 \implies
 $evaluate\ env\ s1\ (Log\ op0\ e1\ e2)\ bv$

|

$log2 : \bigwedge env\ op0\ e1\ e2\ v1\ bv\ s1\ s2.$
 $evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1) \implies$
 $(do-log\ op0\ v1\ e2 = Some\ (Val\ bv))$
 \implies
 $evaluate\ env\ s1\ (Log\ op0\ e1\ e2)\ (s2,\ Rval\ bv)$

|

$log3 : \bigwedge env\ op0\ e1\ e2\ v1\ s1\ s2.$
 $evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1) \implies$
 $(do-log\ op0\ v1\ e2 = None)$
 \implies
 $evaluate\ env\ s1\ (Log\ op0\ e1\ e2)\ (s2,\ Rerr\ (Rabort\ Rtype-error))$

|

$log4 : \bigwedge env\ op0\ e1\ e2\ err\ s\ s'.$
 $evaluate\ env\ s\ e1\ (s',\ Rerr\ err)$
 \implies
 $evaluate\ env\ s\ (Log\ op0\ e1\ e2)\ (s',\ Rerr\ err)$

|

$if1 : \bigwedge env\ e1\ e2\ e3\ v1\ e'\ bv\ s1\ s2.$
 $evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1) \implies$
 $do-if\ v1\ e2\ e3 = Some\ e' \implies$
 $evaluate\ env\ s2\ e'\ bv$
 \implies
 $evaluate\ env\ s1\ (If\ e1\ e2\ e3)\ bv$

|

if2 : $\bigwedge env\ e1\ e2\ e3\ v1\ s1\ s2.$
evaluate env s1 e1 (s2, Rval v1) \implies
(do-if v1 e2 e3 = None)
 \implies
evaluate env s1 (If e1 e2 e3) (s2, Rerr (Rabort Rtype-error))

|

if3 : $\bigwedge env\ e1\ e2\ e3\ err\ s\ s'.$
evaluate env s e1 (s', Rerr err)
 \implies
evaluate env s (If e1 e2 e3) (s', Rerr err)

|

mat1 : $\bigwedge env\ e\ pes\ v1\ bv\ s1\ s2.$
evaluate env s1 e (s2, Rval v1) \implies
match-result env s2 v1 pes Bindv = Rval (e', env') \implies
evaluate (env (| sem-env.v := nsAppend (alist-to-ns env') (sem-env.v env) |)) s2 e'
bv
 \implies
evaluate env s1 (Mat e pes) bv

|

mat1b : $\bigwedge env\ e\ pes\ v1\ s1\ s2.$
evaluate env s1 e (s2, Rval v1) \implies
match-result env s2 v1 pes Bindv = Rerr err
 \implies
evaluate env s1 (Mat e pes) (s2, Rerr err)

|

mat2 : $\bigwedge env\ e\ pes\ err\ s\ s'.$
evaluate env s e (s', Rerr err)
 \implies
evaluate env s (Mat e pes) (s', Rerr err)

|

let1 : $\bigwedge env\ n\ e1\ e2\ v1\ bv\ s1\ s2.$
evaluate env s1 e1 (s2, Rval v1) \implies
evaluate (env (| sem-env.v := (nsOptBind n v1 (sem-env.v env)) |)) s2 e2 bv
 \implies
evaluate env s1 (Let n e1 e2) bv

|

let2 : $\bigwedge env\ n\ e1\ e2\ err\ s\ s'.$

evaluate env s e1 (s', Rerr err)

==>

evaluate env s (Let n e1 e2) (s', Rerr err)

|

letrec1 : \bigwedge env funs e bv s.

distinct (List.map (λx .

(case x of (x,y,z) => x)) funs) ==>

evaluate (env (| sem-env.v := (build-rec-env funs env(sem-env.v env)) |)) s e bv

==>

evaluate env s (Letrec funs e) bv

|

letrec2 : \bigwedge env funs e s.

\neg (distinct (List.map (λx .

(case x of (x,y,z) => x)) funs))

==>

evaluate env s (Letrec funs e) (s, Rerr (Rabort Rtype-error))

|

tannot : \bigwedge env e t0 s bv.

evaluate env s e bv

==>

evaluate env s (Tannot e t0) bv

|

locannot : \bigwedge env e l s bv.

evaluate env s e bv

==>

evaluate env s (Lannot e l) bv

|

empty : \bigwedge env s.

evaluate-list env s [] (s, Rval [])

|

cons1 : \bigwedge env e es v1 vs s1 s2 s3.

evaluate env s1 e (s2, Rval v1) ==>

evaluate-list env s2 es (s3, Rval vs)

==>

evaluate-list env s1 (e # es) (s3, Rval (v1 # vs))

|

cons2 : $\bigwedge env\ e\ es\ err\ s\ s'$.
evaluate env s e (s', Rerr err)
 \implies
evaluate-list env s (e # es) (s', Rerr err)

|

cons3 : $\bigwedge env\ e\ es\ v1\ err\ s1\ s2\ s3$.
evaluate env s1 e (s2, Rval v1) \implies
evaluate-list env s2 es (s3, Rerr err)
 \implies
evaluate-list env s1 (e # es) (s3, Rerr err)

lemma *unlocked-sound*:

evaluate-list v s es bv \implies BigStep.evaluate-list False v s es bv
evaluate v s e bv' \implies BigStep.evaluate False v s e bv'
{proof}

context begin

private lemma *unlocked-complete0*:

BigStep.evaluate-match ck env s v0 pes err-v (s', bv) \implies $\neg ck \implies$ (
 case bv of
 Rval v \implies
 $\exists e\ env'$.
 match-result env s v0 pes err-v = Rval (e, env') \wedge
 evaluate (env \parallel sem-env.v := nsAppend (alist-to-ns env') (sem-env.v env)
) s e (s', Rval v)
 | *Rerr err \implies*
 (match-result env s v0 pes err-v = Rerr err) \vee
 $(\exists e\ env'$.
 match-result env s v0 pes err-v = Rval (e, env') \wedge
 evaluate (env \parallel sem-env.v := nsAppend (alist-to-ns env') (sem-env.v env)
) s e (s', Rerr err))
 BigStep.evaluate-list ck v s es (s', bv0) \implies $\neg ck \implies$ evaluate-list v s es (s', bv0)
 BigStep.evaluate ck v s e (s', bv) \implies $\neg ck \implies$ evaluate v s e (s', bv)
{proof}

lemma *unlocked-complete*:

BigStep.evaluate-list False v s es bv' \implies evaluate-list v s es bv'
BigStep.evaluate False v s e bv \implies evaluate v s e bv
{proof}

end

lemma *unlocked-eq*:

evaluate-list = BigStep.evaluate-list False

evaluate = *BigStep.evaluate False*
 <proof>

lemma *unlocked-determ*:

evaluate-list env s es r2a \implies *evaluate-list env s es r2b* \implies *r2a* = *r2b*
evaluate env s e r3a \implies *evaluate env s e r3b* \implies *r3a* = *r3b*

<proof>

end

22.5 Lemmas about the clocked semantics

theory *Big-Step-Clocked*

imports

Semantic-Extras

Big-Step-Total

Big-Step-Determ

begin

— From HOL4 bigClockScript.sml

lemma *do-app-no-runtime-error*:

assumes *do-app (refs s, ffi s) op0 (rev vs) = Some ((refs', ffi'), res)*
shows *res* \neq *Rerr (Rabort Rtimeout-error)*

<proof>

context

notes *do-app.simps[simp del]*

begin

private lemma *big-unlocked0*:

evaluate-match ck env s v pes err-v r1 \implies *ck* = *False* \implies *snd r1* \neq *Rerr (Rabort Rtimeout-error)* \wedge (*clock s*) = (*clock (fst r1)*)

evaluate-list ck env s es r2 \implies *ck* = *False* \implies *snd r2* \neq *Rerr (Rabort Rtimeout-error)* \wedge (*clock s*) = (*clock (fst r2)*)

evaluate ck env s e r3 \implies *ck* = *False* \implies *snd r3* \neq *Rerr (Rabort Rtimeout-error)* \wedge (*clock s*) = (*clock (fst r3)*)

<proof>

corollary *big-unlocked-notimeout*:

evaluate-match False env s v pes err-v (s', r1) \implies *r1* \neq *Rerr (Rabort Rtimeout-error)*

evaluate-list False env s es (s', r2) \implies *r2* \neq *Rerr (Rabort Rtimeout-error)*

evaluate False env s e (s', r3) \implies *r3* \neq *Rerr (Rabort Rtimeout-error)*

<proof>

corollary *big-unlocked-unchanged*:

evaluate-match False env s v pes err-v (s', r1) \implies *clock s* = *clock s'*

evaluate-list False env s es (s', r2) \implies *clock s* = *clock s'*

$evaluate\ False\ env\ s\ e\ (s', r3) \implies clock\ s = clock\ s'$
 <proof> **lemma big-unclocked1:**
 $evaluate-match\ ck\ env\ s\ v\ pes\ err-v\ r1 \implies \forall st' r. r1 = (st', r) \wedge r \neq Rerr\ (Rabort\ Rtimeout-error)$
 $\longrightarrow evaluate-match\ False\ env\ (s\ \{\!\!|\ clock := cnt\ \!\!\})\ v\ pes\ err-v\ ((st' \{\!\!|\ clock := cnt\ \!\!\}), r)$
 $evaluate-list\ ck\ env\ s\ es\ r2 \implies \forall st' r. r2 = (st', r) \wedge r \neq Rerr\ (Rabort\ Rtimeout-error)$
 $\longrightarrow evaluate-list\ False\ env\ (s\ \{\!\!|\ clock := cnt\ \!\!\})\ es\ ((st' \{\!\!|\ clock := cnt\ \!\!\}), r)$
 $evaluate\ ck\ env\ s\ e\ r3 \implies \forall st' r. r3 = (st', r) \wedge r \neq Rerr\ (Rabort\ Rtimeout-error)$
 $\longrightarrow evaluate\ False\ env\ (s\ \{\!\!|\ clock := cnt\ \!\!\})\ e\ ((st' \{\!\!|\ clock := cnt\ \!\!\}), r)$
 </proof>

lemma big-unclocked-ignore:

$evaluate-match\ ck\ env\ s\ v\ pes\ err-v\ (st', r1) \implies r1 \neq Rerr\ (Rabort\ Rtimeout-error) \implies$
 $evaluate-match\ False\ env\ (s\ \{\!\!|\ clock := cnt\ \!\!\})\ v\ pes\ err-v\ (st' \{\!\!|\ clock := cnt\ \!\!\}, r1)$
 $evaluate-list\ ck\ env\ s\ es\ (st', r2) \implies r2 \neq Rerr\ (Rabort\ Rtimeout-error) \implies$
 $evaluate-list\ False\ env\ (s\ \{\!\!|\ clock := cnt\ \!\!\})\ es\ (st' \{\!\!|\ clock := cnt\ \!\!\}, r2)$
 $evaluate\ ck\ env\ s\ e\ (st', r3) \implies r3 \neq Rerr\ (Rabort\ Rtimeout-error) \implies$
 $evaluate\ False\ env\ (s\ \{\!\!|\ clock := cnt\ \!\!\})\ e\ (st' \{\!\!|\ clock := cnt\ \!\!\}, r3)$
 </proof>

lemma big-unclocked:

assumes $evaluate\ False\ env\ s\ e\ (s', r) \implies r \neq Rerr\ (Rabort\ Rtimeout-error)$
assumes $evaluate\ False\ env\ s\ e\ (s', r) \implies clock\ s = clock\ s'$
assumes $evaluate\ False\ env\ (s\ \{\!\!|\ clock := count1\ \!\!\})\ e\ ((s' \{\!\!|\ clock := count1\ \!\!\}), r)$
shows $evaluate\ False\ env\ (s\ \{\!\!|\ clock := count2\ \!\!\})\ e\ ((s' \{\!\!|\ clock := count2\ \!\!\}), r)$
 <proof> **lemma add-to-counter0:**
 $evaluate-match\ ck\ env\ s\ v\ pes\ err-v\ r1 \implies \forall s' r' extra. (r1 = (s', r')) \wedge (r' \neq Rerr\ (Rabort\ Rtimeout-error)) \wedge (ck = True)$
 $\longrightarrow evaluate-match\ True\ env\ (s\ \{\!\!|\ clock := (clock\ s) + extra\ \!\!\})\ v\ pes\ err-v\ ((s' \{\!\!|\ clock := (clock\ s') + extra\ \!\!\}), r')$
 $evaluate-list\ ck\ env\ s\ es\ r2 \implies \forall s' r' extra. (r2 = (s', r')) \wedge (r' \neq Rerr\ (Rabort\ Rtimeout-error)) \wedge (ck = True)$
 $\longrightarrow evaluate-list\ True\ env\ (s\ \{\!\!|\ clock := (clock\ s) + extra\ \!\!\})\ es\ ((s' \{\!\!|\ clock := (clock\ s') + extra\ \!\!\}), r')$
 $evaluate\ ck\ env\ s\ e\ r3 \implies \forall s' r' extra. (r3 = (s', r')) \wedge (r' \neq Rerr\ (Rabort\ Rtimeout-error)) \wedge (ck = True)$
 $\longrightarrow evaluate\ True\ env\ (s\ \{\!\!|\ clock := (clock\ s) + extra\ \!\!\})\ e\ ((s' \{\!\!|\ clock := (clock\ s') + extra\ \!\!\}), r')$
 </proof>

corollary add-to-counter:

$evaluate-match\ True\ env\ s\ v\ pes\ err-v\ (s', r1) \implies r1 \neq Rerr\ (Rabort\ Rtimeout-error) \implies$
 $evaluate-match\ True\ env\ (s\ \{\!\!|\ clock := clock\ s + extra\ \!\!\})\ v\ pes\ err-v\ ((s' \{\!\!|\ clock := clock\ s' + extra\ \!\!\}), r1)$

$evaluate-list\ True\ env\ s\ es\ (s',\ r2) \implies r2 \neq Rerr\ (Rabort\ Rtimeout-error) \implies$
 $evaluate-list\ True\ env\ (s\ |\ clock := (clock\ s)+extra)\ es\ ((s'\ |\ clock := (clock\ s') + extra)),r2)$
 $evaluate\ True\ env\ s\ e\ (s',\ r3) \implies r3 \neq Rerr\ (Rabort\ Rtimeout-error) \implies$
 $evaluate\ True\ env\ (s\ |\ clock := (clock\ s)+extra)\ e\ ((s'\ |\ clock := (clock\ s') + extra)),r3)$
 <proof>

lemma add-clock:

$evaluate-match\ ck\ env\ s\ v\ pes\ err-v\ r1 \implies \forall s'\ r'.\ (r1 = (s',\ r') \wedge ck = False$
 $\longrightarrow (\exists c.\ evaluate-match\ True\ env\ (s\ |\ clock := c)\ v\ pes\ err-v\ ((s'\ |\ clock := 0)),r'))$
 $evaluate-list\ ck\ env\ s\ es\ r2 \implies \forall s'\ r'.\ (r2 = (s',\ r') \wedge ck = False$
 $\longrightarrow (\exists c.\ evaluate-list\ True\ env\ (s\ |\ clock := c)\ es\ ((s'\ |\ clock := 0)),r'))$
 $evaluate\ ck\ env\ s\ e\ r3 \implies \forall s'\ r'.\ (r3 = (s',\ r') \wedge ck = False$
 $\longrightarrow (\exists c.\ evaluate\ True\ env\ (s\ |\ clock := c)\ e\ ((s'\ |\ clock := 0)),r'))$
 <proof>

lemma clock-monotone:

$evaluate-match\ ck\ env\ s\ v\ pes\ err-v\ r1 \implies \forall s'\ r'.\ r1 = (s',\ r') \wedge (ck = True) \longrightarrow$
 $(clock\ s') \leq (clock\ s)$
 $evaluate-list\ ck\ env\ s\ es\ r2 \implies \forall s'\ r'.\ r2 = (s',\ r') \wedge (ck = True) \longrightarrow (clock\ s')$
 $\leq (clock\ s)$
 $evaluate\ ck\ env\ s\ e\ r3 \implies \forall s'\ r'.\ r3 = (s',\ r') \wedge (ck = True) \longrightarrow (clock\ s') \leq$
 $(clock\ s)$
 <proof>

lemma big-clocked-unclocked-equiv:

$evaluate\ False\ env\ s\ e\ (s',\ r1) =$
 $(\exists c.\ evaluate\ True\ env\ (s\ |\ clock := c)\ e\ ((s'\ |\ clock := 0)),r1) \wedge$
 $r1 \neq Rerr\ (Rabort\ Rtimeout-error) \wedge (clock\ s) = (clock\ s')$ (**is** ?lhs =
 ?rhs)
 <proof>

lemma big-clocked-timeout-0:

$evaluate-match\ ck\ env\ s\ v\ pes\ err-v\ r1 \implies \forall s'.\ r1 = (s',\ Rerr\ (Rabort\ Rtimeout-error)) \wedge ck = True \longrightarrow (clock\ s') = 0$
 $evaluate-list\ ck\ env\ s\ es\ r2 \implies \forall s'.\ r2 = (s',\ Rerr\ (Rabort\ Rtimeout-error)) \wedge$
 $ck = True \longrightarrow (clock\ s') = 0$
 $evaluate\ ck\ env\ s\ e\ r3 \implies \forall s'.\ r3 = (s',\ Rerr\ (Rabort\ Rtimeout-error)) \wedge ck =$
 $True \longrightarrow (clock\ s') = 0$
 <proof>

lemma big-clocked-unclocked-equiv-timeout:

$(\forall r.\ \neg evaluate\ False\ env\ s\ e\ r) =$
 $(\forall c.\ \exists s'.\ evaluate\ True\ env\ (s\ |\ clock := c)\ e\ (s',\ Rerr\ (Rabort\ Rtimeout-error)))$
 $\wedge (clock\ s') = 0)$ (**is** ?lhs = ?rhs)
 <proof>

lemma *sub-from-counter*:

evaluate-match $ck\ env\ s\ v\ pes\ err\text{-}v\ r1 \implies$
 $\forall count\ count'\ s'\ r'.$
 $(clock\ s) = count + extra1 \wedge$
 $r1 = (s',r') \wedge$
 $(clock\ s') = count' + extra1 \wedge$
 $ck = True \implies$
evaluate-match $True\ env\ (s\ (\mid\ clock := count\ \mid))\ v\ pes\ err\text{-}v\ ((s'\ (\mid\ clock := count'\ \mid)),r')$
evaluate-list $ck\ env\ s\ es\ r2 \implies$
 $\forall count\ count'\ s'\ r'.$
 $(clock\ s) = count + extra2 \wedge$
 $r2 = (s',r') \wedge$
 $(clock\ s') = count' + extra2 \wedge$
 $ck = True \implies$
evaluate-list $True\ env\ (s\ (\mid\ clock := count\ \mid))\ es\ ((s'\ (\mid\ clock := count'\ \mid)),r')$
evaluate $ck\ env\ s\ e\ r3 \implies$
 $\forall count\ count'\ s'\ r'.$
 $(clock\ s) = count + extra3 \wedge$
 $r3 = (s',r') \wedge$
 $(clock\ s') = count' + extra3 \wedge$
 $ck = True \implies$
evaluate $True\ env\ (s\ (\mid\ clock := count\ \mid))\ e\ ((s'\ (\mid\ clock := count'\ \mid)),r')$
 $\langle proof \rangle$

lemma *clocked-min-counter*:

assumes *evaluate* $True\ env\ s\ e\ (s',r')$
shows *evaluate* $True\ env\ (s\ (\mid\ clock := (clock\ s) - (clock\ s')\ \mid))\ e\ ((s'\ (\mid\ clock := 0\ \mid)),r')$
 $\langle proof \rangle$

lemma *dec-evaluate-not-timeout*:

evaluate-dec $False\ mn\ env\ s\ d\ (s',r) \implies r \neq Rerr\ (Rabort\ Rtimeout\text{-}error)$
 $\langle proof \rangle$

lemma *dec-unclocked-ignore*:

evaluate-dec $ck\ mn\ env\ s\ d\ res \implies$
 $\forall s'\ r\ count. res = (s',r) \wedge r \neq Rerr\ (Rabort\ Rtimeout\text{-}error) \implies$
evaluate-dec $False\ mn\ env\ (s\ (\mid\ clock := count\ \mid))\ d\ (s'\ (\mid\ clock := count\ \mid),r)$
 $\langle proof \rangle$ **lemma** *dec-unclocked-1*:

assumes *evaluate-dec* $False\ mn\ env\ s\ d\ (s',r)$

shows $(r \neq Rerr\ (Rabort\ Rtimeout\text{-}error)) \wedge (clock\ s) = (clock\ s')$

$\langle proof \rangle$ **lemma** *dec-unclocked-2*:

assumes *evaluate-dec* $False\ mn\ env\ (s\ (\mid\ clock := count1\ \mid))\ d\ ((s'\ (\mid\ clock := count1\ \mid)),r)$

shows *evaluate-dec* $False\ mn\ env\ (s\ (\mid\ clock := count2\ \mid))\ d\ ((s'\ (\mid\ clock := count2\ \mid)),r)$

$\langle proof \rangle$

lemma *dec-unclocked*:

$(\text{evaluate-dec False mn env s d } (s',r) \longrightarrow (r \neq \text{Rerr (Rabort Rtimeout-error)}) \wedge$
 $(\text{clock } s) = (\text{clock } s')) \wedge$
 $(\text{evaluate-dec False mn env } (s \mid \text{clock} := \text{count1} \mid)) \text{ d } ((s' \mid \text{clock} := \text{count1} \mid)),r) \longrightarrow$
 $\text{evaluate-dec False mn env } (s \mid \text{clock} := \text{count2} \mid)) \text{ d } ((s' \mid \text{clock} := \text{count2} \mid)),r))$
 ⟨proof⟩

corollary *big-clocked-unclocked-equiv-timeout-1*:

$(\forall r. \neg \text{evaluate False env s e r}) \implies$
 $(\forall c. \exists s'. \text{evaluate True env } (\lambda-. c) s) \text{ e } (s', \text{Rerr (Rabort Rtimeout-error)}) \wedge \text{clock } s' = 0)$
 ⟨proof⟩

lemma *not-evaluate-dec-timeout*:

assumes $\forall r. \neg \text{evaluate-dec False mn env s d r}$
shows $\exists r. \text{evaluate-dec True mn env s d r} \wedge \text{snd } r = \text{Rerr (Rabort Rtimeout-error)}$
 ⟨proof⟩

lemma *dec-clocked-total*: $\exists \text{res. evaluate-dec True mn env s d res}$

⟨proof⟩

lemma *dec-clocked-min-counter*:

$\text{evaluate-dec ck mn env s d res} \implies \text{ck} = \text{True} \implies$
 $\text{evaluate-dec ck mn env } (s \mid \text{clock} := (\text{clock } s) - (\text{clock } (\text{fst res}))) \mid)) \text{ d } (((\text{fst}$
 $\text{res}) \mid \text{clock} := 0 \mid)), \text{snd res})$
 ⟨proof⟩

lemma *dec-sub-from-counter*:

$\text{evaluate-dec ck mn env s d res} \implies$
 $(\forall \text{count count}' s' r. (\text{clock } s) = \text{count} + \text{extra} \wedge (\text{clock } s') = \text{count}' + \text{extra}$
 $\wedge \text{res} = (s',r) \wedge \text{ck} = \text{True} \longrightarrow$
 $\text{evaluate-dec ck mn env } (s \mid \text{clock} := \text{count} \mid)) \text{ d } ((s' \mid \text{clock} := \text{count}' \mid)),r))$
 ⟨proof⟩

lemma *dec-clock-monotone*:

$\text{evaluate-dec ck mn env s d res} \implies \text{ck} = \text{True} \implies (\text{clock } (\text{fst res})) \leq (\text{clock } s)$
 ⟨proof⟩

lemma *dec-add-clock*:

$\text{evaluate-dec ck mn env s d res} \implies$
 $\forall s' r. \text{res} = (s',r) \wedge \text{ck} = \text{False} \longrightarrow (\exists c. \text{evaluate-dec True mn env } (s \mid \text{clock}$
 $:= c \mid)) \text{ d } ((s' \mid \text{clock} := 0 \mid)),r))$
 ⟨proof⟩

lemma *dec-add-to-counter*:

$\text{evaluate-dec ck mn env s d res} \implies$

$\forall s' r \text{ extra. } \text{res} = (s',r) \wedge \text{ck} = \text{True} \wedge r \neq \text{Rerr} \text{ (Rabort Rtimeout-error)} \longrightarrow$
 $\text{evaluate-dec True mn env (s (| clock := (clock s) + extra |)) d ((s' (| clock$
 $:= (\text{clock s}') + \text{extra |}),r)$
 <proof>

lemma *dec-unclocked-unchanged:*

$\text{evaluate-dec ck mn env s d r} \implies \text{ck} = \text{False} \implies (\text{snd } r) \neq \text{Rerr} \text{ (Rabort Rtime-}$
 $\text{out-error)} \wedge (\text{clock s}) = (\text{clock (fst } r))$
 <proof>

lemma *dec-clocked-unclocked-equiv:*

$\text{evaluate-dec False mn env s1 d (s2,r)} =$
 $(\exists c. \text{evaluate-dec True mn env (s1 (| clock := c |)) d ((s2 (| clock := 0 |)),r) \wedge$
 $r \neq \text{Rerr} \text{ (Rabort Rtimeout-error)} \wedge (\text{clock s1}) = (\text{clock s2})) \text{ (is ?lhs =}$
 $?rhs)$
 <proof>

lemma *decs-add-clock:*

$\text{evaluate-decs ck mn env s ds res} \implies$
 $\forall s' r. \text{res} = (s',r) \wedge \text{ck} = \text{False} \longrightarrow (\exists c. \text{evaluate-decs True mn env (s (| clock$
 $:= c |)) ds (s' (| clock := 0 |),r))$
 <proof>

lemma *decs-evaluate-not-timeout:*

$\text{evaluate-decs ck mn env s ds r} \implies$
 $\forall s' r'. \text{ck} = \text{False} \wedge r = (s',r') \longrightarrow r' \neq \text{Rerr} \text{ (Rabort Rtimeout-error)}$
 <proof>

lemma *decs-unclocked-unchanged:*

$\text{evaluate-decs ck mn env s ds r} \implies$
 $\forall s' r'. \text{ck} = \text{False} \wedge r = (s',r') \longrightarrow r' \neq \text{Rerr} \text{ (Rabort Rtimeout-error)} \wedge (\text{clock}$
 $s) = (\text{clock s'})$
 <proof>

lemma *decs-unclocked-ignore:*

$\text{evaluate-decs ck mn env s d res} \implies \forall s' r \text{ count. } \text{res} = (s',r) \wedge r \neq \text{Rerr} \text{ (Rabort}$
 $\text{Rtimeout-error)} \longrightarrow$

$\text{evaluate-decs False mn env (s (| clock := count |)) d ((s' (| clock := count |)),r)$

<proof> **lemma** *decs-unclocked-2:*

assumes $\text{evaluate-decs False mn env (s (| clock := count1 |)) ds ((s' (| clock :=$
 $\text{count1 |}),r)$

shows $\text{evaluate-decs False mn env (s (| clock := count2 |)) ds ((s' (| clock :=$
 $\text{count2 |}),r)$

<proof>

lemma *decs-unclocked:*

$(\text{evaluate-decs False mn env s ds (s',r)} \longrightarrow r \neq \text{Rerr} \text{ (Rabort Rtimeout-error)}) \wedge$
 $(\text{clock s}) = (\text{clock s'}) \wedge$

$(\text{evaluate-decs False mn env (s (| clock := count1 |)) ds ((s' (| clock := count1$

$\rangle\rangle),r) =$
 $\text{evaluate-decs False mn env (s (| clock := count2 |)) ds ((s' (| clock := count2$
 $\rangle\rangle),r))$
 $\langle\text{proof}\rangle$

lemma not-evaluate-decs-timeout:

assumes $\forall r. \neg \text{evaluate-decs False mn env s ds r}$
shows $\exists r. \text{evaluate-decs True mn env s ds r} \wedge (\text{snd } r) = \text{Rerr (Rabort Rtimeout-error)}$
 $\langle\text{proof}\rangle$

lemma decs-clocked-total: $\exists \text{res. evaluate-decs True mn env s ds res}$
 $\langle\text{proof}\rangle$

lemma decs-clock-monotone:

$\text{evaluate-decs ck mn env s d res} \implies \text{ck} = \text{True} \implies (\text{clock (fst res)}) \leq (\text{clock } s)$
 $\langle\text{proof}\rangle$

lemma decs-sub-from-counter:

$\text{evaluate-decs ck mn env s d res} \implies$
 $\forall \text{extra count count' s' r'.$
 $(\text{clock } s) = \text{count} + \text{extra} \wedge (\text{clock } s') = \text{count}' + \text{extra} \wedge$
 $\text{res} = (s',r') \wedge \text{ck} = \text{True} \longrightarrow \text{evaluate-decs ck mn env (s (| clock := count |))}$
 $d ((s' (| clock := count' |)),r')$
 $\langle\text{proof}\rangle$

lemma decs-clocked-min-counter:

assumes $\text{evaluate-decs ck mn env s ds res ck} = \text{True}$
shows $\text{evaluate-decs ck mn env (s (| clock := clock } s - (\text{clock (fst res)})) |)) ds (((\text{fst}$
 $\text{res}) (| \text{clock} := 0 |)),(\text{snd } \text{res}))$
 $\langle\text{proof}\rangle$

lemma decs-add-to-counter:

$\text{evaluate-decs ck mn env s d res} \implies \forall s' r \text{ extra. res} = (s',r) \wedge \text{ck} = \text{True} \wedge r \neq$
 $\text{Rerr (Rabort Rtimeout-error)} \longrightarrow$
 $\text{evaluate-decs True mn env (s (| clock := clock } s + \text{extra} |)) d ((s' (| \text{clock} :=$
 $\text{clock } s' + \text{extra} |)),r)$
 $\langle\text{proof}\rangle$

lemma top-evaluate-not-timeout:

$\text{evaluate-top False env s tp (s',r)} \implies r \neq \text{Rerr (Rabort Rtimeout-error)}$
 $\langle\text{proof}\rangle$

lemma top-unclocked-ignore:

assumes $\text{evaluate-top ck env s tp (s',r)} r \neq \text{Rerr (Rabort Rtimeout-error)}$
shows $\text{evaluate-top False env (s (| \text{clock} := \text{cnt} |)) tp ((s' (| \text{clock} := \text{cnt} |)),r)$
 $\langle\text{proof}\rangle$

lemma *top-unclocked*:

(*evaluate-top False env s tp (s',r) \longrightarrow (r \neq Rerr (Rabort Rtimeout-error)) \wedge (clock s) = (clock s')) \wedge
 (*evaluate-top False env (s (| clock := count1 |)) tp ((s' (| clock := count1 |)),r)*)
 =
evaluate-top False env (s (| clock := count2 |)) tp ((s' (| clock := count2 |)),r)
 (is ?P \wedge ?Q)
 <proof>*

lemma *not-evaluate-top-timeout*:

assumes $\forall r. \neg \text{evaluate-top False env s tp r}$
shows $\exists r. \text{evaluate-top True env s tp r} \wedge (\text{snd } r) = \text{Rerr (Rabort Rtimeout-error)}$
 <proof>

lemma *top-clocked-total*:

$\exists r. \text{evaluate-top True env s tp r}$
 <proof>

lemma *top-clocked-min-counter*:

assumes *evaluate-top ck env s tp (s',r) ck*
shows *evaluate-top ck env (s (| clock := clock s - clock s' |)) tp (s' (| clock := 0 |),r)*
 <proof>

lemma *top-add-clock*:

assumes *evaluate-top ck env s tp (s',r) \neg ck*
shows $\exists c. \text{evaluate-top True env (s (| clock := c |)) tp ((s' (| clock := 0 |)),r)$
 <proof>

lemma *top-clocked-unclocked-equiv*:

evaluate-top False env s tp (s',r) =
 ($\exists c. \text{evaluate-top True env (s (| clock := c |)) tp ((s' (| clock := 0 |)),r) \wedge r \neq$
 Rerr (Rabort Rtimeout-error) \wedge
 (clock s) = (clock s')) (is ?P = ?Q)
 <proof>

lemma *top-clock-monotone*:

evaluate-top ck env s tp (s',r) \implies ck = True \implies (clock s') \leq (clock s)
 <proof>

lemma *top-sub-from-counter*:

assumes *evaluate-top ck env s tp (s',r) ck = True (clock s) = cnt + extra*
 (clock s') = cnt' + extra
shows *evaluate-top ck env (s (| clock := cnt |)) tp ((s' (| clock := cnt' |)),r)*
 <proof>

lemma *top-add-to-counter*:

assumes *evaluate-top True env s d (s',r) r \neq Rerr (Rabort Rtimeout-error)*
shows *evaluate-top True env (s (| clock := (clock s) + extra |)) d ((s' (| clock*

$:= (\text{clock } s') + \text{extra } \)), r)$
 ⟨proof⟩

lemma prog-clock-monotone:

$\text{evaluate-prog } ck \text{ env } s \text{ prog } res \implies ck \implies (\text{clock } (fst \text{ res})) \leq (\text{clock } s)$
 ⟨proof⟩

lemma prog-unclocked-ignore:

$\text{evaluate-prog } ck \text{ env } s \text{ prog } res \implies \forall cnt \ s' \ r. \text{ res} = (s', r) \wedge r \neq Rerr \text{ (Rabort Rtimeout-error)}$
 $\longrightarrow \text{evaluate-prog } False \text{ env } (s \ (\ | \ \text{clock} := cnt \ |)) \text{ prog } ((s' \ (\ | \ \text{clock} := cnt \ |)), r)$
 ⟨proof⟩

lemma prog-unclocked-unchanged:

$\text{evaluate-prog } ck \text{ env } s \text{ prog } res \implies \neg ck \implies (snd \text{ res}) \neq Rerr \text{ (Rabort Rtimeout-error)} \wedge (\text{clock } (fst \text{ res})) = (\text{clock } s)$

⟨proof⟩ **lemma prog-unclocked-1:**

assumes $\text{evaluate-prog } False \text{ env } s \text{ prog } (s', r)$

shows $r \neq Rerr \text{ (Rabort Rtimeout-error)} \wedge (\text{clock } s = \text{clock } s')$

⟨proof⟩ **lemma prog-unclocked-2:**

assumes $\text{evaluate-prog } False \text{ env } (s \ (\ | \ \text{clock} := cnt1 \ |)) \text{ prog } (s' \ (\ | \ \text{clock} := cnt1 \ |), r)$

shows $\text{evaluate-prog } False \text{ env } (s \ (\ | \ \text{clock} := cnt2 \ |)) \text{ prog } (s' \ (\ | \ \text{clock} := cnt2 \ |), r)$
 ⟨proof⟩

lemma prog-unclocked:

$(\text{evaluate-prog } False \text{ env } s \text{ prog } (s', r) \longrightarrow r \neq Rerr \text{ (Rabort Rtimeout-error)}) \wedge (\text{clock } s = \text{clock } s') \wedge$

$(\text{evaluate-prog } False \text{ env } (s \ (\ | \ \text{clock} := cnt1 \ |)) \text{ prog } (s' \ (\ | \ \text{clock} := cnt1 \ |), r) =$

$\text{evaluate-prog } False \text{ env } (s \ (\ | \ \text{clock} := cnt2 \ |)) \text{ prog } (s' \ (\ | \ \text{clock} := cnt2 \ |), r))$

⟨proof⟩

lemma not-evaluate-prog-timeout:

assumes $\forall res. \neg \text{evaluate-prog } False \text{ env } s \text{ prog } res$

shows $\exists r. \text{evaluate-prog } True \text{ env } s \text{ prog } r \wedge snd \ r = Rerr \text{ (Rabort Rtimeout-error)}$

⟨proof⟩

lemma not-evaluate-whole-prog-timeout:

assumes $\forall res. \neg \text{evaluate-whole-prog } False \text{ env } s \text{ prog } res$

shows $\exists r. \text{evaluate-whole-prog } True \text{ env } s \text{ prog } r \wedge snd \ r = Rerr \text{ (Rabort Rtimeout-error)}$ (**is ?P**)

⟨proof⟩

lemma prog-add-to-counter:

$\text{evaluate-prog } ck \text{ env } s \text{ prog } res \implies \forall s' \ r \ \text{extra}. \text{ res} = (s', r) \wedge ck = True \wedge r \neq Rerr \text{ (Rabort Rtimeout-error)} \longrightarrow$

$\text{evaluate-prog } True \text{ env } (s \ (\ | \ \text{clock} := (\text{clock } s) + \text{extra} \ |)) \text{ prog } ((s' \ (\ | \ \text{clock} := (\text{clock } s') + \text{extra} \ |)), r)$

<proof>

lemma *prog-sub-from-counter:*

evaluate-prog ck env s prog res \implies
 \forall *extra cnt cnt' s' r.*
 $(\text{clock } s) = \text{extra} + \text{cnt} \wedge (\text{clock } s') = \text{extra} + \text{cnt}' \wedge \text{res} = (s', r) \wedge \text{ck} = \text{True} \longrightarrow$
evaluate-prog ck env (s (| clock := cnt |)) prog ((s' (| clock := cnt' |)), r)
<proof>

lemma *prog-clocked-min-counter:*

assumes *evaluate-prog True env s prog (s', r)*
shows *evaluate-prog True env (s (| clock := (clock s) - (clock s') |)) prog (((s' (| clock := 0 |)), r)*
<proof>

lemma *prog-add-clock:*

evaluate-prog False env s prog (s', res) $\implies \exists c. *evaluate-prog True env (s (| clock := c |)) prog ((s' (| clock := 0 |)), res)*
<proof>$

lemma *prog-clocked-unclocked-equiv:*

evaluate-prog False env s prog (s', r) =
 $(\exists c. *evaluate-prog True env (s (| clock := c |)) prog ((s' (| clock := 0 |)), r) \wedge*
 $r \neq \text{Rerr } (\text{Rabort } \text{Rtimeout-error}) \wedge (\text{clock } s) = (\text{clock } s'))$ **(is ?lhs =**
?rhs)
<proof>$

end

lemma *clocked-evaluate:*

$(\exists k. *BigStep.evaluate True env (update-clock (\lambda-. k) s) e (s', r) \wedge r \neq \text{Rerr } (\text{Rabort } \text{Rtimeout-error})*) =
 $(\exists k. *BigStep.evaluate True env (update-clock (\lambda-. k) s) e ((update-clock (\lambda-. 0) s'), r) \wedge r \neq \text{Rerr } (\text{Rabort } \text{Rtimeout-error})*)
<proof>$$

end

22.6 An even simpler version without mutual induction

theory *Big-Step-Unclocked-Single*

imports *Big-Step-Unclocked Big-Step-Clocked Evaluate-Single Big-Step-Fun-Equiv*
begin

inductive *evaluate-list* ::

$(\text{ffi state} \Rightarrow \text{exp} \Rightarrow \text{ffi state} * (v, v) \text{ result} \Rightarrow \text{bool}) \Rightarrow$

'ffi state \Rightarrow exp list \Rightarrow 'ffi state*(v list, v)result \Rightarrow bool for P where empty:

evaluate-list P s [] (s, Rval []) |

cons1:

P s1 e (s2, Rval v) \Longrightarrow
 evaluate-list P s2 es (s3, Rval vs) \Longrightarrow
 evaluate-list P s1 (e#es) (s3, Rval (v#vs)) |

cons2:

P s1 e (s2, Rerr err) \Longrightarrow
 evaluate-list P s1 (e#es) (s2, Rerr err) |

cons3:

P s1 e (s2, Rval v) \Longrightarrow
 evaluate-list P s2 es (s3, Rerr err) \Longrightarrow
 evaluate-list P s1 (e#es) (s3, Rerr err)

lemma evaluate-list-mono-strong[intro?]:

assumes evaluate-list R s es r

assumes \bigwedge s e r. e \in set es \Longrightarrow R s e r \Longrightarrow Q s e r

shows evaluate-list Q s es r

\langle proof \rangle

lemma evaluate-list-mono[mono]:

assumes $R \leq Q$

shows evaluate-list $R \leq$ evaluate-list Q

\langle proof \rangle

inductive evaluate :: v sem-env \Rightarrow 'ffi state \Rightarrow exp \Rightarrow 'ffi state*(v,v) result \Rightarrow bool where

lit:

evaluate env s (Lit l) (s, Rval (Litv l)) |

raise1:

evaluate env s1 e (s2, Rval v) \Longrightarrow
 evaluate env s1 (Raise e) (s2, Rerr (Rraise v)) |

raise2:

evaluate env s1 e (s2, Rerr err) \Longrightarrow
 evaluate env s1 (Raise e) (s2, Rerr err) |

handle1:

evaluate env s1 e (s2, Rval v) \Longrightarrow
 evaluate env s1 (Handle e pes) (s2, Rval v) |

handle2:

evaluate env s1 e (s2, Rerr (Rraise v)) \Longrightarrow

$match\text{-}result\ env\ s2\ v\ pes\ v = Rval\ (e',\ env') \implies$
 $evaluate\ (env\ \{\ sem\text{-}env.v := nsAppend\ (alist\text{-}to\text{-}ns\ env')\ (sem\text{-}env.v\ env)\ \})\ s2$
 $e'\ bv \implies$
 $evaluate\ env\ s1\ (Handle\ e\ pes)\ bv\ |$

handle2b:

$evaluate\ env\ s1\ e\ (s2,\ Rerr\ (Rraise\ v)) \implies$
 $match\text{-}result\ env\ s2\ v\ pes\ v = Rerr\ err \implies$
 $evaluate\ env\ s1\ (Handle\ e\ pes)\ (s2,\ Rerr\ err)\ |$

handle3:

$evaluate\ env\ s1\ e\ (s2,\ Rerr\ (Rabort\ a)) \implies$
 $evaluate\ env\ s1\ (Handle\ e\ pes)\ (s2,\ Rerr\ (Rabort\ a))\ |$

con1:

$do\text{-}con\text{-}check\ (c\ env)\ cn\ (length\ es) \implies$
 $build\text{-}conv\ (c\ env)\ cn\ (rev\ vs) = Some\ v \implies$
 $evaluate\text{-}list\ (evaluate\ env)\ s1\ (rev\ es)\ (s2,\ Rval\ vs) \implies$
 $evaluate\ env\ s1\ (Con\ cn\ es)\ (s2,\ Rval\ v)\ |$

con2:

$\neg(do\text{-}con\text{-}check\ (c\ env)\ cn\ (length\ es)) \implies$
 $evaluate\ env\ s\ (Con\ cn\ es)\ (s,\ Rerr\ (Rabort\ Rtype\text{-}error))\ |$

con3:

$do\text{-}con\text{-}check\ (c\ env)\ cn\ (length\ es) \implies$
 $evaluate\text{-}list\ (evaluate\ env)\ s1\ (rev\ es)\ (s2,\ Rerr\ err) \implies$
 $evaluate\ env\ s1\ (Con\ cn\ es)\ (s2,\ Rerr\ err)\ |$

var1:

$nsLookup\ (sem\text{-}env.v\ env)\ n = Some\ v \implies$
 $evaluate\ env\ s\ (Var\ n)\ (s,\ Rval\ v)\ |$

var2:

$nsLookup\ (sem\text{-}env.v\ env)\ n = None \implies$
 $evaluate\ env\ s\ (Var\ n)\ (s,\ Rerr\ (Rabort\ Rtype\text{-}error))\ |$

fn:

$evaluate\ env\ s\ (Fun\ n\ e)\ (s,\ Rval\ (Closure\ env\ n\ e))\ |$

app1:

$evaluate\text{-}list\ (evaluate\ env)\ s1\ (rev\ es)\ (s2,\ Rval\ vs) \implies$
 $do\text{-}opapp\ (rev\ vs) = Some\ (env',\ e) \implies$
 $evaluate\ env'\ s2\ e\ bv \implies$
 $evaluate\ env\ s1\ (App\ Opapp\ es)\ bv\ |$

app3:

$evaluate\text{-}list\ (evaluate\ env)\ s1\ (rev\ es)\ (s2,\ Rval\ vs) \implies$
 $(do\text{-}opapp\ (rev\ vs) = None) \implies$

$evaluate\ env\ s1\ (App\ Opapp\ es)\ (s2,\ Rerr\ (Rabort\ Rtype-error))\ |$

app4:

$evaluate-list\ (evaluate\ env)\ s1\ (rev\ es)\ (s2,\ Rval\ vs)\ \Longrightarrow$
 $do-app\ (refs\ s2,\ ffi\ s2)\ op0\ (rev\ vs)\ =\ Some\ ((refs',ffi'),\ res)\ \Longrightarrow$
 $op0\ \neq\ Opapp\ \Longrightarrow$
 $evaluate\ env\ s1\ (App\ op0\ es)\ (s2\ (\!|refs:=refs',ffi:=ffi'|),\ res)\ |$

app5:

$evaluate-list\ (evaluate\ env)\ s1\ (rev\ es)\ (s2,\ Rval\ vs)\ \Longrightarrow$
 $do-app\ (refs\ s2,\ ffi\ s2)\ op0\ (rev\ vs)\ =\ None\ \Longrightarrow$
 $op0\ \neq\ Opapp\ \Longrightarrow$
 $evaluate\ env\ s1\ (App\ op0\ es)\ (s2,\ Rerr\ (Rabort\ Rtype-error))\ |$

app6:

$evaluate-list\ (evaluate\ env)\ s1\ (rev\ es)\ (s2,\ Rerr\ err)\ \Longrightarrow$
 $evaluate\ env\ s1\ (App\ op0\ es)\ (s2,\ Rerr\ err)\ |$

log1:

$evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1)\ \Longrightarrow$
 $do-log\ op0\ v1\ e2\ =\ Some\ (Exp\ e')\ \Longrightarrow$
 $evaluate\ env\ s2\ e'\ bv\ \Longrightarrow$
 $evaluate\ env\ s1\ (Log\ op0\ e1\ e2)\ bv\ |$

log2:

$evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1)\ \Longrightarrow$
 $(do-log\ op0\ v1\ e2\ =\ Some\ (Val\ bv))\ \Longrightarrow$
 $evaluate\ env\ s1\ (Log\ op0\ e1\ e2)\ (s2,\ Rval\ bv)\ |$

log3:

$evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1)\ \Longrightarrow$
 $(do-log\ op0\ v1\ e2\ =\ None)\ \Longrightarrow$
 $evaluate\ env\ s1\ (Log\ op0\ e1\ e2)\ (s2,\ Rerr\ (Rabort\ Rtype-error))\ |$

log4:

$evaluate\ env\ s\ e1\ (s',\ Rerr\ err)\ \Longrightarrow$
 $evaluate\ env\ s\ (Log\ op0\ e1\ e2)\ (s',\ Rerr\ err)\ |$

if1:

$evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1)\ \Longrightarrow$
 $do-if\ v1\ e2\ e3\ =\ Some\ e'\ \Longrightarrow$
 $evaluate\ env\ s2\ e'\ bv\ \Longrightarrow$
 $evaluate\ env\ s1\ (If\ e1\ e2\ e3)\ bv\ |$

if2:

$evaluate\ env\ s1\ e1\ (s2,\ Rval\ v1)\ \Longrightarrow$
 $(do-if\ v1\ e2\ e3\ =\ None)\ \Longrightarrow$
 $evaluate\ env\ s1\ (If\ e1\ e2\ e3)\ (s2,\ Rerr\ (Rabort\ Rtype-error))\ |$

if3:

evaluate env s e1 (s', Rerr err) ==>
evaluate env s (If e1 e2 e3) (s', Rerr err) |

mat1:

evaluate env s1 e (s2, Rval v1) ==>
match-result env s2 v1 pes Bindv = Rval (e', env') ==>
evaluate (env (| sem-env.v := nsAppend (alist-to-ns env') (sem-env.v env) |)) s2
e' bv ==>
evaluate env s1 (Mat e pes) bv |

mat1b:

evaluate env s1 e (s2, Rval v1) ==>
match-result env s2 v1 pes Bindv = Rerr err ==>
evaluate env s1 (Mat e pes) (s2, Rerr err) |

mat2:

evaluate env s e (s', Rerr err) ==>
evaluate env s (Mat e pes) (s', Rerr err) |

let1:

evaluate env s1 e1 (s2, Rval v1) ==>
evaluate (env (| sem-env.v := (nsOptBind n v1 (sem-env.v env)) |)) s2 e2 bv ==>
evaluate env s1 (Let n e1 e2) bv |

let2:

evaluate env s e1 (s', Rerr err) ==>
evaluate env s (Let n e1 e2) (s', Rerr err) |

letrec1:

distinct (List.map (λx .
(case x of (x,y,z) => x)) funs) ==>
evaluate (env (| sem-env.v := (build-rec-env funs env (sem-env.v env)) |)) s e bv
==>
evaluate env s (Letrec funs e) bv |

letrec2:

¬ (distinct (List.map (λx .
(case x of (x,y,z) => x)) funs) ==>
evaluate env s (Letrec funs e) (s, Rerr (Rabort Rtype-error)) |

tannot:

evaluate env s e bv ==>
evaluate env s (Tannot e t0) bv |

locannot:

evaluate env s e bv ==>
evaluate env s (Lannot e l) bv

lemma *unclocked-single-list-sound:*

evaluate-list (Big-Step-Unclocked.evaluate v) s es bv \implies Big-Step-Unclocked.evaluate-list v s es bv
<proof>

lemma *unclocked-single-sound:*

evaluate v s e bv \implies Big-Step-Unclocked.evaluate v s e bv
<proof>

lemma *unclocked-single-complete:*

Big-Step-Unclocked.evaluate-list v s es bv1 \implies evaluate-list (evaluate v) s es bv1
Big-Step-Unclocked.evaluate v s e bv2 \implies evaluate v s e bv2
<proof>

corollary *unclocked-single-eq:*

evaluate = Big-Step-Unclocked.evaluate
<proof>

corollary *unclocked-single-eq':*

evaluate = BigStep.evaluate False
<proof>

corollary *unclocked-single-determ:*

evaluate env s e r3a \implies evaluate env s e r3b \implies r3a = r3b
<proof>

lemma *unclocked-single-fun-eq:*

*(($\exists k. Evaluate-Single.evaluate env (s \{ clock := k \}) e = (s', r)$) \wedge $r \neq Rerr$
 $(Rabort Rtimeout-error) \wedge (clock s) = (clock s')$) =
evaluate env s e (s',r)
*<proof>**

end

Chapter 23

Matching adaptation

```
theory Matching
imports Semantic-Extras
begin
```

```
context begin
```

```
qualified fun fold2 where
fold2 f err [] [] init = init |
fold2 f err (x # xs) (y # ys) init = fold2 f err xs ys (f x y init) |
fold2 - err - - - = err
```

```
qualified lemma fold2-cong[fundef-cong]:
assumes init1 = init2 err1 = err2 xs1 = xs2 ys1 = ys2
assumes  $\bigwedge$ init x y. x  $\in$  set xs1  $\implies$  y  $\in$  set ys1  $\implies$  f x y init = g x y init
shows fold2 f err1 xs1 ys1 init1 = fold2 g err2 xs2 ys2 init2
<proof>
```

```
fun pmatch-single :: ((string),(string),(nat*tid-or-exn))namespace  $\implies$  ((v)store-v)list
 $\implies$  pat  $\implies$  v  $\implies$  (string*v)list  $\implies$  ((string*v)list)match-result where
pmatch-single envC s Pany v' env = ( Match env ) |
pmatch-single envC s (Pvar x) v' env = ( Match ((x,v')# env) ) |
pmatch-single envC s (Plit l) (Litv l') env = (
  if l = l' then
    Match env
  else if lit-same-type l l' then
    No-match
  else
    Match-type-error ) |
pmatch-single envC s (Pcon (Some n) ps) (Conv (Some (n', t')) vs) env =
  (case nsLookup envC n of
    Some (l, t1) =>
      if same-tid t1 t'  $\wedge$  (List.length ps = l) then
        if same-ctor (id-to-n n, t1) (n',t') then
          fold2 ( $\lambda$ p v m. case m of
```



```

      Match env ⇒ pmatch-single envC s p v env
    | m ⇒ m) Match-type-error ps vs (Match env)
  else
    No-match
  else
    Match-type-error
  | - => Match-type-error
) |
pmatch-single envC s (Pcon None ps) (Conv None vs) env = (
  if List.length ps = List.length vs then
    fold2 (λp v m. case m of
      Match env ⇒ pmatch-single envC s p v env
    | m ⇒ m)
      Match-type-error ps vs (Match env)
  else
    Match-type-error ) |
pmatch-single envC s (Pref p) (Loc lnum) env =
  (case store-lookup lnum s of
    Some (Refv v2) => pmatch-single envC s p v2 env
  | Some - => Match-type-error
  | None => Match-type-error
) |
pmatch-single envC s (Ptannot p t1) v2 env = pmatch-single envC s p v2 env |
pmatch-single envC - - - env = Match-type-error

```

private lemma *pmatch-list-length-neq*:

```

length vs ≠ length ps ⇒ fold2(λp v m. case m of
  Match env ⇒ pmatch-single envC s p v env
| m ⇒ m) Match-type-error ps vs m = Match-type-error

```

<proof> **lemma** *pmatch-list-nomatch*:

```

length vs = length ps ⇒ fold2(λp v m. case m of
  Match env ⇒ pmatch-single envC s p v env
| m ⇒ m) Match-type-error ps vs No-match = No-match

```

<proof> **lemma** *pmatch-list-typer*:

```

length vs = length ps ⇒ fold2(λp v m. case m of
  Match env ⇒ pmatch-single envC s p v env
| m ⇒ m) Match-type-error ps vs Match-type-error = Match-type-error

```

<proof> **lemma** *pmatch-single-eq0*:

```

length ps = length vs ⇒ pmatch-list envC s ps vs env = fold2(λp v m. case m of
  Match env ⇒ pmatch-single envC s p v env
| m ⇒ m) Match-type-error ps vs (Match env)
pmatch envC s p v0 env = pmatch-single envC s p v0 env

```

<proof>

lemma *pmatch-single-equiv*: *pmatch = pmatch-single*

<proof>

end

```
export-code pmatch-single checking SML  
end
```

Chapter 24

Code generation

```
theory CakeML-Code
imports
  Evaluate-Single
  Matching
  generated/CakeML/PrimTypes
begin

hide-const (open) Lib.the

declare evaluate-list-eq[code-unfold]
declare fix-clock-evaluate[code-unfold]
declare fun-evaluate-equiv[code]
declare pmatch-single-equiv[code]

declare [[code abort: failwith fp64-negate fp64-sqrt fp64-sub fp64-mul fp64-div fp64-add
fp64-abs]]

definition empty-ffi-state :: unit ffi-state where
empty-ffi-state = initial-ffi-state ( $\lambda$ - - - . Oracle-fail) ()

context begin

private definition prim-sem-res where
prim-sem-res = Option.the (prim-sem-env empty-ffi-state)

<ML>

value [simp] prim-sem-res

definition prim-sem-env where prim-sem-env = snd prim-sem-res
definition prim-sem-state where prim-sem-state = fst prim-sem-res

end
```

export-code *evaluate fun-evaluate fun-evaluate-prog prim-sem-env*
checking *SML*

— Test

lemma *snd (evaluate prim-sem-env prim-sem-state (Lit (IntLit 1))) = Rval (Litv*
(IntLit 1))
<proof>

end

Chapter 25

Quickcheck setup (fishy)

```
theory CakeML-Quickcheck
imports
  generated/CakeML/SemanticPrimitives
begin

datatype-compat namespace
datatype-compat t
datatype-compat pat
datatype-compat sem-env

context begin

qualified definition handle-0 where
handle-0 n = Handle n []

qualified definition handle-1 where
handle-1 n p1 e1 = Handle n [(p1, e1)]

qualified definition handle-2 where
handle-2 n p1 e1 p2 e2 = Handle n [(p1, e1), (p2, e2)]

qualified definition con-0 where
con-0 n = Con n []

qualified definition con-1 where
con-1 n e1 = Con n [e1]

qualified definition con-2 where
con-2 n e1 e2 = Con n [e1, e2]

qualified definition app-0 where
app-0 n = App n []

qualified definition app-1 where
```

$app-1\ n\ e1 = App\ n\ [e1]$

qualified definition *app-2* **where**

$app-2\ n\ e1\ e2 = App\ n\ [e1, e2]$

qualified definition *mat-0* **where**

$mat-0\ n = Mat\ n\ []$

qualified definition *mat-1* **where**

$mat-1\ n\ p1\ e1 = Mat\ n\ [(p1, e1)]$

qualified definition *mat-2* **where**

$mat-2\ n\ p1\ e1\ p2\ e2 = Mat\ n\ [(p1, e1), (p2, e2)]$

qualified definition *conv-0* **where**

$conv-0\ n = Conv\ n\ []$

qualified definition *conv-1* **where**

$conv-1\ n\ v1 = Conv\ n\ [v1]$

qualified definition *conv-2* **where**

$conv-2\ n\ v1\ v2 = Conv\ n\ [v1, v2]$

qualified definition *closure-dummy* **where**

$closure-dummy\ es\ var = Closure\ (\ v = Bind\ []\ [],\ c = Bind\ []\ []\)\ es\ var$

qualified definition *recclosure-dummy* **where**

$recclosure-dummy\ es\ var = Recclosure\ (\ v = Bind\ []\ [],\ c = Bind\ []\ []\)\ es\ var$

qualified definition *vectorv-0* **where**

$vectorv-0 = Vectorv\ []$

qualified definition *vectorv-1* **where**

$vectorv-1\ v1 = Vectorv\ [v1]$

qualified definition *vectorv-2* **where**

$vectorv-2\ v1\ v2 = Vectorv\ [v1, v2]$

end

quickcheck-generator *exp0*

constructors:

Raise,

CakeML-Quickcheck.handle-0,

CakeML-Quickcheck.handle-1,

CakeML-Quickcheck.handle-2,

Lit,

CakeML-Quickcheck.con-0,

CakeML-Quickcheck.con-1,

CakeML-Quickcheck.con-2,
Var,
Fun,
CakeML-Quickcheck.app-0,
CakeML-Quickcheck.app-1,
CakeML-Quickcheck.app-2,
Log,
If,
CakeML-Quickcheck.mat-0,
CakeML-Quickcheck.mat-1,
CakeML-Quickcheck.mat-2,
Let,
Tannot,
Lannot

quickcheck-generator *v*

constructors:

Litv,
CakeML-Quickcheck.conv-0,
CakeML-Quickcheck.conv-1,
CakeML-Quickcheck.conv-2,
CakeML-Quickcheck.closure-dummy,
CakeML-Quickcheck.recclosure-dummy,
Loc,
CakeML-Quickcheck.vectorv-0,
CakeML-Quickcheck.vectorv-1,
CakeML-Quickcheck.vectorv-2

quickcheck-generator *dec*

constructors: *Dlet*, *Dletrec*, *Dtype*, *Dabbrev*, *Dexn*

lemma

fixes *t* :: *dec*

shows *t* ≠ *t*

quickcheck [*expect = counterexample, timeout = 90*]

quickcheck [*random, expect = counterexample, timeout = 90*]

⟨*proof*⟩

lemma

fixes *t* :: *v*

shows *t* ≠ *t*

quickcheck [*expect = counterexample, timeout = 90*]

quickcheck [*random, expect = counterexample, timeout = 90*]

⟨*proof*⟩

end

Chapter 26

CakeML Compiler

```
theory CakeML-Compiler
imports
  generated/CakeML/Ast
  Show.Show-Instances
keywords cakeml :: diag
begin

hide-const (open) Lem-string.concat

 $\langle ML \rangle$ 

end
```