# WebAssembly

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**Abstract**

This is a mechanised specification of the WebAssembly language, drawn mainly from the previously published paper formalisation [1]. Also included is a full proof of soundness of the type system, together with a verified type checker and interpreter. We include only a partial procedure for the extraction of the type checker and interpreter here. For more details, please see our paper [2].

## Contents

# 1 WebAssembly Core AST

**theory** *Wasm-Ast*
**imports**
*Main*
*Native-Word.Uint8*
*Word-Lib.Reversed-Bit-Lists*
**begin**

**type-synonym** — immediate
*i* = *nat*
**type-synonym** — static offset
*off* = *nat*
**type-synonym** — alignment exponent
*a* = *nat*

— primitive types
**typedecl** *i32*
**typedecl** *i64*
**typedecl** *f32*
**typedecl** *f64*

— memory
**type-synonym** *byte* = *uint8*

**typedef** *bytes* = *UNIV* :: (*byte list*) *set* **..**
**setup-lifting** *type-definition-bytes*
**declare** *Quotient-bytes*[*transfer-rule*]

**lift-definition** *bytes-takefill* :: *byte* ⇒ *nat* ⇒ *bytes* ⇒ *bytes* **is** (λ*a n as*. *takefill* (*Abs-uint8 a*) *n as*) **.**
**lift-definition** *bytes-replicate* :: *nat* ⇒ *byte* ⇒ *bytes* **is** (λ*n b*. *replicate n* (*Abs-uint8 b*)) **.**
**definition** *msbyte* :: *bytes* ⇒ *byte* **where**
*msbyte bs* = *last* (*Rep-bytes bs*)

**typedef** *mem* = *UNIV* :: (*byte list*) *set* **..**
**setup-lifting** *type-definition-mem*
**declare** *Quotient-mem*[*transfer-rule*]

**lift-definition** *read-bytes* :: *mem* ⇒ *nat* ⇒ *nat* ⇒ *bytes* **is** (λ*m n l*. *take l* (*drop n m*)) **.**
**lift-definition** *write-bytes* :: *mem* ⇒ *nat* ⇒ *bytes* ⇒ *mem* **is** (λ*m n bs*. (*take n m*) @ *bs* @ (*drop* (*n* + *length bs*) *m*)) **.**
**lift-definition** *mem-append* :: *mem* ⇒ *bytes* ⇒ *mem* **is** *append* **.**

— host

**typedecl** *host*
**typedecl** *host-state*

**datatype** — value types
  *t* = *T-i32* | *T-i64* | *T-f32* | *T-f64*

**datatype** — packed types
  *tp* = *Tp-i8* | *Tp-i16* | *Tp-i32*

**datatype** — mutability
  *mut* = *T-immut* | *T-mut*

**record** *tg* = — global types
  *tg-mut* :: *mut*
  *tg-t* :: *t*

**datatype** — function types
  *tf* = *Tf t list t list* (- ′-> - *60*)

**record** *t-context* =
  *types-t* :: *tf list*
  *func-t* :: *tf list*
  *global* :: *tg list*
  *table* :: *nat option*
  *memory* :: *nat option*
  *local* :: *t list*
  *label* :: (*t list*) *list*
  *return* :: (*t list*) *option*

**record** *s-context* =
  *s-inst* :: *t-context list*
  *s-funcs* :: *tf list*
  *s-tab* :: *nat list*
  *s-mem* :: *nat list*
  *s-globs* :: *tg list*

**datatype**
  *sx* = *S* | *U*

**datatype**
  *unop-i* = *Clz* | *Ctz* | *Popcnt*

**datatype**
  *unop-f* = *Neg* | *Abs* | *Ceil* | *Floor* | *Trunc* | *Nearest* | *Sqrt*

**datatype**
  *binop-i* = *Add* | *Sub* | *Mul* | *Div sx* | *Rem sx* | *And* | *Or* | *Xor* | *Shl* | *Shr sx* | *Rotl* | *Rotr*

**datatype**
*binop-f* = *Addf* | *Subf* | *Mulf* | *Divf* | *Min* | *Max* | *Copysign*

**datatype**
*testop* = *Eqz*

**datatype**
*relop-i* = *Eq* | *Ne* | *Lt sx* | *Gt sx* | *Le sx* | *Ge sx*

**datatype**
*relop-f* = *Eqf* | *Nef* | *Ltf* | *Gtf* | *Lef* | *Gef*

**datatype**
*cvtop* = *Convert* | *Reinterpret*

**datatype** — values
*v* =
*ConstInt32 i32*
| *ConstInt64 i64*
| *ConstFloat32 f32*
| *ConstFloat64 f64*

**datatype** — basic instructions
*b-e* =
*Unreachable*
| *Nop*
| *Drop*
| *Select*
| *Block tf b-e list*
| *Loop tf b-e list*
| *If tf b-e list b-e list*
| *Br i*
| *Br-if i*
| *Br-table i list i*
| *Return*
| *Call i*
| *Call-indirect i*
| *Get-local i*
| *Set-local i*
| *Tee-local i*
| *Get-global i*
| *Set-global i*
| *Load t* (*tp* × *sx*) *option a off*
| *Store t tp option a off*
| *Current-memory*
| *Grow-memory*
| *EConst v* (*C - 60*)
| *Unop-i t unop-i*

```
    | Unop-f t unop-f
    | Binop-i t binop-i
    | Binop-f t binop-f
    | Testop t testop
    | Relop-i t relop-i
    | Relop-f t relop-f
    | Cvtop t cvtop t sx option

datatype cl = — function closures
  Func-native i tf t list b-e list
| Func-host tf host

record inst = — instances
  types :: tf list
  funcs :: i list
  tab :: i option
  mem :: i option
  globs :: i list

type-synonym tabinst = (cl option) list

record global =
  g-mut :: mut
  g-val :: v

record s = — store
  inst :: inst list
  funcs :: cl list
  tab :: tabinst list
  mem :: mem list
  globs :: global list

datatype e = — administrative instruction
  Basic b-e ($- 60)
  | Trap
  | Callcl cl
  | Label nat e list e list
  | Local nat i v list e list

datatype Lholed =
    — L0 = v* [<hole>] e*
    LBase e list e list
    — L(i+1) = v* (label n e*  Li) e*
  | LRec e list nat e list Lholed e list
end
```

# 2 Syntactic Typeclasses

```
theory Wasm-Type-Abs imports Main begin
```

**class** *wasm-base* = *zero*

**class** *wasm-int* = *wasm-base* +

  **fixes** *int-clz* :: *'a* ⇒ *'a*
  **fixes** *int-ctz* :: *'a* ⇒ *'a*
  **fixes** *int-popcnt* :: *'a* ⇒ *'a*

  **fixes** *int-add* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-sub* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-mul* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-div-u* :: *'a* ⇒ *'a* ⇒ *'a option*
  **fixes** *int-div-s* :: *'a* ⇒ *'a* ⇒ *'a option*
  **fixes** *int-rem-u* :: *'a* ⇒ *'a* ⇒ *'a option*
  **fixes** *int-rem-s* :: *'a* ⇒ *'a* ⇒ *'a option*
  **fixes** *int-and* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-or* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-xor* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-shl* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-shr-u* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-shr-s* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-rotl* :: *'a* ⇒ *'a* ⇒ *'a*
  **fixes** *int-rotr* :: *'a* ⇒ *'a* ⇒ *'a*

  **fixes** *int-eqz* :: *'a* ⇒ *bool*

  **fixes** *int-eq* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-lt-u* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-lt-s* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-gt-u* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-gt-s* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-le-u* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-le-s* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-ge-u* :: *'a* ⇒ *'a* ⇒ *bool*
  **fixes** *int-ge-s* :: *'a* ⇒ *'a* ⇒ *bool*

  **fixes** *int-of-nat* :: *nat* ⇒ *'a*
  **fixes** *nat-of-int* :: *'a* ⇒ *nat*
**begin**
  **abbreviation** (*input*)
  *int-ne* **where**
    *int-ne x y* ≡ ¬ (*int-eq x y*)
**end**

**class** *wasm-float* = *wasm-base* +

  **fixes** *float-neg*  :: *'a* ⇒ *'a*
  **fixes** *float-abs*  :: *'a* ⇒ *'a*

**fixes** *float-ceil* :: $'a \Rightarrow 'a$
**fixes** *float-floor* :: $'a \Rightarrow 'a$
**fixes** *float-trunc* :: $'a \Rightarrow 'a$
**fixes** *float-nearest* :: $'a \Rightarrow 'a$
**fixes** *float-sqrt* :: $'a \Rightarrow 'a$

**fixes** *float-add* :: $'a \Rightarrow 'a \Rightarrow 'a$
**fixes** *float-sub* :: $'a \Rightarrow 'a \Rightarrow 'a$
**fixes** *float-mul* :: $'a \Rightarrow 'a \Rightarrow 'a$
**fixes** *float-div* :: $'a \Rightarrow 'a \Rightarrow 'a$
**fixes** *float-min* :: $'a \Rightarrow 'a \Rightarrow 'a$
**fixes** *float-max* :: $'a \Rightarrow 'a \Rightarrow 'a$
**fixes** *float-copysign* :: $'a \Rightarrow 'a \Rightarrow 'a$

**fixes** *float-eq* :: $'a \Rightarrow 'a \Rightarrow bool$
**fixes** *float-lt* :: $'a \Rightarrow 'a \Rightarrow bool$
**fixes** *float-gt* :: $'a \Rightarrow 'a \Rightarrow bool$
**fixes** *float-le* :: $'a \Rightarrow 'a \Rightarrow bool$
**fixes** *float-ge* :: $'a \Rightarrow 'a \Rightarrow bool$
**begin**
**abbreviation** (*input*)
*float-ne* **where**
*float-ne x y* $\equiv \neg$ (*float-eq x y*)
**end**
**end**

# 3 WebAssembly Base Definitions

**theory** *Wasm-Base-Defs* **imports** *Wasm-Ast Wasm-Type-Abs* **begin**

**instantiation** *i32* :: *wasm-int* **begin instance .. end**
**instantiation** *i64* :: *wasm-int* **begin instance .. end**
**instantiation** *f32* :: *wasm-float* **begin instance .. end**
**instantiation** *f64* :: *wasm-float* **begin instance .. end**

**consts**

*ui32-trunc-f32* :: *f32* $\Rightarrow$ *i32 option*
*si32-trunc-f32* :: *f32* $\Rightarrow$ *i32 option*
*ui32-trunc-f64* :: *f64* $\Rightarrow$ *i32 option*
*si32-trunc-f64* :: *f64* $\Rightarrow$ *i32 option*

*ui64-trunc-f32* :: *f32* $\Rightarrow$ *i64 option*
*si64-trunc-f32* :: *f32* $\Rightarrow$ *i64 option*
*ui64-trunc-f64* :: *f64* $\Rightarrow$ *i64 option*
*si64-trunc-f64* :: *f64* $\Rightarrow$ *i64 option*

*f32-convert-ui32* :: *i32* $\Rightarrow$ *f32*

```
f32-convert-si32 :: i32 ⇒ f32
f32-convert-ui64 :: i64 ⇒ f32
f32-convert-si64 :: i64 ⇒ f32

f64-convert-ui32 :: i32 ⇒ f64
f64-convert-si32 :: i32 ⇒ f64
f64-convert-ui64 :: i64 ⇒ f64
f64-convert-si64 :: i64 ⇒ f64

wasm-wrap :: i64 ⇒ i32
wasm-extend-u :: i32 ⇒ i64
wasm-extend-s :: i32 ⇒ i64
wasm-demote :: f64 ⇒ f32
wasm-promote :: f32 ⇒ f64

serialise-i32 :: i32 ⇒ bytes
serialise-i64 :: i64 ⇒ bytes
serialise-f32 :: f32 ⇒ bytes
serialise-f64 :: f64 ⇒ bytes
wasm-bool :: bool ⇒ i32
int32-minus-one :: i32


definition mem-size :: mem ⇒ nat where
  mem-size m = length (Rep-mem m)

definition mem-grow :: mem ⇒ nat ⇒ mem where
  mem-grow m n = mem-append m (bytes-replicate (n * 64000) 0)

definition load :: mem ⇒ nat ⇒ off ⇒ nat ⇒ bytes option where
  load m n off l = (if (mem-size m ≥ (n+off+l))
                    then Some (read-bytes m (n+off) l)
                    else None)

definition sign-extend :: sx ⇒ nat ⇒ bytes ⇒ bytes where
  sign-extend sx l bytes = (let msb = msb (msbyte bytes) in
                      let byte = (case sx of U ⇒ 0 | S ⇒ if msb then −1 else 0) in
                       bytes-takefill byte l bytes)

definition load-packed :: sx ⇒ mem ⇒ nat ⇒ off ⇒ nat ⇒ nat ⇒ bytes option
where
  load-packed sx m n off lp l = map-option (sign-extend sx l) (load m n off lp)

definition store :: mem ⇒ nat ⇒ off ⇒ bytes ⇒ nat ⇒ mem option where
  store m n off bs l = (if (mem-size m ≥ (n+off+l))
                        then Some (write-bytes m (n+off) (bytes-takefill 0 l bs))
                        else None)

definition store-packed :: mem ⇒ nat ⇒ off ⇒ bytes ⇒ nat ⇒ mem option
```

**where**
*store-packed* = *store*

**consts**
*wasm-deserialise* :: *bytes* ⇒ *t* ⇒ *v*

*host-apply* :: *s* ⇒ *tf* ⇒ *host* ⇒ *v list* ⇒ *host-state* ⇒ (*s* × *v list*) *option*

**definition** *typeof* :: *v* ⇒ *t* **where**
*typeof v* = (*case v of*
*ConstInt32 -* ⇒ *T-i32*
| *ConstInt64 -* ⇒ *T-i64*
| *ConstFloat32 -* ⇒ *T-f32*
| *ConstFloat64 -* ⇒ *T-f64*)

**definition** *option-projl* :: ('*a* × '*b*) *option* ⇒ '*a option* **where**
*option-projl x* = *map-option fst x*

**definition** *option-projr* :: ('*a* × '*b*) *option* ⇒ '*b option* **where**
*option-projr x* = *map-option snd x*

**definition** *t-length* :: *t* ⇒ *nat* **where**
*t-length t* = (*case t of*
*T-i32* ⇒ *4*
| *T-i64* ⇒ *8*
| *T-f32* ⇒ *4*
| *T-f64* ⇒ *8*)

**definition** *tp-length* :: *tp* ⇒ *nat* **where**
*tp-length tp* = (*case tp of*
*Tp-i8* ⇒ *1*
| *Tp-i16* ⇒ *2*
| *Tp-i32* ⇒ *4*)

**definition** *is-int-t* :: *t* ⇒ *bool* **where**
*is-int-t t* = (*case t of*
*T-i32* ⇒ *True*
| *T-i64* ⇒ *True*
| *T-f32* ⇒ *False*
| *T-f64* ⇒ *False*)

**definition** *is-float-t* :: *t* ⇒ *bool* **where**
*is-float-t t* = (*case t of*
*T-i32* ⇒ *False*
| *T-i64* ⇒ *False*
| *T-f32* ⇒ *True*
| *T-f64* ⇒ *True*)

**definition** *is-mut* :: *tg* ⇒ *bool* **where**

```
  is-mut tg = (tg-mut tg = T-mut)

definition app-unop-i :: unop-i ⇒ 'i::wasm-int ⇒ 'i::wasm-int where
  app-unop-i iop c =
    (case iop of
    Ctz ⇒ int-ctz c
  | Clz ⇒ int-clz c
  | Popcnt ⇒ int-popcnt c)

definition app-unop-f :: unop-f ⇒ 'f::wasm-float ⇒ 'f::wasm-float where
  app-unop-f fop c =
              (case fop of
                 Neg ⇒ float-neg c
               | Abs ⇒ float-abs c
               | Ceil ⇒ float-ceil c
               | Floor ⇒ float-floor c
               | Trunc ⇒ float-trunc c
               | Nearest ⇒ float-nearest c
               | Sqrt ⇒ float-sqrt c)

definition app-binop-i :: binop-i ⇒ 'i::wasm-int ⇒ 'i::wasm-int ⇒ ('i::wasm-int)
option where
  app-binop-i iop c1 c2 = (case iop of
                            Add ⇒ Some (int-add c1 c2)
                          | Sub ⇒ Some (int-sub c1 c2)
                          | Mul ⇒ Some (int-mul c1 c2)
                          | Div U ⇒ int-div-u c1 c2
                          | Div S ⇒ int-div-s c1 c2
                          | Rem U ⇒ int-rem-u c1 c2
                          | Rem S ⇒ int-rem-s c1 c2
                          | And ⇒ Some (int-and c1 c2)
                          | Or ⇒ Some (int-or c1 c2)
                          | Xor ⇒ Some (int-xor c1 c2)
                          | Shl ⇒ Some (int-shl c1 c2)
                          | Shr U ⇒ Some (int-shr-u c1 c2)
                          | Shr S ⇒ Some (int-shr-s c1 c2)
                          | Rotl ⇒ Some (int-rotl c1 c2)
                          | Rotr ⇒ Some (int-rotr c1 c2))

definition app-binop-f :: binop-f ⇒ 'f::wasm-float ⇒ 'f::wasm-float ⇒ ('f::wasm-float)
option where
  app-binop-f fop c1 c2 = (case fop of
                            Addf ⇒ Some (float-add c1 c2)
                          | Subf ⇒ Some (float-sub c1 c2)
                          | Mulf ⇒ Some (float-mul c1 c2)
                          | Divf ⇒ Some (float-div c1 c2)
                          | Min ⇒ Some (float-min c1 c2)
                          | Max ⇒ Some (float-max c1 c2)
                          | Copysign ⇒ Some (float-copysign c1 c2))
```

**definition** *app-testop-i* :: *testop* ⇒ *'i*::*wasm-int* ⇒ *bool* **where**
*app-testop-i testop c* = (*case testop of Eqz* ⇒ *int-eqz c*)

**definition** *app-relop-i* :: *relop-i* ⇒ *'i*::*wasm-int* ⇒ *'i*::*wasm-int* ⇒ *bool* **where**
*app-relop-i rop c1 c2* = (*case rop of*
*Eq* ⇒ *int-eq c1 c2*
| *Ne* ⇒ *int-ne c1 c2*
| *Lt U* ⇒ *int-lt-u c1 c2*
| *Lt S* ⇒ *int-lt-s c1 c2*
| *Gt U* ⇒ *int-gt-u c1 c2*
| *Gt S* ⇒ *int-gt-s c1 c2*
| *Le U* ⇒ *int-le-u c1 c2*
| *Le S* ⇒ *int-le-s c1 c2*
| *Ge U* ⇒ *int-ge-u c1 c2*
| *Ge S* ⇒ *int-ge-s c1 c2*)

**definition** *app-relop-f* :: *relop-f* ⇒ *'f*::*wasm-float* ⇒ *'f*::*wasm-float* ⇒ *bool* **where**
*app-relop-f rop c1 c2* = (*case rop of*
*Eqf* ⇒ *float-eq c1 c2*
| *Nef* ⇒ *float-ne c1 c2*
| *Ltf* ⇒ *float-lt c1 c2*
| *Gtf* ⇒ *float-gt c1 c2*
| *Lef* ⇒ *float-le c1 c2*
| *Gef* ⇒ *float-ge c1 c2*)

**definition** *types-agree* :: *t* ⇒ *v* ⇒ *bool* **where**
*types-agree t v* = (*typeof v* = *t*)

**definition** *cl-type* :: *cl* ⇒ *tf* **where**
*cl-type cl* = (*case cl of Func-native - tf - -* ⇒ *tf* | *Func-host tf -* ⇒ *tf*)

**definition** *rglob-is-mut* :: *global* ⇒ *bool* **where**
*rglob-is-mut g* = (*g-mut g* = *T-mut*)

**definition** *stypes* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *tf* **where**
*stypes s i j* = ((*types* ((*inst s*)!*i*))!*j*)

**definition** *sfunc-ind* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *nat* **where**
*sfunc-ind s i j* = ((*inst.funcs* ((*inst s*)!*i*))!*j*)

**definition** *sfunc* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *cl* **where**
*sfunc s i j* = (*funcs s*)!(*sfunc-ind s i j*)

**definition** *sglob-ind* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *nat* **where**
*sglob-ind s i j* = ((*inst.globs* ((*inst s*)!*i*))!*j*)

**definition** *sglob* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *global* **where**
*sglob s i j* = (*globs s*)!(*sglob-ind s i j*)

**definition** *sglob-val* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *v* **where**
*sglob-val s i j* = *g-val* (*sglob s i j*)

**definition** *smem-ind* :: *s* ⇒ *nat* ⇒ *nat option* **where**
*smem-ind s i* = (*inst.mem* ((*inst s*)!*i*))

**definition** *stab-s* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *cl option* **where**
*stab-s s i j* = (*let stabinst* = ((*tab s*)!*i*) *in* (*if* (*length* (*stabinst*) > *j*) *then* (*stabinst*!*j*) *else None*))

**definition** *stab* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *cl option* **where**
*stab s i j* = (*case* (*inst.tab* ((*inst s*)!*i*)) *of Some k* => *stab-s s k j* | *None* => *None*)

**definition** *supdate-glob-s* :: *s* ⇒ *nat* ⇒ *v* ⇒ *s* **where**
*supdate-glob-s s k v* = *s*(|*globs* := (*globs s*)[*k*:=((*globs s*)!*k*)(|*g-val* := *v*|)]|)

**definition** *supdate-glob* :: *s* ⇒ *nat* ⇒ *nat* ⇒ *v* ⇒ *s* **where**
*supdate-glob s i j v* = (*let k* = *sglob-ind s i j in supdate-glob-s s k v*)

**definition** *is-const* :: *e* ⇒ *bool* **where**
*is-const e* = (*case e of Basic* (*C* -) ⇒ *True* | - ⇒ *False*)

**definition** *const-list* :: *e list* ⇒ *bool* **where**
*const-list xs* = *list-all is-const xs*

**inductive** *store-extension* :: *s* ⇒ *s* ⇒ *bool* **where**
⟦*insts* = *insts'*; *fs* = *fs'*; *tclss* = *tclss'*; *list-all2* (λ*bs bs'*. *mem-size bs* ≤ *mem-size bs'*) *bss bss'*; *gs* = *gs'*⟧ ⟹
*store-extension* (|*s.inst* = *insts*, *s.funcs* = *fs*, *s.tab* = *tclss*, *s.mem* = *bss*, *s.globs* = *gs*|)
(|*s.inst* = *insts'*, *s.funcs* = *fs'*, *s.tab* = *tclss'*, *s.mem* = *bss'*, *s.globs* = *gs'*|)

**abbreviation** *to-e-list* :: *b-e list* ⇒ *e list* (*$∗ - 60*) **where**
*to-e-list b-es* ≡ *map Basic b-es*

**abbreviation** *v-to-e-list* :: *v list* ⇒ *e list* (*$$∗ - 60*) **where**
*v-to-e-list ves* ≡ *map* (λ*v*. *$C v*) *ves*

**inductive** *Lfilled* :: *nat* ⇒ *Lholed* ⇒ *e list* ⇒ *e list* ⇒ *bool* **where**

*L0*:⟦*const-list vs*; *lholed* = (*LBase vs es'*)⟧ ⟹ *Lfilled 0 lholed es* (*vs* @ *es* @ *es'*)

| *LN*:⟦*const-list vs*; *lholed* = (*LRec vs n es' l es''*); *Lfilled k l es lfilledk*⟧ ⟹ *Lfilled* (*k*+*1*) *lholed es* (*vs* @ [*Label n es' lfilledk*] @ *es''*)

**inductive** *Lfilled-exact* :: *nat* ⇒ *Lholed* ⇒ *e list* ⇒ *e list* ⇒ *bool* **where**

*L0*:⟦*lholed* = (*LBase* [] [])⟧ ⟹ *Lfilled-exact 0 lholed es es*

| *LN*:⟦*const-list vs*; *lholed* = (*LRec vs n es' l es''*); *Lfilled-exact k l es lfilledk*⟧ ⟹ *Lfilled-exact* (*k*+*1*) *lholed es* (*vs* @ [*Label n es' lfilledk*] @ *es''*)

**definition** *load-store-t-bounds* :: *a* ⇒ *tp option* ⇒ *t* ⇒ *bool* **where**
*load-store-t-bounds a tp t* = (*case tp of*
*None* ⇒ *2^a* ≤ *t-length t*
| *Some tp* ⇒ *2^a* ≤ *tp-length tp* ∧ *tp-length tp* < *t-length t* ∧ *is-int-t t*)

**definition** *cvt-i32* :: *sx option* ⇒ *v* ⇒ *i32 option* **where**
*cvt-i32 sx v* = (*case v of*
*ConstInt32 c* ⇒ *None*
| *ConstInt64 c* ⇒ *Some* (*wasm-wrap c*)
| *ConstFloat32 c* ⇒ (*case sx of*
*Some U* ⇒ *ui32-trunc-f32 c*
| *Some S* ⇒ *si32-trunc-f32 c*
| *None* ⇒ *None*)
| *ConstFloat64 c* ⇒ (*case sx of*
*Some U* ⇒ *ui32-trunc-f64 c*
| *Some S* ⇒ *si32-trunc-f64 c*
| *None* ⇒ *None*))

**definition** *cvt-i64* :: *sx option* ⇒ *v* ⇒ *i64 option* **where**
*cvt-i64 sx v* = (*case v of*
*ConstInt32 c* ⇒ (*case sx of*
*Some U* ⇒ *Some* (*wasm-extend-u c*)
| *Some S* ⇒ *Some* (*wasm-extend-s c*)
| *None* ⇒ *None*)
| *ConstInt64 c* ⇒ *None*
| *ConstFloat32 c* ⇒ (*case sx of*
*Some U* ⇒ *ui64-trunc-f32 c*
| *Some S* ⇒ *si64-trunc-f32 c*
| *None* ⇒ *None*)
| *ConstFloat64 c* ⇒ (*case sx of*
*Some U* ⇒ *ui64-trunc-f64 c*
| *Some S* ⇒ *si64-trunc-f64 c*
| *None* ⇒ *None*))

**definition** *cvt-f32* :: *sx option* ⇒ *v* ⇒ *f32 option* **where**
*cvt-f32 sx v* = (*case v of*
*ConstInt32 c* ⇒ (*case sx of*
*Some U* ⇒ *Some* (*f32-convert-ui32 c*)
| *Some S* ⇒ *Some* (*f32-convert-si32 c*)
| - ⇒ *None*)

```
    | ConstInt64 c ⇒ (case sx of
                        Some U ⇒ Some (f32-convert-ui64 c)
                      | Some S ⇒ Some (f32-convert-si64 c)
                      | - ⇒ None)
    | ConstFloat32 c ⇒ None
    | ConstFloat64 c ⇒ Some (wasm-demote c))

definition cvt-f64 :: sx option ⇒ v ⇒ f64 option where
  cvt-f64 sx v = (case v of
                   ConstInt32 c ⇒ (case sx of
                                     Some U ⇒ Some (f64-convert-ui32 c)
                                   | Some S ⇒ Some (f64-convert-si32 c)
                                   | - ⇒ None)
                 | ConstInt64 c ⇒ (case sx of
                                     Some U ⇒ Some (f64-convert-ui64 c)
                                   | Some S ⇒ Some (f64-convert-si64 c)
                                   | - ⇒ None)
                 | ConstFloat32 c ⇒ Some (wasm-promote c)
                 | ConstFloat64 c ⇒ None)

definition cvt :: t ⇒ sx option ⇒ v ⇒ v option where
  cvt t sx v = (case t of
                  T-i32 ⇒ (case (cvt-i32 sx v) of Some c ⇒ Some (ConstInt32 c) |
None ⇒ None)
                | T-i64 ⇒ (case (cvt-i64 sx v) of Some c ⇒ Some (ConstInt64 c) |
None ⇒ None)
                | T-f32 ⇒ (case (cvt-f32 sx v) of Some c ⇒ Some (ConstFloat32 c) |
None ⇒ None)
                | T-f64 ⇒ (case (cvt-f64 sx v) of Some c ⇒ Some (ConstFloat64 c) |
None ⇒ None))

definition bits :: v ⇒ bytes where
  bits v = (case v of
              ConstInt32 c ⇒ (serialise-i32 c)
            | ConstInt64 c ⇒ (serialise-i64 c)
            | ConstFloat32 c ⇒ (serialise-f32 c)
            | ConstFloat64 c ⇒ (serialise-f64 c))

definition bitzero :: t ⇒ v where
  bitzero t = (case t of
                 T-i32 ⇒ ConstInt32 0
               | T-i64 ⇒ ConstInt64 0
               | T-f32 ⇒ ConstFloat32 0
               | T-f64 ⇒ ConstFloat64 0)

definition n-zeros :: t list ⇒ v list where
  n-zeros ts = (map (λt. bitzero t) ts)

lemma is-int-t-exists:
```

**assumes** *is-int-t t*
**shows** *t = T-i32 ∨ t = T-i64*
**using** *assms*
**by** (*cases t*) (*auto simp add*: *is-int-t-def*)

**lemma** *is-float-t-exists*:
**assumes** *is-float-t t*
**shows** *t = T-f32 ∨ t = T-f64*
**using** *assms*
**by** (*cases t*) (*auto simp add*: *is-float-t-def*)

**lemma** *int-float-disjoint*: *is-int-t t = −*(*is-float-t t*)
**by** *simp* (*metis is-float-t-def is-int-t-def t.exhaust t.simps*(*13−16*))

**lemma** *stab-unfold*:
**assumes** *stab s i j = Some cl*
**shows** ∃ *k*. *inst.tab* ((*inst s*)!*i*) = *Some k* ∧ *length* ((*tab s*)!*k*) > *j* ∧((*tab s*)!*k*)!*j* = *Some cl*
**proof** −
**obtain** *k* **where** *have-k*:(*inst.tab* ((*inst s*)!*i*)) = *Some k*
**using** *assms*
**unfolding** *stab-def*
**by** *fastforce*
**hence** *s-o*:*stab s i j = stab-s s k j*
**using** *assms*
**unfolding** *stab-def*
**by** *simp*
**then obtain** *stabinst* **where** *stabinst-def*:*stabinst* = ((*tab s*)!*k*)
**by** *blast*
**hence** *stab-s s k j* = (*stabinst*!*j*) ∧ (*length stabinst* > *j*)
**using** *assms s-o*
**unfolding** *stab-s-def*
**by** (*cases* (*length stabinst* > *j*), *auto*)
**thus** *?thesis*
**using** *have-k stabinst-def assms s-o*
**by** *auto*
**qed**

**lemma** *inj-basic*: *inj Basic*
**by** (*meson e.inject*(*1*) *injI*)

**lemma** *inj-basic-econst*: *inj* (λ*v*. $*C v*)
**by** (*meson b-e.inject*(*16*) *e.inject*(*1*) *injI*)

**lemma** *to-e-list-1*:[$ *a*] = $∗ [*a*]
**by** *simp*

**lemma** *to-e-list-2*:[$ *a*, $ *b*] = $∗ [*a*, *b*]

**by** *simp*

**lemma** *to-e-list-3*:[$ *a*, $ *b*, $ *c*] = $∗ [*a*, *b*, *c*]
**by** *simp*

**lemma** *v-exists-b-e*:∃ *ves*. ($$∗*vs*) = ($∗*ves*)
**proof** (*induction vs*)
**case** (*Cons a vs*)
**thus** *?case*
**by** (*metis list.simps*(*9*))
**qed** *auto*

**lemma** *Lfilled-exact-imp-Lfilled*:
**assumes** *Lfilled-exact n lholed es LI*
**shows** *Lfilled n lholed es LI*
**using** *assms*
**proof** (*induction rule*: *Lfilled-exact.induct*)
**case** (*L0 lholed es*)
**thus** *?case*
**using** *const-list-def Lfilled.intros*(*1*)
**by** *fastforce*
**next**
**case** (*LN vs lholed n es′ l es″ k es lfilledk*)
**thus** *?case*
**using** *Lfilled.intros*(*2*)
**by** *fastforce*
**qed**

**lemma** *Lfilled-exact-app-imp-exists-Lfilled*:
**assumes** *const-list ves*
*Lfilled-exact n lholed* (*ves*@*es*) *LI*
**shows** ∃ *lholed′*. *Lfilled n lholed′ es LI*
**using** *assms*(*2*,*1*)
**proof** (*induction* (*ves*@*es*) *LI rule*: *Lfilled-exact.induct*)
**case** (*L0 lholed*)
**show** *?case*
**using** *Lfilled.intros*(*1*)[*OF L0*(*2*), *of* - []]
**by** *fastforce*
**next**
**case** (*LN vs lholed n es′ l es″ k lfilledk*)
**thus** *?case*
**using** *Lfilled.intros*(*2*)
**by** *fastforce*
**qed**

**lemma** *Lfilled-imp-exists-Lfilled-exact*:
**assumes** *Lfilled n lholed es LI*
**shows** ∃ *lholed′ ves es-c*. *const-list ves* ∧ *Lfilled-exact n lholed′* (*ves*@*es*@*es-c*) *LI*
**using** *assms Lfilled-exact.intros*

**by** (*induction rule*: *Lfilled.induct*) *fastforce+*

**lemma** *n-zeros-typeof*:
*n-zeros ts* = *vs* ⟹ (*ts* = *map typeof vs*)
**proof** (*induction ts arbitrary*: *vs*)
**case** *Nil*
**thus** *?case*
**unfolding** *n-zeros-def*
**by** *simp*
**next**
**case** (*Cons t ts*)
**obtain** *vs′* **where** *n-zeros ts* = *vs′*
**using** *n-zeros-def*
**by** *blast*
**moreover**
**have** *typeof* (*bitzero t*) = *t*
**unfolding** *typeof-def bitzero-def*
**by** (*cases t*, *simp-all*)
**ultimately**
**show** *?case*
**using** *Cons*
**unfolding** *n-zeros-def*
**by** *auto*
**qed**

**end**
**theory** *Wasm* **imports** *Wasm-Base-Defs* **begin**

**inductive** *b-e-typing* :: [*t-context*, *b-e list*, *tf*] ⇒ *bool* (- ⊢ - : - *60*) **where**
— *num ops*
*const*:*C* ⊢ [*C v*] : ([] -> [(*typeof v*)])
| *unop-i*:*is-int-t t* ⟹ *C* ⊢ [*Unop-i t* -] : ([*t*] -> [*t*])
| *unop-f*:*is-float-t t* ⟹ *C* ⊢ [*Unop-f t* -] : ([*t*] -> [*t*])
| *binop-i*:*is-int-t t* ⟹ *C* ⊢ [*Binop-i t iop*] : ([*t*,*t*] -> [*t*])
| *binop-f*:*is-float-t t* ⟹ *C* ⊢ [*Binop-f t* -] : ([*t*,*t*] -> [*t*])
| *testop*:*is-int-t t* ⟹ *C* ⊢ [*Testop t* -] : ([*t*] -> [*T-i32*])
| *relop-i*:*is-int-t t* ⟹ *C* ⊢ [*Relop-i t* -] : ([*t*,*t*] -> [*T-i32*])
| *relop-f*:*is-float-t t* ⟹ *C* ⊢ [*Relop-f t* -] : ([*t*,*t*] -> [*T-i32*])
— *convert*
| *convert*:⟦(*t1* ≠ *t2*); (*sx* = *None*) = ((*is-float-t t1* ∧ *is-float-t t2*) ∨ (*is-int-t t1* ∧ *is-int-t t2* ∧ (*t-length t1* < *t-length t2*)))⟧ ⟹ *C* ⊢ [*Cvtop t1 Convert t2 sx*] : ([*t2*] -> [*t1*])
— *reinterpret*
| *reinterpret*:⟦(*t1* ≠ *t2*); *t-length t1* = *t-length t2*⟧ ⟹ *C* ⊢ [*Cvtop t1 Reinterpret t2 None*] : ([*t2*] -> [*t1*])
— *unreachable*, *nop*, *drop*, *select*
| *unreachable*:*C* ⊢ [*Unreachable*] : (*ts* -> *ts′*)
| *nop*:*C* ⊢ [*Nop*] : ([] -> [])

| *drop*:$\mathcal{C} \vdash [Drop] : ([t] \text{ -> } [])$
| *select*:$\mathcal{C} \vdash [Select] : ([t,t,T\text{-}i32] \text{ -> } [t])$
— *block*
| *block*:$[\![tf = (tn \text{ -> } tm); \mathcal{C}(\!|label := ([tm] \text{ @ } (label\ \mathcal{C}))|\!) \vdash es : (tn \text{ -> } tm)]\!] \Longrightarrow \mathcal{C} \vdash [Block\ tf\ es] : (tn \text{ -> } tm)$
— *loop*
| *loop*:$[\![tf = (tn \text{ -> } tm); \mathcal{C}(\!|label := ([tn] \text{ @ } (label\ \mathcal{C}))|\!) \vdash es : (tn \text{ -> } tm)]\!] \Longrightarrow \mathcal{C} \vdash [Loop\ tf\ es] : (tn \text{ -> } tm)$
— *if then else*
| *if-wasm*:$[\![tf = (tn \text{ -> } tm); \mathcal{C}(\!|label := ([tm] \text{ @ } (label\ \mathcal{C}))|\!) \vdash es1 : (tn \text{ -> } tm); \mathcal{C}(\!|label := ([tm] \text{ @ } (label\ \mathcal{C}))|\!) \vdash es2 : (tn \text{ -> } tm)]\!] \Longrightarrow \mathcal{C} \vdash [If\ tf\ es1\ es2] : (tn \text{ @ } [T\text{-}i32] \text{ -> } tm)$
— *br*
| *br*:$[\![i < length(label\ \mathcal{C}); (label\ \mathcal{C})!i = ts]\!] \Longrightarrow \mathcal{C} \vdash [Br\ i] : (t1s \text{ @ } ts \text{ -> } t2s)$
— *br-if*
| *br-if*:$[\![i < length(label\ \mathcal{C}); (label\ \mathcal{C})!i = ts]\!] \Longrightarrow \mathcal{C} \vdash [Br\text{-}if\ i] : (ts \text{ @ } [T\text{-}i32] \text{ -> } ts)$
— *br-table*
| *br-table*:$[\![list\text{-}all\ (\lambda i.\ i < length(label\ \mathcal{C}) \wedge (label\ \mathcal{C})!i = ts)\ (is@[i])]\!] \Longrightarrow \mathcal{C} \vdash [Br\text{-}table\ is\ i] : (t1s \text{ @ } ts \text{ @ } [T\text{-}i32] \text{ -> } t2s)$
— *return*
| *return*:$[\![(return\ \mathcal{C}) = Some\ ts]\!] \Longrightarrow \mathcal{C} \vdash [Return] : (t1s \text{ @ } ts \text{ -> } t2s)$
— *call*
| *call*:$[\![i < length(func\text{-}t\ \mathcal{C}); (func\text{-}t\ \mathcal{C})!i = tf]\!] \Longrightarrow \mathcal{C} \vdash [Call\ i] : tf$
— *call-indirect*
| *call-indirect*:$[\![i < length(types\text{-}t\ \mathcal{C}); (types\text{-}t\ \mathcal{C})!i = (t1s \text{ -> } t2s); (table\ \mathcal{C}) \neq None]\!] \Longrightarrow \mathcal{C} \vdash [Call\text{-}indirect\ i] : (t1s \text{ @ } [T\text{-}i32] \text{ -> } t2s)$
— *get-local*
| *get-local*:$[\![i < length(local\ \mathcal{C}); (local\ \mathcal{C})!i = t]\!] \Longrightarrow \mathcal{C} \vdash [Get\text{-}local\ i] : ([] \text{ -> } [t])$
— *set-local*
| *set-local*:$[\![i < length(local\ \mathcal{C}); (local\ \mathcal{C})!i = t]\!] \Longrightarrow \mathcal{C} \vdash [Set\text{-}local\ i] : ([t] \text{ -> } [])$
— *tee-local*
| *tee-local*:$[\![i < length(local\ \mathcal{C}); (local\ \mathcal{C})!i = t]\!] \Longrightarrow \mathcal{C} \vdash [Tee\text{-}local\ i] : ([t] \text{ -> } [t])$
— *get-global*
| *get-global*:$[\![i < length(global\ \mathcal{C}); tg\text{-}t\ ((global\ \mathcal{C})!i) = t]\!] \Longrightarrow \mathcal{C} \vdash [Get\text{-}global\ i] : ([] \text{ -> } [t])$
— *set-global*
| *set-global*:$[\![i < length(global\ \mathcal{C}); tg\text{-}t\ ((global\ \mathcal{C})!i) = t; is\text{-}mut\ ((global\ \mathcal{C})!i)]\!] \Longrightarrow \mathcal{C} \vdash [Set\text{-}global\ i] : ([t] \text{ -> } [])$
— *load*
| *load*:$[\![(memory\ \mathcal{C}) = Some\ n; load\text{-}store\text{-}t\text{-}bounds\ a\ (option\text{-}projl\ tp\text{-}sx)\ t]\!] \Longrightarrow \mathcal{C} \vdash [Load\ t\ tp\text{-}sx\ a\ off] : ([T\text{-}i32] \text{ -> } [t])$
— *store*
| *store*:$[\![(memory\ \mathcal{C}) = Some\ n; load\text{-}store\text{-}t\text{-}bounds\ a\ tp\ t]\!] \Longrightarrow \mathcal{C} \vdash [Store\ t\ tp\ a\ off] : ([T\text{-}i32,t] \text{ -> } [])$
— *current-memory*
| *current-memory*:$(memory\ \mathcal{C}) = Some\ n \Longrightarrow \mathcal{C} \vdash [Current\text{-}memory] : ([] \text{ -> } [T\text{-}i32])$
— *Grow-memory*
| *grow-memory*:$(memory\ \mathcal{C}) = Some\ n \Longrightarrow \mathcal{C} \vdash [Grow\text{-}memory] : ([T\text{-}i32] \text{ -> } [T\text{-}i32])$

— *empty program*
| *empty*:$\mathcal{C} \vdash [] : ([] \text{ -> } [])$
— *composition*
| *composition*:$[\![\mathcal{C} \vdash es : (t1s \text{ -> } t2s); \mathcal{C} \vdash [e] : (t2s \text{ -> } t3s)]\!] \Longrightarrow \mathcal{C} \vdash es \mathbin{@} [e] : (t1s \text{ -> } t3s)$
— *weakening*
| *weakening*:$\mathcal{C} \vdash es : (t1s \text{ -> } t2s) \Longrightarrow \mathcal{C} \vdash es : (ts \mathbin{@} t1s \text{ -> } ts \mathbin{@} t2s)$

**inductive** *cl-typing* :: $[s\text{-}context, cl, tf] \Rightarrow bool$ **where**
$[\![i < length\ (s\text{-}inst\ \mathcal{S}); ((s\text{-}inst\ \mathcal{S})!i) = \mathcal{C}; tf = (t1s \text{ -> } t2s); \mathcal{C}(\!|local := (local\ \mathcal{C}) \mathbin{@} t1s \mathbin{@} ts, label := ([t2s] \mathbin{@} (label\ \mathcal{C})), return := Some\ t2s|\!) \vdash es : ([] \text{ -> } t2s)]\!] \Longrightarrow cl\text{-}typing\ \mathcal{S}\ (Func\text{-}native\ i\ tf\ ts\ es)\ (t1s \text{ -> } t2s)$
| $cl\text{-}typing\ \mathcal{S}\ (Func\text{-}host\ tf\ h)\ tf$

**inductive** *e-typing* :: $[s\text{-}context, t\text{-}context, e\ list, tf] \Rightarrow bool$ (-•- ⊢ - : - *60*)
**and** *s-typing* :: $[s\text{-}context, (t\ list)\ option, nat, v\ list, e\ list, t\ list] \Rightarrow bool$ (-•- ⊢'- - -;- : - *60*) **where**

$\mathcal{C} \vdash b\text{-}es : tf \Longrightarrow \mathcal{S}{\cdot}\mathcal{C} \vdash \${*}b\text{-}es : tf$

| $[\![\mathcal{S}{\cdot}\mathcal{C} \vdash es : (t1s \text{ -> } t2s); \mathcal{S}{\cdot}\mathcal{C} \vdash [e] : (t2s \text{ -> } t3s)]\!] \Longrightarrow \mathcal{S}{\cdot}\mathcal{C} \vdash es \mathbin{@} [e] : (t1s \text{ -> } t3s)$

| $\mathcal{S}{\cdot}\mathcal{C} \vdash es : (t1s \text{ -> } t2s) \Longrightarrow \mathcal{S}{\cdot}\mathcal{C} \vdash es : (ts \mathbin{@} t1s \text{ -> } ts \mathbin{@} t2s)$

| $\mathcal{S}{\cdot}\mathcal{C} \vdash [Trap] : tf$

| $[\![\mathcal{S}{\cdot}Some\ ts \Vdash i\ vs; es : ts; length\ ts = n]\!] \Longrightarrow \mathcal{S}{\cdot}\mathcal{C} \vdash [Local\ n\ i\ vs\ es] : ([] \text{ -> } ts)$

| $[\![cl\text{-}typing\ \mathcal{S}\ cl\ tf]\!] \Longrightarrow \mathcal{S}{\cdot}\mathcal{C}\ \vdash [Callcl\ cl] : tf$

| $[\![\mathcal{S}{\cdot}\mathcal{C} \vdash e0s : (ts \text{ -> } t2s); \mathcal{S}{\cdot}\mathcal{C}(\!|label := ([ts] \mathbin{@} (label\ \mathcal{C}))|\!) \vdash es : ([] \text{ -> } t2s); length\ ts = n]\!] \Longrightarrow \mathcal{S}{\cdot}\mathcal{C} \vdash [Label\ n\ e0s\ es] : ([] \text{ -> } t2s)$

| $[\![i < (length\ (s\text{-}inst\ \mathcal{S})); tvs = map\ typeof\ vs; \mathcal{C} = ((s\text{-}inst\ \mathcal{S})!i)(\!|local := (local\ ((s\text{-}inst\ \mathcal{S})!i) \mathbin{@} tvs), return := rs|\!); \mathcal{S}{\cdot}\mathcal{C} \vdash es : ([] \text{ -> } ts); (rs = Some\ ts) \vee rs = None]\!] \Longrightarrow \mathcal{S}{\cdot}rs \Vdash i\ vs; es : ts$

**definition** $globi\text{-}agree\ gs\ n\ g = (n < length\ gs \wedge gs!n = g)$

**definition** $memi\text{-}agree\ sm\ j\ m = ((\exists j'\ m'.\ j = Some\ j' \wedge j' < length\ sm \wedge\ m = Some\ m' \wedge sm!j' = m') \vee j = None \wedge m = None)$

**definition** $funci\text{-}agree\ fs\ n\ f = (n < length\ fs \wedge fs!n = f)$

**inductive** *inst-typing* :: $[s\text{-}context, inst, t\text{-}context] \Rightarrow bool$ **where**
$[\![list\text{-}all2\ (funci\text{-}agree\ (s\text{-}funcs\ \mathcal{S}))\ fs\ tfs; list\text{-}all2\ (globi\text{-}agree\ (s\text{-}globs\ \mathcal{S}))\ gs\ tgs;$

$(i = Some\ i' \wedge i' < length\ (s\text{-}tab\ \mathcal{S}) \wedge (s\text{-}tab\ \mathcal{S})!i' = (the\ n)) \vee (i = None \wedge n = None)$; *memi-agree* $(s\text{-}mem\ \mathcal{S})\ j\ m\rrbracket \Longrightarrow$ *inst-typing* $\mathcal{S}$ $\lparr types = ts, funcs = fs, tab = i, mem = j, globs = gs\rparr$ $\lparr types\text{-}t = ts, func\text{-}t = tfs, global = tgs, table = n, memory = m, local = [], label = [], return = None\rparr$

**definition** *glob-agree g tg* = $(tg\text{-}mut\ tg = g\text{-}mut\ g \wedge tg\text{-}t\ tg = typeof\ (g\text{-}val\ g))$

**definition** *tab-agree* $\mathcal{S}$ *tcl* = $(case\ tcl\ of\ None \Rightarrow True \mid Some\ cl \Rightarrow \exists\, tf.\ cl\text{-}typing\ \mathcal{S}\ cl\ tf)$

**definition** *mem-agree bs m* = $(\lambda\ bs\ m.\ m \leq mem\text{-}size\ bs)\ bs\ m$

**inductive** *store-typing* :: $[s, s\text{-}context] \Rightarrow bool$ **where**
$\llbracket \mathcal{S} = \lparr s\text{-}inst = \mathcal{C}s, s\text{-}funcs = tfs, s\text{-}tab = ns, s\text{-}mem = ms, s\text{-}globs = tgs\rparr;$ *list-all2* $(inst\text{-}typing\ \mathcal{S})\ insts\ \mathcal{C}s$; *list-all2* $(cl\text{-}typing\ \mathcal{S})\ fs\ tfs$; *list-all* $(tab\text{-}agree\ \mathcal{S})$ $(concat\ tclss)$; *list-all2* $(\lambda\ tcls\ n.\ n \leq length\ tcls)\ tclss\ ns$; *list-all2 mem-agree bss ms*; *list-all2 glob-agree gs tgs*$\rrbracket \Longrightarrow$ *store-typing* $\lparr s.inst = insts, s.funcs = fs, s.tab = tclss, s.mem = bss, s.globs = gs\rparr\ \mathcal{S}$

**inductive** *config-typing* :: $[nat, s, v\ list, e\ list, t\ list] \Rightarrow bool$ $(\vdash'\text{- - -;-;- : - } 60)$ **where**
$\llbracket store\text{-}typing\ s\ \mathcal{S}; \mathcal{S}\cdot None \vdash\!\!\!=\text{-}i\ vs;es : ts\rrbracket \Longrightarrow \vdash\text{-}i\ s;vs;es : ts$

**inductive** *reduce-simple* :: $[e\ list, e\ list] \Rightarrow bool$ $(\lparr\text{-}\rparr \rightsquigarrow \lparr\text{-}\rparr\ 60)$ **where**
— *integer unary ops*
*unop-i32*:$\lparr[\$C\ (ConstInt32\ c), \$(Unop\text{-}i\ T\text{-}i32\ iop)]\rparr \rightsquigarrow \lparr[\$C\ (ConstInt32\ (app\text{-}unop\text{-}i\ iop\ c))]\rparr$
| *unop-i64*:$\lparr[\$C\ (ConstInt64\ c), \$(Unop\text{-}i\ T\text{-}i64\ iop)]\rparr \rightsquigarrow \lparr[\$C\ (ConstInt64\ (app\text{-}unop\text{-}i\ iop\ c))]\rparr$
— *float unary ops*
| *unop-f32*:$\lparr[\$C\ (ConstFloat32\ c), \$(Unop\text{-}f\ T\text{-}f32\ fop)]\rparr \rightsquigarrow \lparr[\$C\ (ConstFloat32\ (app\text{-}unop\text{-}f\ fop\ c))]\rparr$
| *unop-f64*:$\lparr[\$C\ (ConstFloat64\ c), \$(Unop\text{-}f\ T\text{-}f64\ fop)]\rparr \rightsquigarrow \lparr[\$C\ (ConstFloat64\ (app\text{-}unop\text{-}f\ fop\ c))]\rparr$
— *int32 binary ops*
| *binop-i32-Some*:$\llbracket app\text{-}binop\text{-}i\ iop\ c1\ c2 = (Some\ c)\rrbracket \Longrightarrow \lparr[\$C\ (ConstInt32\ c1), \$C\ (ConstInt32\ c2), \$(Binop\text{-}i\ T\text{-}i32\ iop)]\rparr \rightsquigarrow \lparr[\$C\ (ConstInt32\ c)]\rparr$
| *binop-i32-None*:$\llbracket app\text{-}binop\text{-}i\ iop\ c1\ c2 = None\rrbracket \Longrightarrow \lparr[\$C\ (ConstInt32\ c1), \$C\ (ConstInt32\ c2), \$(Binop\text{-}i\ T\text{-}i32\ iop)]\rparr \rightsquigarrow \lparr[Trap]\rparr$
— *int64 binary ops*
| *binop-i64-Some*:$\llbracket app\text{-}binop\text{-}i\ iop\ c1\ c2 = (Some\ c)\rrbracket \Longrightarrow \lparr[\$C\ (ConstInt64\ c1), \$C\ (ConstInt64\ c2), \$(Binop\text{-}i\ T\text{-}i64\ iop)]\rparr \rightsquigarrow \lparr[\$C\ (ConstInt64\ c)]\rparr$
| *binop-i64-None*:$\llbracket app\text{-}binop\text{-}i\ iop\ c1\ c2 = None\rrbracket \Longrightarrow \lparr[\$C\ (ConstInt64\ c1), \$C\ (ConstInt64\ c2), \$(Binop\text{-}i\ T\text{-}i64\ iop)]\rparr \rightsquigarrow \lparr[Trap]\rparr$
— *float32 binary ops*
| *binop-f32-Some*:$\llbracket app\text{-}binop\text{-}f\ fop\ c1\ c2 = (Some\ c)\rrbracket \Longrightarrow \lparr[\$C\ (ConstFloat32\ c1), \$C\ (ConstFloat32\ c2), \$(Binop\text{-}f\ T\text{-}f32\ fop)]\rparr \rightsquigarrow \lparr[\$C\ (ConstFloat32\ c)]\rparr$

| *binop-f32-None*:⟦*app-binop-f fop c1 c2 = None*⟧ ⟹ (|[$*C* (*ConstFloat32 c1*), $*C* (*ConstFloat32 c2*), $(*Binop-f T-f32 fop*)]|) ⇝ (|[*Trap*]|)
— *float64 binary ops*
| *binop-f64-Some*:⟦*app-binop-f fop c1 c2 = (Some c)*⟧ ⟹ (|[$*C* (*ConstFloat64 c1*), $*C* (*ConstFloat64 c2*), $(*Binop-f T-f64 fop*)]|) ⇝ (|[$*C* (*ConstFloat64 c*)]|)
| *binop-f64-None*:⟦*app-binop-f fop c1 c2 = None*⟧ ⟹ (|[$*C* (*ConstFloat64 c1*), $*C* (*ConstFloat64 c2*), $(*Binop-f T-f64 fop*)]|) ⇝ (|[*Trap*]|)
— *testops*
| *testop-i32*:(|[$*C* (*ConstInt32 c*), $(*Testop T-i32 testop*)]|) ⇝ (|[$*C ConstInt32* (*wasm-bool* (*app-testop-i testop c*))]|)
| *testop-i64*:(|[$*C* (*ConstInt64 c*), $(*Testop T-i64 testop*)]|) ⇝ (|[$*C ConstInt32* (*wasm-bool* (*app-testop-i testop c*))]|)
— *int relops*
| *relop-i32*:(|[$*C* (*ConstInt32 c1*), $*C* (*ConstInt32 c2*), $(*Relop-i T-i32 iop*)]|) ⇝ (|[$*C* (*ConstInt32* (*wasm-bool* (*app-relop-i iop c1 c2*)))]|)
| *relop-i64*:(|[$*C* (*ConstInt64 c1*), $*C* (*ConstInt64 c2*), $(*Relop-i T-i64 iop*)]|) ⇝ (|[$*C* (*ConstInt32* (*wasm-bool* (*app-relop-i iop c1 c2*)))]|)
— *float relops*
| *relop-f32*:(|[$*C* (*ConstFloat32 c1*), $*C* (*ConstFloat32 c2*), $(*Relop-f T-f32 fop*)]|) ⇝ (|[$*C* (*ConstInt32* (*wasm-bool* (*app-relop-f fop c1 c2*)))]|)
| *relop-f64*:(|[$*C* (*ConstFloat64 c1*), $*C* (*ConstFloat64 c2*), $(*Relop-f T-f64 fop*)]|) ⇝ (|[$*C* (*ConstInt32* (*wasm-bool* (*app-relop-f fop c1 c2*)))]|)
— *convert*
| *convert-Some*:⟦*types-agree t1 v*; *cvt t2 sx v = (Some v′)*⟧ ⟹ (|[$(*C v*), $(*Cvtop t2 Convert t1 sx*)]|) ⇝ (|[$(*C v′*)]|)
| *convert-None*:⟦*types-agree t1 v*; *cvt t2 sx v = None*⟧ ⟹ (|[$(*C v*), $(*Cvtop t2 Convert t1 sx*)]|) ⇝ (|[*Trap*]|)
— *reinterpret*
| *reinterpret*:*types-agree t1 v* ⟹ (|[$(*C v*), $(*Cvtop t2 Reinterpret t1 None*)]|) ⇝ (|[$(*C* (*wasm-deserialise* (*bits v*) *t2*))]|)
— *unreachable*
| *unreachable*:(|[$ *Unreachable*]|) ⇝ (|[*Trap*]|)
— *nop*
| *nop*:(|[$ *Nop*]|) ⇝ (|[]|)
— *drop*
| *drop*:(|[$(*C v*), ($ *Drop*)]|) ⇝ (|[]|)
— *select*
| *select-false*:*int-eq n 0* ⟹ (|[$(*C v1*), $(*C v2*), $*C* (*ConstInt32 n*), ($ *Select*)]|) ⇝ (|[$(*C v2*)]|)
| *select-true*:*int-ne n 0* ⟹ (|[$(*C v1*), $(*C v2*), $*C* (*ConstInt32 n*), ($ *Select*)]|) ⇝ (|[$(*C v1*)]|)
— *block*
| *block*:⟦*const-list vs*; *length vs = n*; *length t1s = n*; *length t2s = m*⟧ ⟹ (|*vs* @ [$(*Block* (*t1s -> t2s*) *es*)]|) ⇝ (|[*Label m* [] (*vs* @ ($∗ *es*))]|)
— *loop*
| *loop*:⟦*const-list vs*; *length vs = n*; *length t1s = n*; *length t2s = m*⟧ ⟹ (|*vs* @ [$(*Loop* (*t1s -> t2s*) *es*)]|) ⇝ (|[*Label n* [$(*Loop* (*t1s -> t2s*) *es*)] (*vs* @ ($∗ *es*))]|)
— *if*
| *if-false*:*int-eq n 0* ⟹ (|[$*C* (*ConstInt32 n*), $(*If tf e1s e2s*)]|) ⇝ (|[$(*Block tf e2s*)]|)

| *if-true*:*int-ne n 0* $\Longrightarrow$ ($\lfloor$[$C (*ConstInt32 n*), $(*If tf e1s e2s*)]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[$(*Block tf e1s*)]$\rfloor$)
— *label*
| *label-const*:*const-list vs* $\Longrightarrow$ ($\lfloor$[*Label n es vs*]$\rfloor$) $\rightsquigarrow$ ($\lfloor$*vs*$\rfloor$)
| *label-trap*:($\lfloor$[*Label n es* [*Trap*]]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[*Trap*]$\rfloor$)
— *br*
| *br*:$[\![$*const-list vs*; *length vs* = *n*; *Lfilled i lholed* (*vs* @ [$(*Br i*)]) *LI*$]\!]$ $\Longrightarrow$ ($\lfloor$[*Label n es LI*]$\rfloor$) $\rightsquigarrow$ ($\lfloor$*vs* @ *es*$\rfloor$)
— *br-if*
| *br-if-false*:*int-eq n 0* $\Longrightarrow$ ($\lfloor$[$C (*ConstInt32 n*), $(*Br-if i*)]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[]$\rfloor$)
| *br-if-true*:*int-ne n 0* $\Longrightarrow$ ($\lfloor$[$C (*ConstInt32 n*), $(*Br-if i*)]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[$(*Br i*)]$\rfloor$)
— *br-table*
| *br-table*:$[\![$*length is* > (*nat-of-int c*)$]\!]$ $\Longrightarrow$ ($\lfloor$[$C (*ConstInt32 c*), $(*Br-table is i*)]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[$(*Br* (*is*!(*nat-of-int c*)))]$\rfloor$)
| *br-table-length*:$[\![$*length is* $\leq$ (*nat-of-int c*)$]\!]$ $\Longrightarrow$ ($\lfloor$[$C (*ConstInt32 c*), $(*Br-table is i*)]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[$(*Br i*)]$\rfloor$)
— *local*
| *local-const*:$[\![$*const-list es*; *length es* = *n*$]\!]$ $\Longrightarrow$ ($\lfloor$[*Local n i vs es*]$\rfloor$) $\rightsquigarrow$ ($\lfloor$*es*$\rfloor$)
| *local-trap*:($\lfloor$[*Local n i vs* [*Trap*]]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[*Trap*]$\rfloor$)
— *return*
| *return*:$[\![$*const-list vs*; *length vs* = *n*; *Lfilled j lholed* (*vs* @ [$*Return*]) *es*$]\!]$ $\Longrightarrow$ ($\lfloor$[*Local n i vls es*]$\rfloor$) $\rightsquigarrow$ ($\lfloor$*vs*$\rfloor$)
— *tee-local*
| *tee-local*:*is-const v* $\Longrightarrow$ ($\lfloor$[*v*, $(*Tee-local i*)]$\rfloor$) $\rightsquigarrow$ ($\lfloor$[*v*, *v*, $(*Set-local i*)]$\rfloor$)
| *trap*:$[\![$*es* $\neq$ [*Trap*]; *Lfilled 0 lholed* [*Trap*] *es*$]\!]$ $\Longrightarrow$ ($\lfloor$*es*$\rfloor$) $\rightsquigarrow$ ($\lfloor$[*Trap*]$\rfloor$)

**inductive** *reduce* :: [*s*, *v list*, *e list*, *nat*, *s*, *v list*, *e list*] $\Rightarrow$ *bool* (($\lfloor$-;-;-$\rfloor$) $\rightsquigarrow'$- - ($\lfloor$-;-;-$\rfloor$) *60*) **where**
— *lifting basic reduction*
*basic*:($\lfloor$*e*$\rfloor$) $\rightsquigarrow$ ($\lfloor$*e′*$\rfloor$) $\Longrightarrow$ ($\lfloor$*s*;*vs*;*e*$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s*;*vs*;*e′*$\rfloor$)
— *call*
| *call*:($\lfloor$*s*;*vs*;[$(*Call j*)]$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s*;*vs*;[*Callcl* (*sfunc s i j*)]$\rfloor$)
— *call-indirect*
| *call-indirect-Some*:$[\![$*stab s i* (*nat-of-int c*) = *Some cl*; *stypes s i j* = *tf*; *cl-type cl* = *tf*$]\!]$ $\Longrightarrow$ ($\lfloor$*s*;*vs*;[$C (*ConstInt32 c*), $(*Call-indirect j*)]$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s*;*vs*;[*Callcl cl*]$\rfloor$)
| *call-indirect-None*:$[\![$(*stab s i* (*nat-of-int c*) = *Some cl* $\wedge$ *stypes s i j* $\neq$ *cl-type cl*) $\vee$ *stab s i* (*nat-of-int c*) = *None*$]\!]$ $\Longrightarrow$ ($\lfloor$*s*;*vs*;[$C (*ConstInt32 c*), $(*Call-indirect j*)]$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s*;*vs*;[*Trap*]$\rfloor$)
— *call*
| *callcl-native*:$[\![$*cl* = *Func-native j* (*t1s* -> *t2s*) *ts es*; *ves* = ($$∗ *vcs*); *length vcs* = *n*; *length ts* = *k*; *length t1s* = *n*; *length t2s* = *m*; (*n-zeros ts* = *zs*) $]\!]$ $\Longrightarrow$ ($\lfloor$*s*;*vs*;*ves* @ [*Callcl cl*]$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s*;*vs*;[*Local m j* (*vcs*@*zs*) [$(*Block* ([] -> *t2s*) *es*)]]$\rfloor$)
| *callcl-host-Some*:$[\![$*cl* = *Func-host* (*t1s* -> *t2s*) *f*; *ves* = ($$∗ *vcs*); *length vcs* = *n*; *length t1s* = *n*; *length t2s* = *m*; *host-apply s* (*t1s* -> *t2s*) *f vcs hs* = *Some* (*s′*, *vcs′*)$]\!]$ $\Longrightarrow$ ($\lfloor$*s*;*vs*;*ves* @ [*Callcl cl*]$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s′*;*vs*;($$∗ *vcs′*)$\rfloor$)
| *callcl-host-None*:$[\![$*cl* = *Func-host* (*t1s* -> *t2s*) *f*; *ves* = ($$∗ *vcs*); *length vcs* = *n*; *length t1s* = *n*; *length t2s* = *m*$]\!]$ $\Longrightarrow$ ($\lfloor$*s*;*vs*;*ves* @ [*Callcl cl*]$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s*;*vs*;[*Trap*]$\rfloor$)
— *get-local*
| *get-local*:$[\![$*length vi* = *j*$]\!]$ $\Longrightarrow$ ($\lfloor$*s*;(*vi* @ [*v*] @ *vs*);[$(*Get-local j*)]$\rfloor$) $\rightsquigarrow$-*i* ($\lfloor$*s*;(*vi* @ [*v*]

@ $vs$);[$(C\ v)$]⦈
— *set-local*
| *set-local*:⟦*length vi* = *j*⟧ ⟹ ⦇*s*;(*vi* @ [*v*] @ *vs*);[$(C\ v'), $(*Set-local j*)]⦈ ⇝-*i* ⦇*s*;(*vi* @ [*v'*] @ *vs*);[]⦈
— *get-global*
| *get-global*:⦇*s*;*vs*;[$(*Get-global j*)]⦈ ⇝-*i* ⦇*s*;*vs*;[$ *C*(*sglob-val s i j*)]⦈
— *set-global*
| *set-global*:*supdate-glob s i j v* = *s'* ⟹ ⦇*s*;*vs*;[$(*C v*), $(*Set-global j*)]⦈ ⇝-*i* ⦇*s'*;*vs*;[]⦈
— *load*
| *load-Some*:⟦*smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *load m* (*nat-of-int k*) *off* (*t-length t*) = *Some bs*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $(*Load t None a off*)]⦈ ⇝-*i* ⦇*s*;*vs*;[$*C* (*wasm-deserialise bs t*)]⦈
| *load-None*:⟦*smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *load m* (*nat-of-int k*) *off* (*t-length t*) = *None*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $(*Load t None a off*)]⦈ ⇝-*i* ⦇*s*;*vs*;[*Trap*]⦈
— *load packed*
| *load-packed-Some*:⟦*smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *load-packed sx m* (*nat-of-int k*) *off* (*tp-length tp*) (*t-length t*) = *Some bs*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $(*Load t* (*Some* (*tp*, *sx*)) *a off*)]⦈ ⇝-*i* ⦇*s*;*vs*;[$*C* (*wasm-deserialise bs t*)]⦈
| *load-packed-None*:⟦*smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *load-packed sx m* (*nat-of-int k*) *off* (*tp-length tp*) (*t-length t*) = *None*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $(*Load t* (*Some* (*tp*, *sx*)) *a off*)]⦈ ⇝-*i* ⦇*s*;*vs*;[*Trap*]⦈
— *store*
| *store-Some*:⟦*types-agree t v*; *smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *store m* (*nat-of-int k*) *off* (*bits v*) (*t-length t*) = *Some mem'*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $*C v*, $(*Store t None a off*)]⦈ ⇝-*i* ⦇*s*⦇*mem*:= ((*mem s*)[*j* := *mem'*])⦈;*vs*;[]⦈
| *store-None*:⟦*types-agree t v*; *smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *store m* (*nat-of-int k*) *off* (*bits v*) (*t-length t*) = *None*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $*C v*, $(*Store t None a off*)]⦈ ⇝-*i* ⦇*s*;*vs*;[*Trap*]⦈
— *store packed*
| *store-packed-Some*:⟦*types-agree t v*; *smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *store-packed m* (*nat-of-int k*) *off* (*bits v*) (*tp-length tp*) = *Some mem'*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $*C v*, $(*Store t* (*Some tp*) *a off*)]⦈ ⇝-*i* ⦇*s*⦇*mem*:= ((*mem s*)[*j* := *mem'*])⦈;*vs*;[]⦈
| *store-packed-None*:⟦*types-agree t v*; *smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *store-packed m* (*nat-of-int k*) *off* (*bits v*) (*tp-length tp*) = *None*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 k*), $*C v*, $(*Store t* (*Some tp*) *a off*)]⦈ ⇝-*i* ⦇*s*;*vs*;[*Trap*]⦈
— *current-memory*
| *current-memory*:⟦*smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *mem-size m* = *n*⟧ ⟹ ⦇*s*;*vs*;[ $(*Current-memory*)]⦈ ⇝-*i* ⦇*s*;*vs*;[$*C* (*ConstInt32* (*int-of-nat n*))]⦈
— *grow-memory*
| *grow-memory*:⟦*smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *mem-size m* = *n*; *mem-grow m* (*nat-of-int c*) = *mem'*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 c*), $(*Grow-memory*)]⦈ ⇝-*i* ⦇*s*⦇*mem*:= ((*mem s*)[*j* := *mem'*])⦈;*vs*;[$*C* (*ConstInt32* (*int-of-nat n*))]⦈
— *grow-memory fail*
| *grow-memory-fail*:⟦*smem-ind s i* = *Some j*; ((*mem s*)!*j*) = *m*; *mem-size m* = *n*⟧ ⟹ ⦇*s*;*vs*;[$*C* (*ConstInt32 c*),$(*Grow-memory*)]⦈ ⇝-*i* ⦇*s*;*vs*;[$*C* (*ConstInt32 int32-minus-one*)]⦈

— *inductive label reduction*
| *label*:⟦(|*s*;*vs*;*es*|) ⇝-*i* (|*s'*;*vs'*;*es'*|); *Lfilled k lholed es les*; *Lfilled k lholed es' les'*⟧ ⟹ (|*s*;*vs*;*les*|) ⇝-*i* (|*s'*;*vs'*;*les'*|)
— *inductive local reduction*
| *local*:⟦(|*s*;*vs*;*es*|) ⇝-*i* (|*s'*;*vs'*;*es'*|)⟧ ⟹ (|*s*;*v0s*;[*Local n i vs es*]|) ⇝-*j* (|*s'*;*v0s*;[*Local n i vs' es'*]|)

**end**

# 4 Host Properties

**theory** *Wasm-Axioms* **imports** *Wasm* **begin**

**lemma** *mem-grow-size*:
**assumes** *mem-grow m n* = *m'*
**shows** (*mem-size m* + (*64000* ∗ *n*)) = *mem-size m'*
**using** *assms Abs-mem-inverse Abs-bytes-inverse*
**unfolding** *mem-grow-def mem-size-def mem-append-def bytes-replicate-def*
**by** *auto*

**lemma** *load-size*:
(*load m n off l* = *None*) = (*mem-size m* < (*off* + *n* + *l*))
**unfolding** *load-def*
**by** (*cases n* + *off* + *l* ≤ *mem-size m*) *auto*

**lemma** *load-packed-size*:
(*load-packed sx m n off lp l* = *None*) = (*mem-size m* < (*off* + *n* + *lp*))
**using** *load-size*
**unfolding** *load-packed-def*
**by** (*cases n* + *off* + *l* ≤ *mem-size m*) *auto*

**lemma** *store-size1*:
(*store m n off v l* = *None*) = (*mem-size m* < (*off* + *n* + *l*))
**unfolding** *store-def*
**by** (*cases n* + *off* + *l* ≤ *mem-size m*) *auto*

**lemma** *store-size*:
**assumes** (*store m n off v l* = *Some m'*)
**shows** *mem-size m* = *mem-size m'*
**using** *assms Abs-mem-inverse Abs-bytes-inverse*
**unfolding** *store-def write-bytes-def bytes-takefill-def*
**by** (*cases n* + *off* + *l* ≤ *mem-size m*) (*auto simp add*: *mem-size-def*)

**lemma** *store-packed-size1*:
(*store-packed m n off v l* = *None*) = (*mem-size m* < (*off* + *n* + *l*))
**using** *store-size1*
**unfolding** *store-packed-def*
**by** *simp*

**lemma** *store-packed-size*:
**assumes** (*store-packed m n off v l* = *Some m'*)
**shows** *mem-size m* = *mem-size m'*
**using** *assms store-size*
**unfolding** *store-packed-def*
**by** *simp*

**axiomatization where**
*wasm-deserialise-type*:*typeof* (*wasm-deserialise bs t*) = *t*

**axiomatization where**
*host-apply-preserve-store*: *list-all2 types-agree t1s vs* ⟹ *host-apply s* (*t1s* -> *t2s*) *f vs hs* = *Some* (*s'*, *vs'*) ⟹ *store-extension s s'*
**and** *host-apply-respect-type*:*list-all2 types-agree t1s vs* ⟹ *host-apply s* (*t1s* -> *t2s*) *f vs hs* = *Some* (*s'*, *vs'*) ⟹ *list-all2 types-agree t2s vs'*
**end**

# 5 Auxiliary Type System Properties

**theory** *Wasm-Properties-Aux* **imports** *Wasm-Axioms* **begin**

**lemma** *typeof-i32*:
**assumes** *typeof v* = *T-i32*
**shows** ∃ *c*. *v* = *ConstInt32 c*
**using** *assms*
**unfolding** *typeof-def*
**by** (*cases v*) *auto*

**lemma** *typeof-i64*:
**assumes** *typeof v* = *T-i64*
**shows** ∃ *c*. *v* = *ConstInt64 c*
**using** *assms*
**unfolding** *typeof-def*
**by** (*cases v*) *auto*

**lemma** *typeof-f32*:
**assumes** *typeof v* = *T-f32*
**shows** ∃ *c*. *v* = *ConstFloat32 c*
**using** *assms*
**unfolding** *typeof-def*
**by** (*cases v*) *auto*

**lemma** *typeof-f64*:
**assumes** *typeof v* = *T-f64*
**shows** ∃ *c*. *v* = *ConstFloat64 c*
**using** *assms*
**unfolding** *typeof-def*
**by** (*cases v*) *auto*

**lemma** *exists-v-typeof*: $\exists\, v\ v.\ typeof\ v = t$
**proof** (*cases t*)
  **case** *T-i32*
  **fix** *v*
  **have** *typeof* (*ConstInt32 v*) = *t*
    **using** *T-i32*
    **unfolding** *typeof-def*
    **by** *simp*
  **thus** *?thesis*
    **using** *T-i32*
    **by** *fastforce*
**next**
  **case** *T-i64*
  **fix** *v*
  **have** *typeof* (*ConstInt64 v*) = *t*
    **using** *T-i64*
    **unfolding** *typeof-def*
    **by** *simp*
  **thus** *?thesis*
    **using** *T-i64*
    **by** *fastforce*
**next**
  **case** *T-f32*
  **fix** *v*
  **have** *typeof* (*ConstFloat32 v*) = *t*
    **using** *T-f32*
    **unfolding** *typeof-def*
    **by** *simp*
  **thus** *?thesis*
    **using** *T-f32*
    **by** *fastforce*
**next**
  **case** *T-f64*
  **fix** *v*
  **have** *typeof* (*ConstFloat64 v*) = *t*
    **using** *T-f64*
    **unfolding** *typeof-def*
    **by** *simp*
  **thus** *?thesis*
    **using** *T-f64*
    **by** *fastforce*
**qed**

**lemma** *lfilled-collapse1*:
  **assumes** *Lfilled n lholed* (*vs*@*es*) *LI*
        *const-list vs*
        *length vs* $\geq$ *l*
  **shows** $\exists\, lholed'.$ *Lfilled n lholed'* ((*drop* (*length vs* − *l*) *vs*)@*es*) *LI*

```
  using assms(1)
proof (induction vs@es LI rule: Lfilled.induct)
  case (L0 vs' lholed es')
  obtain vs1 vs2 where vs = vs1@vs2 length vs2 = l
    using assms(3)
    by (metis append-take-drop-id diff-diff-cancel length-drop)
  moreover
  hence const-list (vs'@vs1)
    using L0(1) assms(2)
    unfolding const-list-def
    by simp
  ultimately
  show ?case
    using Lfilled.intros(1)[of vs'@vs1 - es' vs2@es]
      by fastforce
next
  case (LN vs lholed n es' l es'' k lfilledk)
  thus ?case
    using Lfilled.intros(2)
    by fastforce
qed

lemma lfilled-collapse2:
  assumes Lfilled n lholed (es@es') LI
  shows ∃ lholed' vs'. Lfilled n lholed' es LI
  using assms
proof (induction es@es' LI rule: Lfilled.induct)
  case (L0 vs lholed es')
  thus ?case
    using Lfilled.intros(1)
    by fastforce
next
  case (LN vs lholed n es' l es'' k lfilledk)
  thus ?case
    using Lfilled.intros(2)
    by fastforce
qed

lemma lfilled-collapse3:
  assumes Lfilled k lholed [Label n les es] LI
  shows ∃ lholed'. Lfilled (Suc k) lholed' es LI
  using assms
proof (induction [Label n les es] LI rule: Lfilled.induct)
  case (L0 vs lholed es')
  have Lfilled 0 (LBase [] []) es es
    using Lfilled.intros(1)
    unfolding const-list-def
    by (metis append.left-neutral append-Nil2 list-all-simps(2))
  thus ?case
```

```
    using Lfilled.intros(2) L0
    by fastforce
next
  case (LN vs lholed n es' l es'' k lfilledk)
  thus ?case
    using Lfilled.intros(2)
    by fastforce
qed


lemma unlift-b-e: assumes S·C ⊢ $∗b-es : tf shows C ⊢ b-es : tf
using assms proof (induction S C ($∗b-es) tf arbitrary: b-es)
  case (1 C b-es tf S)
  then show ?case
    using inj-basic map-injective
    by auto
next
  case (2 S C es t1s t2s e t3s)
  obtain es' e' where es' @ [e'] = b-es
    using 2(5)
    by (simp add: snoc-eq-iff-butlast)
  then show ?case using 2
    using b-e-typing.composition
    by fastforce
next
  case (3 S C t1s t2s ts)
  then show ?case
    using b-e-typing.weakening
    by blast
qed auto

lemma store-typing-imp-inst-length-eq:
  assumes store-typing s S
  shows length (inst s) = length (s-inst S)
  using assms list-all2-lengthD
  unfolding store-typing.simps
  by fastforce

lemma store-typing-imp-func-length-eq:
  assumes store-typing s S
  shows length (funcs s) = length (s-funcs S)
  using assms list-all2-lengthD
  unfolding store-typing.simps
  by fastforce

lemma store-typing-imp-mem-length-eq:
  assumes store-typing s S
  shows length (s.mem s) = length (s-mem S)
  using assms list-all2-lengthD
```

**unfolding** *store-typing.simps*
**by** *fastforce*

**lemma** *store-typing-imp-glob-length-eq*:
**assumes** *store-typing s* $\mathcal{S}$
**shows** *length* (*globs s*) = *length* (*s-globs* $\mathcal{S}$)
**using** *assms list-all2-lengthD*
**unfolding** *store-typing.simps*
**by** *fastforce*

**lemma** *store-typing-imp-inst-typing*:
**assumes** *store-typing s* $\mathcal{S}$
*i* < *length* (*inst s*)
**shows** *inst-typing* $\mathcal{S}$ ((*inst s*)!*i*) ((*s-inst* $\mathcal{S}$)!*i*)
**using** *assms*
**unfolding** *list-all2-conv-all-nth store-typing.simps*
**by** *fastforce*

**lemma** *stab-typed-some-imp-member*:
**assumes** *stab s i c* = *Some cl*
*store-typing s* $\mathcal{S}$
*i* < *length* (*inst s*)
**shows** *Some cl* ∈ *set* (*concat* (*s.tab s*))
**proof** −
**obtain** *k'* **where** *k-def*:*inst.tab* ((*inst s*)!*i*) = *Some k'*
*length* ((*s.tab s*)!*k'*) > *c*
((*s.tab s*)!*k'*)!*c* = *Some cl*
**using** *stab-unfold assms*(*1*,*3*)
**by** *fastforce*
**hence** *Some cl* ∈ *set* ((*s.tab s*)!*k'*)
**using** *nth-mem*
**by** *fastforce*
**moreover**
**have** *inst-typing* $\mathcal{S}$ ((*inst s*)!*i*) ((*s-inst* $\mathcal{S}$)!*i*)
**using** *assms*(*2*,*3*) *store-typing-imp-inst-typing*
**by** *blast*
**hence** *k'* < *length* (*s-tab* $\mathcal{S}$)
**using** *k-def*(*1*)
**unfolding** *inst-typing.simps stypes-def*
**by** *auto*
**hence** *k'* < *length* (*s.tab s*)
**using** *assms*(*2*) *list-all2-lengthD*
**unfolding** *store-typing.simps*
**by** *fastforce*
**ultimately**
**show** *?thesis*
**using** *k-def*
**by** *auto*
**qed**

**lemma** *stab-typed-some-imp-cl-typed*:
  **assumes** *stab s i c = Some cl*
        *store-typing s $\mathcal{S}$*
        *i < length (inst s)*
  **shows** $\exists$ *tf. cl-typing $\mathcal{S}$ cl tf*
**proof** −
  **have** *Some cl ∈ set (concat (s.tab s))*
    **using** *assms stab-typed-some-imp-member*
    **by** *auto*
  **moreover**
  **have** *list-all (tab-agree $\mathcal{S}$) (concat (s.tab s))*
    **using** *assms(2)*
    **unfolding** *store-typing.simps*
    **by** *auto*
  **ultimately**
  **show** *?thesis*
    **unfolding** *in-set-conv-nth list-all-length tab-agree-def*
    **by** *fastforce*
**qed**

**lemma** *b-e-type-empty1*[*dest*]: **assumes** $\mathcal{C}$ ⊢ [] : (*ts -> ts'*) **shows** *ts = ts'*
  **using** *assms*
  **by** (*induction* []::(*b-e list*) (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *simp-all*)

**lemma** *b-e-type-empty*: ($\mathcal{C}$ ⊢ [] : (*ts -> ts'*)) = (*ts = ts'*)
**proof** (*safe*)
  **assume** $\mathcal{C}$ ⊢ [] : (*ts -> ts'*)
  **thus** *ts = ts'*
    **by** *blast*
**next**
  **assume** *ts = ts'*
  **thus** $\mathcal{C}$ ⊢ [] : (*ts' -> ts'*)
    **using** *b-e-typing.empty b-e-typing.weakening*
    **by** *fastforce*
**qed**

**lemma** *b-e-type-value*:
  **assumes** $\mathcal{C}$ ⊢ [*e*] : (*ts -> ts'*)
        *e = C v*
  **shows** *ts' = ts* @ [*typeof v*]
  **using** *assms*
  **by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-load*:
  **assumes** $\mathcal{C}$ ⊢ [*e*] : (*ts -> ts'*)
        *e = Load t tp-sx a off*
  **shows** $\exists$ *ts'' sec n. ts = ts''*@[*T-i32*] ∧ *ts' = ts''*@[*t*] ∧ (*memory $\mathcal{C}$*) = *Some n*

*load-store-t-bounds a* (*option-projl tp-sx*) *t*
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-store*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
*e = Store t tp a off*
**shows** *ts = ts'*@[*T-i32*, *t*]
$\exists$ *sec n*. (*memory* $\mathcal{C}$) = *Some n*
*load-store-t-bounds a tp t*
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-current-memory*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
*e = Current-memory*
**shows** $\exists$ *sec n*. *ts'* = *ts* @ [*T-i32*] $\wedge$ (*memory* $\mathcal{C}$) = *Some n*
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-grow-memory*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
*e = Grow-memory*
**shows** $\exists$ *ts''*. *ts* = *ts''*@[*T-i32*] $\wedge$ *ts* = *ts'* $\wedge$ ($\exists$ *n*. (*memory* $\mathcal{C}$) = *Some n*)
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*) *auto*

**lemma** *b-e-type-nop*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
*e = Nop*
**shows** *ts* = *ts'*
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**definition** *arity-2-result* :: *b-e* $\Rightarrow$ *t* **where**
*arity-2-result op2* = (*case op2 of*
*Binop-i t* - $\Rightarrow$ *t*
| *Binop-f t* - $\Rightarrow$ *t*
| *Relop-i t* - $\Rightarrow$ *T-i32*
| *Relop-f t* - $\Rightarrow$ *T-i32*)

**lemma** *b-e-type-binop-relop*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
*e = Binop-i t iop* $\vee$ *e = Binop-f t fop* $\vee$ *e = Relop-i t irop* $\vee$ *e = Relop-f t frop*
**shows** $\exists$ *ts''*. *ts* = *ts''*@[*t*,*t*] $\wedge$ *ts'* = *ts''*@[*arity-2-result*(*e*)]
*e = Binop-f t fop* $\Longrightarrow$ *is-float-t t*
*e = Relop-f t frop* $\Longrightarrow$ *is-float-t t*
**using** *assms*

**unfolding** *arity-2-result-def*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-testop-drop-cvt0*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Testop\ t\ testop \vee e = Drop \vee e = Cvtop\ t1\ cvtop\ t2\ sx$
**shows** $ts \neq []$
**using** *assms*
**by** (*induction* [*e*] *ts -> ts' arbitrary*: *ts' rule*: *b-e-typing.induct*, *auto*)

**definition** *arity-1-result* :: *b-e* ⇒ *t* **where**
*arity-1-result op1* = (*case op1 of*
*Unop-i t* - ⇒ *t*
| *Unop-f t* - ⇒ *t*
| *Testop t* - ⇒ *T-i32*
| *Cvtop t1 Convert* - - ⇒ *t1*
| *Cvtop t1 Reinterpret* - - ⇒ *t1*)

**lemma** *b-e-type-unop-testop*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Unop\text{-}i\ t\ iop \vee e = Unop\text{-}f\ t\ fop \vee e = Testop\ t\ testop$
**shows** $\exists ts''.\ ts = ts''@[t] \wedge ts' = ts''@[arity\text{-}1\text{-}result\ e]$
$e = Unop\text{-}f\ t\ fop \Longrightarrow is\text{-}float\text{-}t\ t$
**using** *assms int-float-disjoint*
**unfolding** *arity-1-result-def*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*) *fastforce+*

**lemma** *b-e-type-cvtop*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Cvtop\ t1\ cvtop\ t\ sx$
**shows** $\exists ts''.\ ts = ts''@[t] \wedge ts' = ts''@[arity\text{-}1\text{-}result\ e]$
$cvtop = Convert \Longrightarrow (t1 \neq t) \wedge (sx = None) = ((is\text{-}float\text{-}t\ t1 \wedge is\text{-}float\text{-}t\ t) \vee (is\text{-}int\text{-}t\ t1 \wedge is\text{-}int\text{-}t\ t \wedge (t\text{-}length\ t1 < t\text{-}length\ t)))$
$cvtop = Reinterpret \Longrightarrow (t1 \neq t) \wedge t\text{-}length\ t1 = t\text{-}length\ t$
**using** *assms*
**unfolding** *arity-1-result-def*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-drop*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Drop$
**shows** $\exists t.\ ts = ts'@[t]$
**using** *assms b-e-type-testop-drop-cvt0*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-select*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Select$
**shows** $\exists ts''\ t.\ ts = ts''@[t,t,T\text{-}i32] \wedge ts' = ts''@[t]$

**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-call*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Call\ i$
**shows** $i < length\ (func\text{-}t\ \mathcal{C})$
$\exists\, ts''\ tf1\ tf2.\ ts = ts''@tf1 \wedge ts' = ts''@tf2 \wedge (func\text{-}t\ \mathcal{C})!i = (tf1 \text{ -> } tf2)$
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-call-indirect*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Call\text{-}indirect\ i$
**shows** $i < length\ (types\text{-}t\ \mathcal{C})$
$\exists\, ts''\ tf1\ tf2.\ ts = ts''@tf1@[T\text{-}i32] \wedge ts' = ts''@tf2 \wedge (types\text{-}t\ \mathcal{C})!i = (tf1 \text{ -> } tf2)$
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-get-local*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Get\text{-}local\ i$
**shows** $\exists\, t.\ ts' = ts@[t] \wedge (local\ \mathcal{C})!i = t\ i < length(local\ \mathcal{C})$
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-set-local*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Set\text{-}local\ i$
**shows** $\exists\, t.\ ts = ts'@[t] \wedge (local\ \mathcal{C})!i = t\ i < length(local\ \mathcal{C})$
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-tee-local*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Tee\text{-}local\ i$
**shows** $\exists\, ts''\ t.\ ts = ts''@[t] \wedge ts' = ts''@[t] \wedge (local\ \mathcal{C})!i = t\ i < length(local\ \mathcal{C})$
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-get-global*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Get\text{-}global\ i$
**shows** $\exists\, t.\ ts' = ts@[t] \wedge tg\text{-}t((global\ \mathcal{C})!i) = t\ i < length(global\ \mathcal{C})$
**using** *assms*
**by** (*induction* [*e*] (*ts -> ts'*) *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-set-global*:

**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = \textit{Set-global } i$
**shows** $\exists t.\ ts = ts'@[t] \wedge (\textit{global } \mathcal{C})!i = (\!|\textit{tg-mut} = \textit{T-mut},\ \textit{tg-t} = t|\!) \wedge i < \textit{length}(\textit{global } \mathcal{C})$
**using** *assms is-mut-def*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*) *auto*

**lemma** *b-e-type-block*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = \textit{Block tf es}$
**shows** $\exists ts''\ tfn\ tfm.\ tf = (tfn \text{ -> } tfm) \wedge (ts = ts''@tfn) \wedge (ts' = ts''@tfm) \wedge (\mathcal{C}(\!|\textit{label} := [tfm] @ \textit{label } \mathcal{C}|\!) \vdash es : tf)$
**using** *assms*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-loop*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = \textit{Loop tf es}$
**shows** $\exists ts''\ tfn\ tfm.\ tf = (tfn \text{ -> } tfm) \wedge (ts = ts''@tfn) \wedge (ts' = ts''@tfm) \wedge (\mathcal{C}(\!|\textit{label} := [tfn] @ \textit{label } \mathcal{C}|\!) \vdash es : tf)$
**using** *assms*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-if*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = \textit{If tf es1 es2}$
**shows** $\exists ts''\ tfn\ tfm.\ tf = (tfn \text{ -> } tfm) \wedge (ts = ts''@tfn @ [\textit{T-i32}]) \wedge (ts' = ts''@tfm) \wedge$
$(\mathcal{C}(\!|\textit{label} := [tfm] @ \textit{label } \mathcal{C}|\!) \vdash es1 : tf) \wedge$
$(\mathcal{C}(\!|\textit{label} := [tfm] @ \textit{label } \mathcal{C}|\!) \vdash es2 : tf)$
**using** *assms*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-br*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = \textit{Br } i$
**shows** $i < \textit{length}(\textit{label } \mathcal{C})$
$\exists \textit{ts-c } ts''.\ ts = \textit{ts-c} @ ts'' \wedge (\textit{label } \mathcal{C})!i = ts''$
**using** *assms*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-br-if*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = \textit{Br-if } i$
**shows** $i < \textit{length}(\textit{label } \mathcal{C})$
$\exists \textit{ts-c } ts''.\ ts = \textit{ts-c} @ ts'' @ [\textit{T-i32}] \wedge ts' = \textit{ts-c} @ ts'' \wedge (\textit{label } \mathcal{C})!i = ts''$
**using** *assms*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-br-table*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Br\text{-}table\ is\ i$
**shows** $\exists\, ts\text{-}c\ ts''.\ list\text{-}all\ (\lambda i.\ i < length(label\ \mathcal{C}) \wedge (label\ \mathcal{C})!i = ts'')\ (is@[i]) \wedge ts = ts\text{-}c\ @\ ts''@[T\text{-}i32]$
**using** *assms*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *fastforce+*)

**lemma** *b-e-type-return*:
**assumes** $\mathcal{C} \vdash [e] : (ts \text{ -> } ts')$
$e = Return$
**shows** $\exists\, ts\text{-}c\ ts''.\ ts = ts\text{-}c\ @\ ts'' \wedge (return\ \mathcal{C}) = Some\ ts''$
**using** *assms*
**by** (*induction* $[e]$ $(ts \text{ -> } ts')$ *arbitrary*: *ts ts' rule*: *b-e-typing.induct*, *auto*)

**lemma** *b-e-type-comp*:
**assumes** $\mathcal{C} \vdash es@[e] : (t1s \text{ -> } t4s)$
**shows** $\exists\, ts'.\ (\mathcal{C} \vdash es : (t1s \text{ -> } ts')) \wedge (\mathcal{C} \vdash [e] : (ts' \text{ -> } t4s))$
**proof** (*cases es rule*: *List.rev-cases*)
**case** *Nil*
**then show** *?thesis*
**using** *assms b-e-typing.empty b-e-typing.weakening*
**by** *fastforce*
**next**
**case** (*snoc es' e'*)
**show** *?thesis* **using** *assms snoc b-e-typing.weakening*
**by** (*induction es@*$[e]$ $(t1s \text{ -> } t4s)$ *arbitrary*: *t1s t4s*, *fastforce+*)
**qed**

**lemma** *b-e-type-comp2-unlift*:
**assumes** $\mathcal{S}\cdot\mathcal{C} \vdash [\$e1, \$e2] : (t1s \text{ -> } t2s)$
**shows** $\exists\, ts'.\ (\mathcal{C} \vdash [e1] : (t1s \text{ -> } ts')) \wedge (\mathcal{C} \vdash [e2] : (ts' \text{ -> } t2s))$
**using** *assms*
*unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ $([e1, e2])$ $(t1s \text{ -> } t2s)$]
*b-e-type-comp*[*of* $\mathcal{C}$ $[e1]$ *e2 t1s t2s*]
**by** *simp*

**lemma** *b-e-type-comp2-relift*:
**assumes** $\mathcal{C} \vdash [e1] : (t1s \text{ -> } ts')$ $\mathcal{C} \vdash [e2] : (ts' \text{ -> } t2s)$
**shows** $\mathcal{S}\cdot\mathcal{C} \vdash [\$e1, \$e2] : (ts@t1s \text{ -> } ts@t2s)$
**using** *assms*
*b-e-typing.composition*[*OF assms*]
*e-typing-s-typing.intros*(*1*)[*of* $\mathcal{C}$ $[e1, e2]$ $(t1s \text{ -> } t2s)$]
*e-typing-s-typing.intros*(*3*)[*of* $\mathcal{S}$ $\mathcal{C}$ $([\$e1,\$e2])$ *t1s t2s ts*]
**by** *simp*

**lemma** *b-e-type-value2*:

**assumes** $\mathcal{C} \vdash [C\ v1,\ C\ v2] : (t1s \text{ -> } t2s)$
**shows** $t2s = t1s\ @\ [typeof\ v1,\ typeof\ v2]$
**proof** −
**obtain** $ts'$ **where** $ts'\text{-}def{:}\mathcal{C} \vdash [C\ v1] : (t1s \text{ -> } ts')$
$\mathcal{C} \vdash [C\ v2] : (ts' \text{ -> } t2s)$
**using** *b-e-type-comp assms*
**by** (*metis append-butlast-last-id butlast.simps*(2) *last-ConsL last-ConsR list.distinct*(1))
**have** $ts' = t1s\ @\ [typeof\ v1]$
**using** *b-e-type-value ts'-def*(1)
**by** *fastforce*
**thus** *?thesis*
**using** *b-e-type-value ts'-def*(2)
**by** *fastforce*
**qed**

**lemma** *e-type-comp*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash es@[e] : (t1s \text{ -> } t3s)$
**shows** $\exists\, ts'.\ (\mathcal{S}{\cdot}\mathcal{C} \vdash es : (t1s \text{ -> } ts')) \wedge (\mathcal{S}{\cdot}\mathcal{C} \vdash [e] : (ts' \text{ -> } t3s))$
**proof** (*cases es rule*: *List.rev-cases*)
**case** *Nil*
**thus** *?thesis*
**using** *assms e-typing-s-typing.intros*(1)
**by** (*metis append-Nil b-e-type-empty list.simps*(8))
**next**
**case** (*snoc es' e'*)
**show** *?thesis* **using** *assms snoc*
**proof** (*induction es*@[*e*] (*t1s* -> *t3s*) *arbitrary*: *t1s t3s*)
**case** (*1 C b-es S*)
**obtain** *es'' e''* **where** *b-e-defs*:($\$*\ (es'' @ [e''])) = (\$*\ b\text{-}es)$
**using** *1*(*1*,*2*)
**by** (*metis Nil-is-map-conv append-is-Nil-conv not-Cons-self2 rev-exhaust*)
**hence** $(\$*es'') = es\ (\$e'') = e$
**using** *1*(*2*) *inj-basic map-injective*
**by** *auto*
**moreover**
**have** $\mathcal{C} \vdash (es'' @ [e'']) : (t1s \text{ -> } t3s)$ **using** *1*(*1*)
**using** *inj-basic map-injective b-e-defs*
**by** *blast*
**then obtain** *t2s* **where** $\mathcal{C} \vdash es'' : (t1s \text{ -> } t2s)\ \mathcal{C} \vdash [e''] : (t2s \text{ -> } t3s)$
**using** *b-e-type-comp*
**by** *blast*
**ultimately**
**show** *?case*
**using** *e-typing-s-typing.intros*(1)
**by** *fastforce*
**next**
**case** (*3 S C t1s t2s ts*)
**thus** *?case*

```
    using e-typing-s-typing.intros(3)
    by fastforce
  qed auto
qed

lemma e-type-comp-conc:
  assumes S·C ⊢ es : (t1s -> t2s)
          S·C ⊢ es' : (t2s -> t3s)
  shows S·C ⊢ es@es' : (t1s -> t3s)
  using assms(2)
proof (induction es' arbitrary: t3s rule: List.rev-induct)
  case Nil
  hence t2s = t3s
    using unlift-b-e[of - - []] b-e-type-empty[of - t2s t3s]
    by fastforce
  then show ?case
    using Nil assms(1) e-typing-s-typing.intros(2)
    by fastforce
next
  case (snoc x xs)
  then obtain ts' where S·C ⊢ xs : (t2s -> ts') S·C ⊢ [x] : (ts' -> t3s)
    using e-type-comp[of - - xs x]
    by fastforce
  then show ?case
    using snoc(1)[of ts'] e-typing-s-typing.intros(2)[of - - es @ xs t1s ts' x t3s]
    by simp
qed


lemma b-e-type-comp-conc:
  assumes C ⊢ es : (t1s -> t2s)
          C ⊢ es' : (t2s -> t3s)
  shows C ⊢ es@es' : (t1s -> t3s)
proof −
  fix S
  have 1:S·C ⊢ $*es : (t1s -> t2s)
    using e-typing-s-typing.intros(1)[OF assms(1)]
    by fastforce
  have 2:S·C ⊢ $*es' : (t2s -> t3s)
    using e-typing-s-typing.intros(1)[OF assms(2)]
    by fastforce
  show ?thesis
    using e-type-comp-conc[OF 1 2]
    by (simp add: unlift-b-e)
qed

lemma e-type-comp-conc1:
  assumes S·C ⊢ es@es' : (ts -> ts')
  shows ∃ts''. (S·C ⊢ es : (ts -> ts'')) ∧ (S·C ⊢ es' : (ts'' -> ts'))
```

**using** *assms*
**proof** (*induction es′ arbitrary*: *ts ts′ rule*: *List.rev-induct*)
**case** *Nil*
**thus** *?case*
**using** *b-e-type-empty*[*of - ts′ ts′*] *e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**next**
**case** (*snoc x xs*)
**then show** *?case*
**using** *e-type-comp*[*of* $\mathcal{S}$ $\mathcal{C}$ *es* @ *xs x ts ts′*] *e-typing-s-typing.intros*(*2*)[*of* $\mathcal{S}$ $\mathcal{C}$ *xs - - x ts′*]
**by** *fastforce*
**qed**

**lemma** *e-type-comp-conc2*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash es@es'@es'' : (t1s \text{ -> } t2s)$
**shows** $\exists\, ts'\ ts''.\ (\mathcal{S}{\cdot}\mathcal{C} \vdash es : (t1s \text{ -> } ts')) \wedge (\mathcal{S}{\cdot}\mathcal{C} \vdash es' : (ts' \text{ -> } ts'')) \wedge (\mathcal{S}{\cdot}\mathcal{C} \vdash es'' : (ts'' \text{ -> } t2s))$
**proof** −
**obtain** $ts'$ **where** $\mathcal{S}{\cdot}\mathcal{C} \vdash es : (t1s \text{ -> } ts')$ $\mathcal{S}{\cdot}\mathcal{C} \vdash es'@es'' : (ts' \text{ -> } t2s)$
**using** *assms*(*1*) *e-type-comp-conc1*
**by** *fastforce*
**moreover**
**then obtain** $ts''$ **where** $\mathcal{S}{\cdot}\mathcal{C} \vdash es' : (ts' \text{ -> } ts'')$ $\mathcal{S}{\cdot}\mathcal{C} \vdash es'' : (ts'' \text{ -> } t2s)$
**using** *e-type-comp-conc1*
**by** *fastforce*
**ultimately**
**show** *?thesis*
**by** *fastforce*
**qed**

**lemma** *b-e-type-value-list*:
**assumes** $(\mathcal{C} \vdash es@[C\ v] : (ts \text{ -> } ts'@[t]))$
**shows** $(\mathcal{C} \vdash es : (ts \text{ -> } ts'))$ $(typeof\ v = t)$
**proof** −
**obtain** $ts''$ **where** $(\mathcal{C} \vdash es : (ts \text{ -> } ts''))$ $(\mathcal{C} \vdash [C\ v] : (ts'' \text{ -> } ts' @ [t]))$
**using** *b-e-type-comp assms*
**by** *blast*
**thus** $(\mathcal{C} \vdash es : (ts \text{ -> } ts'))$ $(typeof\ v = t)$
**using** *b-e-type-value*[*of* $\mathcal{C}$ *C v ts″ ts′* @ [*t*]]
**by** *auto*
**qed**

**lemma** *e-type-label*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [Label\ n\ es0\ es] : (ts \text{ -> } ts')$
**shows** $\exists\, tls\ t2s.\ (ts' = (ts@t2s)) \wedge length\ tls = n$

```
                ∧ (S·C ⊢ es0 : (tls -> t2s))
                ∧ (S·C(|label := [tls] @ (label C)|) ⊢ es : ([] -> t2s))
  using assms
proof (induction S C [Label n es0 es] (ts -> ts') arbitrary: ts ts')
  case (1 C b-es S)
  then show ?case
    by (simp add: map-eq-Cons-conv)
next
  case (2 S C es t1s t2s e t3s)
  then show ?case
    by (metis append-self-conv2 b-e-type-empty last-snoc list.simps(8) unlift-b-e)
next
  case (3 S C t1s t2s ts)
  then show ?case
    by simp
next
  case (7 S C t2s)
  then show ?case
    by fastforce
qed

lemma e-type-callcl-native:
  assumes S·C ⊢ [Callcl cl] : (t1s' -> t2s')
          cl = Func-native i tf ts es
  shows ∃ t1s t2s ts-c. (t1s' = ts-c @ t1s)
                      ∧ (t2s' = ts-c @ t2s)
                      ∧ tf = (t1s -> t2s)
                      ∧ i < length (s-inst S)
                     ∧ (((s-inst S)!i)(|local := (local ((s-inst S)!i)) @ t1s @ ts, label
:= ([t2s] @ (label ((s-inst S)!i))), return := Some t2s|) ⊢ es : ([] -> t2s))
  using assms
proof (induction S C [Callcl cl] (t1s' -> t2s') arbitrary: t1s' t2s')
  case (1 C b-es S)
  thus ?case
    by auto
next
  case (2 S C es t1s t2s e t3s)
  have C ⊢ [] : (t1s -> t2s)
    using 2(1,5) unlift-b-e
    by (metis Nil-is-map-conv append-Nil butlast-snoc)
  thus ?case
    using 2(4,5,6)
    by fastforce
next
  case (3 S C t1s t2s ts)
    thus ?case
    by fastforce
next
  case (6 S C)
```

```
  thus ?case
    unfolding cl-typing.simps
    by fastforce
qed

lemma e-type-callcl-host:
  assumes S·C ⊢ [Callcl cl] : (t1s' -> t2s')
          cl = Func-host tf f
  shows ∃ t1s t2s ts-c. (t1s' = ts-c @ t1s)
                      ∧ (t2s' = ts-c @ t2s)
                      ∧ tf = (t1s -> t2s)
  using assms
proof (induction S C [Callcl cl] (t1s' -> t2s') arbitrary: t1s' t2s')
  case (1 C b-es S)
  thus ?case
    by auto
next
  case (2 S C es t1s t2s e t3s)
  have C ⊢ [] : (t1s -> t2s)
    using 2(1,5) unlift-b-e
    by (metis Nil-is-map-conv append-Nil butlast-snoc)
  thus ?case
    using 2(4,5,6)
    by fastforce
next
  case (3 S C t1s t2s ts)
    thus ?case
    by fastforce
next
  case (6 S C)
  thus ?case
    unfolding cl-typing.simps
    by fastforce
qed

lemma e-type-callcl:
  assumes S·C ⊢ [Callcl cl] : (t1s' -> t2s')
  shows ∃ t1s t2s ts-c. (t1s' = ts-c @ t1s)
                      ∧ (t2s' = ts-c @ t2s)
                      ∧ cl-type cl = (t1s -> t2s)
proof (cases cl)
  case (Func-native x11 x12 x13 x14)
  thus ?thesis
    using e-type-callcl-native[OF assms]
    unfolding cl-type-def
    by (cases x12) fastforce
next
  case (Func-host x21 x22)
  thus ?thesis
```

**using** *e-type-callcl-host*[*OF assms*]
**unfolding** *cl-type-def*
**by** *fastforce*
**qed**

**lemma** *s-type-unfold*:
**assumes** $\mathcal{S}{\cdot}rs \vdash i\ vs;es : ts$
**shows** $i < length\ (s\text{-}inst\ \mathcal{S})$
$(rs = Some\ ts) \vee rs = None$
$(\mathcal{S}{\cdot}((s\text{-}inst\ \mathcal{S})!i)(\!|local := (local\ ((s\text{-}inst\ \mathcal{S})!i))\ @\ (map\ typeof\ vs),\ return := rs|\!) \vdash es : ([]\ \text{->}\ ts))$
**using** *assms*
**by** (*induction vs es ts*, *auto*)

**lemma** *e-type-local*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [Local\ n\ i\ vs\ es] : (ts\ \text{->}\ ts')$
**shows** $\exists tls.\ i < length\ (s\text{-}inst\ \mathcal{S})$
$\wedge\ length\ tls = n$
$\wedge\ (\mathcal{S}{\cdot}((s\text{-}inst\ \mathcal{S})!i)(\!|local := (local\ ((s\text{-}inst\ \mathcal{S})!i))\ @\ (map\ typeof\ vs),\ return := Some\ tls|\!) \vdash es : ([]\ \text{->}\ tls)$
$\wedge\ ts' = ts\ @\ tls$
**using** *assms*
**proof** (*induction* $\mathcal{S}\ \mathcal{C}\ [Local\ n\ i\ vs\ es]\ (ts\ \text{->}\ ts')$ *arbitrary*: *ts ts'*)
**case** (*2* $\mathcal{S}\ \mathcal{C}$ *es' t1s t2s e t3s*)
**have** *t1s* = *t2s*
**using** *2 unlift-b-e*
**by** *force*
**thus** *?case*
**using** *2*
**by** *simp*
**qed** (*auto simp add*: *unlift-b-e s-typing.simps*)

**lemma** *e-type-local-shallow*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [Local\ n\ i\ vs\ es] : (ts\ \text{->}\ ts')$
**shows** $\exists tls.\ length\ tls = n \wedge ts' = ts@tls \wedge (\mathcal{S}{\cdot}(Some\ tls) \vdash i\ vs;es : tls)$
**using** *assms*
**proof** (*induction* $\mathcal{S}\ \mathcal{C}\ [Local\ n\ i\ vs\ es]\ (ts\ \text{->}\ ts')$ *arbitrary*: *ts ts'*)
**case** (*1* $\mathcal{C}$ *b-es* $\mathcal{S}$)
**thus** *?case*
**by** (*metis e.distinct*(*7*) *map-eq-Cons-D*)
**next**
**case** (*2* $\mathcal{S}\ \mathcal{C}$ *es t1s t2s e t3s*)
**thus** *?case*
**by** *simp* (*metis append-Nil append-eq-append-conv e-type-comp-conc e-type-local*)
**qed** *simp-all*

**lemma** *e-type-const-unwrap*:
**assumes** *is-const e*

```
  shows ∃ v. e = $C v
  using assms
proof (cases e)
  case (Basic x1)
  then show ?thesis
    using assms
  proof (cases x1)
    case (EConst x23)
      thus ?thesis
        using Basic e-typing-s-typing.intros(1,3)
        by fastforce
  qed  (simp-all add: is-const-def)
qed (simp-all add: is-const-def)

lemma is-const-list1:
  assumes ves = map (Basic ∘ EConst) vs
  shows const-list ves
  using assms
proof (induction vs arbitrary: ves)
  case Nil
  then show ?case
    unfolding const-list-def
    by simp
next
  case (Cons a vs)
  then obtain ves' where ves' = map (Basic ∘ EConst) vs
    by blast
  moreover
  have is-const ((Basic ∘ EConst) a)
    unfolding is-const-def
    by simp
  ultimately
  show ?case
    using Cons
    unfolding const-list-def

    by auto
qed

lemma is-const-list:
  assumes ves = $$* vs
  shows const-list ves
  using assms is-const-list1
  unfolding comp-def
  by auto

lemma const-list-cons-last:
  assumes const-list (es@[e])
  shows const-list es
```

```
      is-const e
  using assms list-all-append[of is-const es [e]]
  unfolding const-list-def
  by auto

lemma e-type-const1:
  assumes is-const e
  shows ∃ t. (S·C ⊢ [e] : (ts -> ts@[t]))
  using assms
proof (cases e)
  case (Basic x1)
  then show ?thesis
    using assms
  proof (cases x1)
    case (EConst x23)
      hence C ⊢ [x1] : ([] -> [typeof x23])
        by (simp add: b-e-typing.intros(1))
      thus ?thesis
        using Basic e-typing-s-typing.intros(1,3)
        by (metis append-Nil2 to-e-list-1)
  qed (simp-all add: is-const-def)
qed (simp-all add: is-const-def)

lemma e-type-const:
  assumes is-const e
        S·C ⊢ [e] : (ts -> ts')
  shows ∃ t. (ts' = ts@[t]) ∧ (S·C' ⊢ [e] : ([] -> [t]))
  using assms
proof (cases e)
  case (Basic x1)
  then show ?thesis
    using assms
  proof (cases x1)
    case (EConst x23)
      then have ts' = ts @ [typeof x23]
       by (metis (no-types) Basic assms(2) b-e-type-value list.simps(8,9) unlift-b-e)
      moreover
      have S·C' ⊢ [e] : ([] -> [typeof x23])
        using Basic EConst b-e-typing.intros(1) e-typing-s-typing.intros(1)
        by fastforce
      ultimately
      show ?thesis
        by simp
  qed (simp-all add: is-const-def)
qed (simp-all add: is-const-def)

lemma const-typeof:
  assumes S·C ⊢ [$C v] : ([] -> [t])
  shows typeof v = t
```

**using** *assms*
**proof** −
**have** $\mathcal{C} \vdash [C\ v] : ([] \text{ -> } [t])$
**using** *unlift-b-e assms*
**by** *fastforce*
**thus** *?thesis*
**by** (*induction* $[C\ v]$ $([] \text{ -> } [t])$ *rule*: *b-e-typing.induct*, *auto*)
**qed**

**lemma** *e-type-const-list*:
**assumes** *const-list vs*
$\mathcal{S}\text{•}\mathcal{C} \vdash vs : (ts \text{ -> } ts')$
**shows** $\exists tvs.\ ts' = ts\ @\ tvs \wedge length\ vs = length\ tvs \wedge (\mathcal{S}\text{•}\mathcal{C}' \vdash vs : ([] \text{ -> } tvs))$
**using** *assms*
**proof** (*induction vs arbitrary*: *ts ts' rule*: *List.rev-induct*)
**case** *Nil*
**have** $\mathcal{S}\text{•}\mathcal{C}' \vdash [] : ([] \text{ -> } [])$
**using** *b-e-type-empty*[*of* $\mathcal{C}'$ [] []] *e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**thus** *?case*
**using** *Nil*
**by** (*metis append-Nil2 b-e-type-empty list.map*(*1*) *list.size*(*3*) *unlift-b-e*)
**next**
**case** (*snoc x xs*)
**hence** *v-lists*:*list-all is-const xs is-const x*
**unfolding** *const-list-def*
**by** *simp-all*
**obtain** *ts''* **where** *ts''-def*:$\mathcal{S}\text{•}\mathcal{C} \vdash xs : (ts \text{ -> } ts'')$ $\mathcal{S}\text{•}\mathcal{C} \vdash [x] : (ts'' \text{ -> } ts')$
**using** *snoc*(*3*) *e-type-comp*
**by** *fastforce*
**then obtain** *ts-b* **where** *ts-b-def*:$ts'' = ts\ @\ ts\text{-}b\ length\ xs = length\ ts\text{-}b\ \mathcal{S}\text{•}\mathcal{C}' \vdash xs : ([] \text{ -> } ts\text{-}b)$
**using** *snoc*(*1*) *v-lists*(*1*)
**unfolding** *const-list-def*
**by** *fastforce*
**then obtain** *t* **where** *t-def*:$ts' = ts\ @\ ts\text{-}b\ @\ [t]$ $\mathcal{S}\text{•}\mathcal{C}' \vdash [x] : ([] \text{ -> } [t])$
**using** *e-type-const v-lists*(*2*) *ts''-def*
**by** *fastforce*
**moreover**
**then have** *length* (*ts-b*@[*t*]) = *length* (*xs*@[*x*])
**using** *ts-b-def*(*2*)
**by** *simp*
**moreover**
**have** $\mathcal{S}\text{•}\mathcal{C}' \vdash (xs@[x]) : ([] \text{ -> } ts\text{-}b@[t])$
**using** *ts-b-def*(*3*) *t-def e-typing-s-typing.intros*(*2*,*3*)
**by** *fastforce*
**ultimately**
**show** *?case*
**by** *simp*

**qed**

**lemma** *e-type-const-list-snoc*:
**assumes** *const-list vs*
$\mathcal{S}\cdot\mathcal{C} \vdash vs : ([] \text{ -> } ts@[t])$
**shows** $\exists$ *vs1 v2*. $(\mathcal{S}\cdot\mathcal{C} \vdash vs1 : ([] \text{ -> } ts))$
$\wedge\ (\mathcal{S}\cdot\mathcal{C} \vdash [v2] : (ts \text{ -> } ts@[t]))$
$\wedge\ (vs = vs1@[v2])$
$\wedge$ *const-list vs1*
$\wedge$ *is-const v2*
**using** *assms*
**proof** −
**obtain** *vs′ v* **where** *vs-def*:*vs* = *vs′*@[*v*]
**using** *e-type-const-list*[*OF assms*(*1*,*2*)]
**by** (*metis append-Nil append-eq-append-conv list.size*(*3*) *snoc-eq-iff-butlast*)
**hence** *consts-def*:*const-list vs′ is-const v*
**using** *assms*(*1*)
**unfolding** *const-list-def*
**by** *auto*
**obtain** *ts′* **where** *ts′-def*:$\mathcal{S}\cdot\mathcal{C} \vdash vs' : ([] \text{ -> } ts')$ $\mathcal{S}\cdot\mathcal{C} \vdash [v] : (ts' \text{ -> } ts@[t])$
**using** *vs-def assms*(*2*) *e-type-comp*[*of* $\mathcal{S}$ $\mathcal{C}$ *vs′ v* [] *ts*@[*t*]]
**by** *fastforce*
**obtain** *c* **where** *v* = $*C c*
**using** *e-type-const-unwrap consts-def*(*2*)
**by** *fastforce*
**hence** *ts′* = *ts*
**using** *ts′-def*(*2*) *unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*C c*]] *b-e-type-value*
**by** *fastforce*
**thus** *?thesis* **using** *ts′-def vs-def consts-def*
**by** *simp*
**qed**

**lemma** *e-type-const-list-cons*:
**assumes** *const-list vs*
$\mathcal{S}\cdot\mathcal{C} \vdash vs : ([] \text{ -> } (ts1@ts2))$
**shows** $\exists$ *vs1 vs2*. $(\mathcal{S}\cdot\mathcal{C} \vdash vs1 : ([] \text{ -> } ts1))$
$\wedge\ (\mathcal{S}\cdot\mathcal{C} \vdash vs2 : (ts1 \text{ -> } (ts1@ts2)))$
$\wedge\ (vs = vs1@vs2)$
$\wedge$ *const-list vs1*
$\wedge$ *const-list vs2*
**using** *assms*
**proof** (*induction ts1*@*ts2 arbitrary*: *vs ts1 ts2 rule*: *List.rev-induct*)
**case** *Nil*
**thus** *?case*
**using** *e-type-const-list*
**by** *fastforce*
**next**
**case** (*snoc t ts*)
**note** *snoc-outer* = *snoc*

```
  show ?case
  proof (cases ts2 rule: List.rev-cases)
    case Nil
    have S·C ⊢ [] : (ts1 -> ts1 @ [])
      using b-e-typing.empty b-e-typing.weakening e-typing-s-typing.intros(1)
      by fastforce
    then show ?thesis
      using snoc(3,4) Nil
      unfolding const-list-def
      by auto
  next
    case (snoc ts2' a)
    obtain vs1 v2 where vs1-def:(S·C ⊢ vs1 : ([] -> ts1 @ ts2'))
                        (S·C ⊢ [v2] : (ts1 @ ts2' -> ts1 @ ts2' @[t]))
                        (vs = vs1@[v2])
                        const-list vs1
                        is-const v2
                        ts = ts1 @ ts2'
      using e-type-const-list-snoc[OF snoc-outer(3), of S C ts1@ts2' t]
          snoc-outer(2,4) snoc
      by fastforce
    show ?thesis
      using snoc-outer(1)[OF vs1-def(6,4,1)] snoc-outer(2) vs1-def(3,5)
          e-typing-s-typing.intros(2)[OF - vs1-def(2), of - ts1]
          snoc
      unfolding const-list-def
      by fastforce
  qed
qed

lemma e-type-const-conv-vs:
  assumes const-list ves
  shows ∃ vs. ves = $$* vs
  using assms
proof (induction ves)
  case Nil
  thus ?case
    by simp
next
  case (Cons a ves)
  thus ?case
  using e-type-const-unwrap
  unfolding const-list-def
  by (metis (no-types, lifting) list.pred-inject(2) list.simps(9))
qed

lemma types-exist-lfilled:
  assumes Lfilled k lholed es lfilled
        S·C ⊢ lfilled : (ts -> ts')
```

**shows** $\exists$ *t1s t2s* $\mathcal{C}'$ *arb-label*. ($\mathcal{S}$·$\mathcal{C}$⦇*label* := *arb-label*@(*label* $\mathcal{C}$)⦈ ⊢ *es* : (*t1s* -> *t2s*))
**using** *assms*
**proof** (*induction arbitrary*: $\mathcal{C}$ *ts ts'' rule*: *Lfilled.induct*)
**case** (*L0 vs lholed es' es*)
**hence** $\mathcal{S}$·($\mathcal{C}$⦇*label* := *label* $\mathcal{C}$⦈) ⊢ *vs* @ *es* @ *es'* : (*ts* -> *ts''*)
**by** *simp*
**thus** *?case*
**using** *e-type-comp-conc2*
**by** (*metis append-Nil*)
**next**
**case** (*LN vs lholed n es' l es'' k es lfilledk*)
**obtain** *ts' ts'''* **where** $\mathcal{S}$·$\mathcal{C}$ ⊢ [*Label n es' lfilledk*] : (*ts'* -> *ts'''*)
**using** *e-type-comp-conc2*[*OF LN*(*5*)]
**by** *fastforce*
**then obtain** *t1s t2s ts* **where** *test*:$\mathcal{S}$·$\mathcal{C}$⦇*label* := [*ts*] @ (*label* $\mathcal{C}$)⦈ ⊢ *lfilledk* : (*t1s* -> *t2s*)
**using** *e-type-label*
**by** *metis*
**show** *?case*
**using** *LN*(*4*)[*OF test*(*1*)]
**by** *simp* (*metis append.assoc append-Cons append-Nil*)
**qed**

**lemma** *types-exist-lfilled-weak*:
**assumes** *Lfilled k lholed es lfilled*
$\mathcal{S}$·$\mathcal{C}$ ⊢ *lfilled* : (*ts* -> *ts'*)
**shows** $\exists$ *t1s t2s* $\mathcal{C}'$ *arb-label arb-return*. ($\mathcal{S}$·$\mathcal{C}$⦇*label* := *arb-label*, *return* := *arb-return*⦈ ⊢ *es* : (*t1s* -> *t2s*))
**proof** −
**have** $\exists$ *t1s t2s* $\mathcal{C}'$ *arb-label*. ($\mathcal{S}$·$\mathcal{C}$⦇*label* := *arb-label*, *return* := (*return* $\mathcal{C}$)⦈ ⊢ *es* : (*t1s* -> *t2s*))
**using** *types-exist-lfilled*[*OF assms*]
**by** *fastforce*
**thus** *?thesis*
**by** *fastforce*
**qed**

**lemma** *store-typing-imp-func-agree*:
**assumes** *store-typing s* $\mathcal{S}$
*i* < *length* (*s-inst* $\mathcal{S}$)
*j* < *length* (*func-t* ((*s-inst* $\mathcal{S}$)!*i*))
**shows** (*sfunc-ind s i j*) < *length* (*s-funcs* $\mathcal{S}$)
*cl-typing* $\mathcal{S}$ (*sfunc s i j*) ((*s-funcs* $\mathcal{S}$)!(*sfunc-ind s i j*))
((*s-funcs* $\mathcal{S}$)!(*sfunc-ind s i j*)) = (*func-t* ((*s-inst* $\mathcal{S}$)!*i*))!*j*
**proof** −
**have** *funcs-agree*:*list-all2* (*cl-typing* $\mathcal{S}$) (*funcs s*) (*s-funcs* $\mathcal{S}$)
**using** *assms*(*1*)
**unfolding** *store-typing.simps*

**by** *auto*
**have** *list-all2* (*funci-agree* (*s-funcs* $\mathcal{S}$)) (*inst.funcs* ((*inst s*)!*i*)) (*func-t* ((*s-inst* $\mathcal{S}$)!*i*))
**using** *assms*(*1*,*2*) *store-typing-imp-inst-length-eq store-typing-imp-inst-typing*
**by** (*fastforce simp add*: *inst-typing.simps*)
**hence** *funci-agree* (*s-funcs* $\mathcal{S}$) ((*inst.funcs* ((*inst s*)!*i*))!*j*) ((*func-t* ((*s-inst* $\mathcal{S}$)!*i*))!*j*)
**using** *assms*(*3*) *list-all2-nthD2*
**by** *blast*
**thus** (*sfunc-ind s i j*) < *length* (*s-funcs* $\mathcal{S}$)
((*s-funcs* $\mathcal{S}$)!(*sfunc-ind s i j*)) = (*func-t* ((*s-inst* $\mathcal{S}$)!*i*))!*j*
**unfolding** *funci-agree-def sfunc-ind-def*
**by** *auto*
**thus** *cl-typing* $\mathcal{S}$ (*sfunc s i j*) ((*s-funcs* $\mathcal{S}$)!(*sfunc-ind s i j*))
**using** *funcs-agree list-all2-nthD2*
**unfolding** *sfunc-def*
**by** *fastforce*
**qed**

**lemma** *store-typing-imp-glob-agree*:
**assumes** *store-typing s* $\mathcal{S}$
*i* < *length* (*s-inst* $\mathcal{S}$)
*j* < *length* (*global* ((*s-inst* $\mathcal{S}$)!*i*))
**shows** (*sglob-ind s i j*) < *length* (*s-globs* $\mathcal{S}$)
*glob-agree* (*sglob s i j*) ((*s-globs* $\mathcal{S}$)!(*sglob-ind s i j*))
((*s-globs* $\mathcal{S}$)!(*sglob-ind s i j*)) = (*global* ((*s-inst* $\mathcal{S}$)!*i*))!*j*
**proof** −
**have** *globs-agree*:*list-all2 glob-agree* (*globs s*) (*s-globs* $\mathcal{S}$)
**using** *assms*(*1*)
**unfolding** *store-typing.simps*
**by** *auto*
**have** *list-all2* (*globi-agree* (*s-globs* $\mathcal{S}$)) (*inst.globs* ((*inst s*)!*i*)) (*global* ((*s-inst* $\mathcal{S}$)!*i*))
**using** *assms*(*1*,*2*) *store-typing-imp-inst-length-eq store-typing-imp-inst-typing*
**by** (*fastforce simp add*: *inst-typing.simps*)
**hence** *globi-agree* (*s-globs* $\mathcal{S}$) ((*inst.globs* ((*inst s*)!*i*))!*j*) ((*global* ((*s-inst* $\mathcal{S}$)!*i*))!*j*)
**using** *assms*(*3*) *list-all2-nthD2*
**by** *blast*
**thus** (*sglob-ind s i j*) < *length* (*s-globs* $\mathcal{S}$)
((*s-globs* $\mathcal{S}$)!(*sglob-ind s i j*)) = (*global* ((*s-inst* $\mathcal{S}$)!*i*))!*j*
**unfolding** *globi-agree-def sglob-ind-def*
**by** *auto*
**thus** *glob-agree* (*sglob s i j*) ((*s-globs* $\mathcal{S}$)!(*sglob-ind s i j*))
**using** *globs-agree list-all2-nthD2*
**unfolding** *sglob-def*
**by** *fastforce*
**qed**

**lemma** *store-typing-imp-mem-agree-Some*:
**assumes** *store-typing s* $\mathcal{S}$

$i < length\ (s\text{-}inst\ \mathcal{S})$
$smem\text{-}ind\ s\ i = Some\ j$
**shows** $j < length\ (s\text{-}mem\ \mathcal{S})$
$mem\text{-}agree\ ((mem\ s)!j)\ ((s\text{-}mem\ \mathcal{S})!j)$
$\exists x.\ ((s\text{-}mem\ \mathcal{S})!j) = x \wedge (memory\ ((s\text{-}inst\ \mathcal{S})!i)) = Some\ x$
**proof** −
**have** *mems-agree*:*list-all2 mem-agree* $(mem\ s)$ $(s\text{-}mem\ \mathcal{S})$
**using** *assms*(*1*)
**unfolding** *store-typing.simps*
**by** *auto*
**hence** *memi-agree* $(s\text{-}mem\ \mathcal{S})$ $((inst.mem\ ((inst\ s)!i)))$ $((memory\ ((s\text{-}inst\ \mathcal{S})!i)))$
**using** *assms*(*1*,*2*) *store-typing-imp-inst-length-eq store-typing-imp-inst-typing*
**by** (*fastforce simp add*: *inst-typing.simps*)
**thus** $j < length\ (s\text{-}mem\ \mathcal{S})$
$\exists x.\ ((s\text{-}mem\ \mathcal{S})!j) = x \wedge (memory\ ((s\text{-}inst\ \mathcal{S})!i)) = Some\ x$
**using** *assms*(*3*)
**unfolding** *memi-agree-def smem-ind-def*
**by** *auto*
**thus** $mem\text{-}agree\ ((mem\ s)!j)\ ((s\text{-}mem\ \mathcal{S})!j)$
**using** *mems-agree list-all2-nthD2*
**unfolding** *sglob-def*
**by** *fastforce*
**qed**

**lemma** *store-typing-imp-mem-agree-None*:
**assumes** *store-typing s* $\mathcal{S}$
$i < length\ (s\text{-}inst\ \mathcal{S})$
$smem\text{-}ind\ s\ i = None$
**shows** $(memory\ ((s\text{-}inst\ \mathcal{S})!i)) = None$
**proof** −
**have** *mems-agree*:*list-all2 mem-agree* $(mem\ s)$ $(s\text{-}mem\ \mathcal{S})$
**using** *assms*(*1*)
**unfolding** *store-typing.simps*
**by** *auto*
**hence** *memi-agree* $(s\text{-}mem\ \mathcal{S})$ $((inst.mem\ ((inst\ s)!i)))$ $((memory\ ((s\text{-}inst\ \mathcal{S})!i)))$
**using** *assms*(*1*,*2*) *store-typing-imp-inst-length-eq store-typing-imp-inst-typing*
**by** (*fastforce simp add*: *inst-typing.simps*)
**thus** *?thesis*
**using** *assms*(*3*)
**unfolding** *memi-agree-def smem-ind-def*
**by** *auto*
**qed**

**lemma** *store-mem-exists*:
**assumes** $i < length\ (s\text{-}inst\ \mathcal{S})$
*store-typing s* $\mathcal{S}$
**shows** *Option.is-none* $(memory\ ((s\text{-}inst\ \mathcal{S})!i)) = Option.is\text{-}none\ (inst.mem\ ((inst\ s)!i))$
**proof** −

**obtain** $j$ **where** $j\text{-}def{:}j = (inst.mem\ ((inst\ s)!i))$
**by** *blast*
**obtain** $m$ **where** $m\text{-}def{:}m = (memory\ ((s\text{-}inst\ \mathcal{S})!i))$
**by** *blast*
**have** $inst\text{-}typ{:}inst\text{-}typing\ \mathcal{S}\ ((inst\ s)!i)\ ((s\text{-}inst\ \mathcal{S})!i)$
**using** *assms*
**unfolding** *store-typing.simps list-all2-conv-all-nth*
**by** *auto*
**thus** *?thesis*
**unfolding** *inst-typing.simps memi-agree-def*
**by** *auto*
**qed**

**lemma** *store-preserved-mem*:
**assumes** *store-typing s* $\mathcal{S}$
$s' = s(\!|s.mem := (s.mem\ s)[i := mem']|\!)$
$mem\text{-}size\ mem' \geq mem\text{-}size\ orig\text{-}mem$
$((s.mem\ s)!i) = orig\text{-}mem$
**shows** *store-typing* $s'\ \mathcal{S}$
**proof** −
**obtain** *insts fs clss bss gs* **where** $s = (\!|inst = insts, funcs = fs, tab = clss, mem = bss, globs = gs|\!)$
**using** *s.cases*
**by** *blast*
**moreover**
**obtain** $insts'\ fs'\ clss'\ bss'\ gs'$ **where** $s' = (\!|inst = insts', funcs = fs', tab = clss', mem = bss', globs = gs'|\!)$
**using** *s.cases*
**by** *blast*
**moreover**
**obtain** $\mathcal{C}s\ tfs\ ns\ ms\ tgs$ **where** $\mathcal{S} = (\!|s\text{-}inst = \mathcal{C}s, s\text{-}funcs = tfs, s\text{-}tab = ns, s\text{-}mem = ms, s\text{-}globs = tgs|\!)$
**using** *s-context.cases*
**by** *blast*
**moreover**
**note** *s-S-defs = calculation*
**hence**
$insts = insts'$
$fs = fs'$
$clss = clss'$
$gs = gs'$
**using** *assms*(*2*)
**by** *simp-all*
**hence**
$list\text{-}all2\ (inst\text{-}typing\ \mathcal{S})\ insts'\ \mathcal{C}s$
$list\text{-}all2\ (cl\text{-}typing\ \mathcal{S})\ fs'\ tfs$
$list\text{-}all\ (tab\text{-}agree\ \mathcal{S})\ (concat\ clss')$
$list\text{-}all2\ (\lambda cls\ n.\ n \leq length\ cls)\ clss'\ ns$
$list\text{-}all2\ glob\text{-}agree\ gs'\ tgs$

```
    using s-S-defs assms(1)
    unfolding store-typing.simps
    by auto
  moreover
  have list-all2 (λ bs m. m ≤ mem-size bs) bss' ms
  proof −
    have length bss = length bss'
      using assms(2)  s-S-defs
      by (simp)
    moreover

    have initial-mem:list-all2 (λ bs m. m ≤ mem-size bs) bss ms
      using assms(1) s-S-defs
      unfolding store-typing.simps mem-agree-def
      by blast
    have ⋀n. n < length bss ⟹ (λ bs m. m ≤ mem-size bs) (bss'!n) (ms!n)
    proof −
      fix n
      assume local-assms:n < length bss
      obtain C-m where cmdef:C-m = Cs ! n
        by blast
      hence (λ bs m. m ≤ mem-size bs) (bss!n) (ms!n)
        using initial-mem local-assms
        unfolding list-all2-conv-all-nth
        by simp
      thus (λ bs m. m ≤ mem-size bs) (bss'!n) (ms!n)
        using assms(2,3,4) s-S-defs local-assms
        by (cases n=i, auto)
    qed
    ultimately
    show ?thesis
      by (metis initial-mem list-all2-all-nthI list-all2-lengthD)
  qed
  ultimately
  show ?thesis
    unfolding store-typing.simps mem-agree-def
    by simp
qed

lemma types-agree-imp-e-typing:
  assumes types-agree t v
  shows S·C ⊢ [$C v] : ([] -> [t])
  using assms e-typing-s-typing.intros(1)[OF b-e-typing.intros(1)]
  unfolding types-agree-def
  by fastforce

lemma list-types-agree-imp-e-typing:
  assumes list-all2 types-agree ts vs
  shows S·C ⊢ $$* vs : ([] -> ts)
```

**using** *assms*
**proof** (*induction rule*: *list-all2-induct*)
**case** *Nil*
**thus** *?case*
**using** *b-e-typing.empty e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**next**
**case** (*Cons t ts v vs*)
**hence** $\mathcal{S}{\cdot}\mathcal{C} \vdash$ [$C *v*] : ([] -> [*t*])
**using** *types-agree-imp-e-typing*
**by** *fastforce*
**thus** *?case*
**using** *e-typing-s-typing.intros*(*3*)[*OF Cons*(*3*), *of* [*t*]] *e-type-comp-conc*
**by** *fastforce*
**qed**

**lemma** *b-e-typing-imp-list-types-agree*:
**assumes** $\mathcal{C} \vdash$ (*map* (λ*v*. *C v*) *vs*) : (*ts'* -> *ts'*@*ts*)
**shows** *list-all2 types-agree ts vs*
**using** *assms*
**proof** (*induction* (*map* (λ*v*. *C v*) *vs*) (*ts'* -> *ts'*@*ts*) *arbitrary*: *ts ts' vs rule*: *b-e-typing.induct*)
**case** (*composition* $\mathcal{C}$ *es t1s t2s e*)
**obtain** *vs1 vs2* **where** *es-e-def*:*es* = *map EConst vs1* [*e*] = *map EConst vs2 vs1*@*vs2*=*vs*
**using** *composition*(*5*)
**by** (*metis* (*no-types*) *last-map list.simps*(*8*,*9*) *map-butlast snoc-eq-iff-butlast*)
**have** *const-list* ($∗*es*)
**using** *es-e-def*(*1*) *is-const-list1*
**by** *auto*
**then obtain** *tvs1* **where** *t2s* = *t1s*@*tvs1*
**using** *e-type-const-list e-typing-s-typing.intros*(*1*)[*OF composition*(*1*)]
**by** *fastforce*
**moreover**
**have** *const-list* ($∗[*e*])
**using** *es-e-def*(*2*) *is-const-list1*
**by** *auto*
**then obtain** *tvs2* **where** *t1s* @ *ts* = *t2s* @ *tvs2*
**using** *e-type-const-list e-typing-s-typing.intros*(*1*)[*OF composition*(*3*)]
**by** *fastforce*
**ultimately**
**show** *?case*
**using** *composition*(*2*,*4*,*5*) *es-e-def*
**by** (*auto simp add*: *list-all2-appendI*)
**qed** (*auto simp add*: *types-agree-def*)

**lemma** *e-typing-imp-list-types-agree*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash$ ($$∗ *vs*) : (*ts'* -> *ts'*@*ts*)
**shows** *list-all2 types-agree ts vs*

**proof** −
**have** (\$\$∗ *vs*) = \$∗ (*map* (λ*v*. *C v*) *vs*)
**by** *simp*
**thus** *?thesis*
**using** *assms unlift-b-e b-e-typing-imp-list-types-agree*
**by** (*fastforce simp del*: *map-map*)
**qed**

**lemma** *store-extension-imp-store-typing*:
**assumes** *store-extension s s′*
*store-typing s* $\mathcal{S}$
**shows** *store-typing s′* $\mathcal{S}$
**proof** −
**obtain** *insts fs clss bss gs* **where** *s* = (|*inst* = *insts*, *funcs* = *fs*, *tab* = *clss*, *mem* = *bss*, *globs* = *gs*|)
**using** *s.cases*
**by** *blast*
**moreover**
**obtain** *insts′ fs′ clss′ bss′ gs′* **where** *s′* = (|*inst* = *insts′*, *funcs* = *fs′*, *tab* = *clss′*, *mem* = *bss′*, *globs* = *gs′*|)
**using** *s.cases*
**by** *blast*
**moreover**
**obtain** $\mathcal{C}s$ *tfs ns ms tgs* **where** $\mathcal{S}$ = (|*s-inst* = $\mathcal{C}s$, *s-funcs* = *tfs*, *s-tab* = *ns*, *s-mem* = *ms*, *s-globs* = *tgs*|)
**using** *s-context.cases*
**by** *blast*
**moreover**
**note** *s-S-defs* = *calculation*
**hence**
*insts* = *insts′*
*fs* = *fs′*
*clss* = *clss′*
*gs* = *gs′*
**using** *assms*(*1*)
**unfolding** *store-extension.simps*
**by** *simp-all*
**hence**
*list-all2* (*inst-typing* $\mathcal{S}$) *insts′* $\mathcal{C}s$
*list-all2* (*cl-typing* $\mathcal{S}$) *fs′ tfs*
*list-all* (*tab-agree* $\mathcal{S}$) (*concat clss′*)
*list-all2* (λ*cls n*. *n* ≤ *length cls*) *clss′ ns*
*list-all2 glob-agree gs′ tgs*
**using** *s-S-defs assms*(*2*)
**unfolding** *store-typing.simps*
**by** *auto*
**moreover**
**have** *list-all2* (λ *bs m*. *m* ≤ *mem-size bs*) *bss ms*
**using** *s-S-defs*(*1*,*3*) *assms*(*2*)

**unfolding** *store-typing.simps mem-agree-def*
**by** *simp*
**hence** *list-all2 mem-agree bss' ms*
**using** *assms(1) s-S-defs(1,2)*
**unfolding** *store-extension.simps list-all2-conv-all-nth mem-agree-def*
**by** *fastforce*
**ultimately**
**show** *?thesis*
**using** *store-typing.intros*
**by** *fastforce*
**qed**

**lemma** *lfilled-deterministic*:
**assumes** *Lfilled k lfilled es les*
*Lfilled k lfilled es les'*
**shows** *les = les'*
**using** *assms*
**proof** (*induction arbitrary*: *les' rule*: *Lfilled.induct*)
**case** (*L0 vs lholed es' es*)
**thus** *?case*
**by** (*fastforce simp add*: *Lfilled.simps*[*of 0*])
**next**
**case** (*LN vs lholed n es' l es'' k es lfilledk*)
**thus** *?case*
**unfolding** *Lfilled.simps*[*of* (*k* + *1*)]
**by** *fastforce*
**qed**
**end**

# 6 Lemmas for Soundness Proof

**theory** *Wasm-Properties* **imports** *Wasm-Properties-Aux* **begin**

## 6.1 Preservation

**lemma** *t-cvt*: **assumes** *cvt t sx v = Some v'* **shows** *t = typeof v'*
**using** *assms*
**unfolding** *cvt-def typeof-def*
**apply** (*cases t*)
**apply** (*simp add*: *option.case-eq-if*, *metis option.discI option.inject v.simps*(*17*))
**apply** (*simp add*: *option.case-eq-if*, *metis option.discI option.inject v.simps*(*18*))
**apply** (*simp add*: *option.case-eq-if*, *metis option.discI option.inject v.simps*(*19*))
**apply** (*simp add*: *option.case-eq-if*, *metis option.discI option.inject v.simps*(*20*))
**done**

**lemma** *store-preserved1*:
**assumes** (|*s*;*vs*;*es*|) ↪-*i* (|*s'*;*vs'*;*es'*|)
*store-typing s* $\mathcal{S}$
$\mathcal{S}$·$\mathcal{C}$ ⊢ *es* : (*ts* -> *ts'*)

$\mathcal{C} = ((s\text{-}inst\ \mathcal{S})!i)(\!|local := local\ ((s\text{-}inst\ \mathcal{S})!i)\ @\ (map\ typeof\ vs),\ label := arb\text{-}label,\ return := arb\text{-}return|\!)$
$i < length\ (s\text{-}inst\ \mathcal{S})$
**shows** *store-typing s' S*
**using** *assms*
**proof** (*induction arbitrary*: $\mathcal{C}$ *arb-label arb-return ts ts' rule*: *reduce.induct*)
**case** (*callcl-host-Some cl t1s t2s f ves vcs n m s hs s' vcs' vs i*)
**obtain** *ts''* **where** *ts''-def*:$\mathcal{S}\cdot\mathcal{C} \vdash ves : (ts\ ->\ ts'')$ $\mathcal{S}\cdot\mathcal{C} \vdash [Callcl\ cl] : (ts''\ ->\ ts')$
**using** *callcl-host-Some*(*8*) *e-type-comp*
**by** *fastforce*
**have** *ves-c*:*const-list ves*
**using** *is-const-list*[*OF callcl-host-Some*(*2*)]
**by** *simp*
**then obtain** *tvs* **where** *tvs-def*:*ts'' = ts @ tvs*
*length t1s = length tvs*
$\mathcal{S}\cdot\mathcal{C} \vdash ves : ([]\ ->\ tvs)$
**using** *ts''-def*(*1*) *e-type-const-list*[*of ves* $\mathcal{S}$ $\mathcal{C}$ *ts ts''*] *callcl-host-Some*
**by** *fastforce*
**hence** *ts'' = ts @ t1s*
*ts' = ts @ t2s*
**using** *e-type-callcl-host*[*OF ts''-def*(*2*) *callcl-host-Some*(*1*)]
**by** *auto*
**moreover**
**hence** *list-all2 types-agree t1s vcs*
**using** *e-typing-imp-list-types-agree*[**where** *?ts' = []*] *callcl-host-Some*(*2*) *tvs-def*(*1*,*3*)
**by** *fastforce*
**thus** *?case*
**using** *store-extension-imp-store-typing*
*host-apply-preserve-store*[*OF - callcl-host-Some*(*6*)] *callcl-host-Some*(*7*)
**by** *fastforce*
**next**
**case** (*set-global s i j v s' vs*)
**obtain** *insts fs clss bss gs* **where** $s = (\!|inst = insts,\ funcs = fs,\ tab = clss,\ mem = bss,\ globs = gs|\!)$
**using** *s.cases*
**by** *blast*
**moreover**
**obtain** *insts' fs' clss' bss' gs'* **where** $s' = (\!|inst = insts',\ funcs = fs',\ tab = clss',\ mem = bss',\ globs = gs'|\!)$
**using** *s.cases*
**by** *blast*
**moreover**
**obtain** $\mathcal{C}s$ *tfs ns ms tgs* **where** $\mathcal{S} = (\!|s\text{-}inst = \mathcal{C}s,\ s\text{-}funcs = tfs,\ s\text{-}tab = ns,\ s\text{-}mem = ms,\ s\text{-}globs = tgs|\!)$
**using** *s-context.cases*
**by** *blast*
**moreover**

**note** *s-S-defs = calculation*

**have**
*insts* = *insts′*
*fs* = *fs′*
*clss* = *clss′*
*bss* = *bss′*
**using** *set-global*(*1*) *s-S-defs*(*1*,*2*)
**unfolding** *supdate-glob-def supdate-glob-s-def*
**by** (*metis s.ext-inject s.update-convs*(*5*))+
**hence**
*list-all2* (*inst-typing* $\mathcal{S}$) *insts′* $\mathcal{C}$*s*
*list-all2* (*cl-typing* $\mathcal{S}$) *fs′ tfs*
*list-all* (*tab-agree* $\mathcal{S}$) (*concat clss′*)
*list-all2* ($\lambda$*cls n*. *n* $\leq$ *length cls*) *clss′ ns*
*list-all2 mem-agree bss′ ms*
**using** *set-global*(*2*) *s-S-defs*
**unfolding** *store-typing.simps*
**by** *auto*
**moreover**
**have** *list-all2 glob-agree gs′ tgs*
**proof** −
**have** *gs-agree*:*list-all2 glob-agree gs tgs*
**using** *set-global*(*2*) *s-S-defs*
**unfolding** *store-typing.simps*
**by** *auto*
**have** *length gs* = *length gs′*
**using** *s-S-defs*(*1*,*2*) *set-global*(*1*)
**unfolding** *supdate-glob-def supdate-glob-s-def*
**by** (*metis length-list-update s.select-convs*(*5*) *s.update-convs*(*5*))
**moreover**
**obtain** *k* **where** *k-def*:(*sglob-ind s i j*) = *k*
**by** *blast*
**hence** $\bigwedge j'$. $[\![j' \neq k; j' < \mathit{length}\ gs]\!] \Longrightarrow gs!j' = gs'!j'$
**using** *s-S-defs*(*1*,*2*) *set-global*(*1*)
**unfolding** *supdate-glob-def supdate-glob-s-def*
**by** *auto*
**hence** $\bigwedge j'$. $[\![j' \neq k; j' < \mathit{length}\ gs]\!] \Longrightarrow$ *glob-agree* (*gs′*!*j′*) (*tgs*!*j′*)
**using** *gs-agree*
**by** (*metis list-all2-conv-all-nth*)
**moreover**
**have** *glob-agree* (*gs′*!*k*) (*tgs*!*k*)
**proof** −
**obtain** *ts″* **where** *ts″-def*:$\mathcal{C}$ ⊢ [*C v*] : (*ts* -> *ts″*) $\mathcal{C}$ ⊢ [*Set-global j*] : (*ts″* -> *ts′*)
**by** (*metis b-e-type-comp2-unlift set-global.prems*(*2*))
**have** *b-es*:*ts″* = *ts*@[*typeof v*]
*ts* = *ts′*
*global* $\mathcal{C}$ ! *j* = ⦇*tg-mut* = *T-mut*, *tg-t* = *typeof v*⦈

```
            j < length (global C)
        using b-e-type-value[OF ts''-def(1)] b-e-type-set-global[OF ts''-def(2)]
        by auto
      hence j < length (global ((s-inst S)!i))
        using set-global(4)
        by fastforce
      hence globs-agree:k < length (s-globs S)
                        glob-agree (gs!k) (tgs!k)
                        (tgs!k) = (global C)!j
        using store-typing-imp-glob-agree[OF set-global(2,5)] b-es(4) s-S-defs(1,3)
k-def set-global(4)
        unfolding sglob-def
        by auto
      hence g-mut (gs!k) = T-mut
          typeof (g-val (gs!k)) = typeof v
        using b-es(3)
        unfolding glob-agree-def
        by auto
      hence g-mut (gs'!k) = T-mut
          typeof (g-val (gs'!k)) = typeof v
         using set-global(1) k-def globs-agree(1) store-typing-imp-glob-length-eq[OF
set-global(2)] s-S-defs(1,2)
        unfolding supdate-glob-def supdate-glob-s-def
        by auto
      thus ?thesis
        using globs-agree(3) b-es(3)
        unfolding glob-agree-def
        by fastforce
    qed
    ultimately
    show ?thesis
      using gs-agree
      unfolding list-all2-conv-all-nth
      by fastforce
  qed
  ultimately
  show ?case
    using store-typing.intros
    by simp
next

  case (store-Some t v s i j m k off mem' vs a)
  show ?case
    using store-preserved-mem[OF store-Some(5) - - store-Some(3)] store-size[OF
store-Some(4)]
    by fastforce
next
  case (store-packed-Some t v s i j m k off tp mem' vs a)
  thus ?case
```

**using** *store-preserved-mem*[*OF store-packed-Some*(5) - - *store-packed-Some*(3)] *store-packed-size*[*OF store-packed-Some*(4)]
**by** *simp*
**next**
**case** (*grow-memory s i j n mem c mem' vs*)
**show** *?case*
**using** *store-preserved-mem*[*OF grow-memory*(5)- - *grow-memory*(2)] *mem-grow-size*[*OF grow-memory*(4)]
**by** *simp*
**next**
**case** (*label s vs es i s' vs' es' k lholed les les'*)
**obtain** $\mathcal{C}'$ *t1s t2s arb-label' arb-return'* **where** *es-def*:$\mathcal{C}' = \mathcal{C}$⦇*label* := *arb-label'*, *return* := *arb-return'*⦈ $\mathcal{S}$·$\mathcal{C}'$ ⊢ *es* : (*t1s* -> *t2s*)
**using** *types-exist-lfilled-weak*[*OF label*(2,6)]
**by** *fastforce*
**thus** *?case*
**using** *label*(4)[*OF label*(5) *es-def*(2) - *label*(8)] *label*(7)
**by** *fastforce*
**next**
**case** (*local s vs es i s' vs' es' v0s n j*)
**obtain** *tls* **where** *t-local*:($\mathcal{S}$·((*s-inst* $\mathcal{S}$)!*i*)⦇*local* := (*local* ((*s-inst* $\mathcal{S}$)!*i*)) @ (*map typeof vs*), *return* := *Some tls*⦈ ⊢ *es* : ([] -> *tls*))
*ts'* = *ts* @ *tls i* < *length* (*s-inst* $\mathcal{S}$)
**using** *e-type-local*[*OF local*(4)]
**by** *blast+*
**show** *?case*
**using** *local*(2)[*OF local*(3) *t-local*(1) - *t-local*(3), *of* (*Some tls*) *label* ((*s-inst* $\mathcal{S}$)!*i*) ]
**by** *fastforce*
**qed** (*simp-all*)

**lemma** *store-preserved*:
**assumes** ⦇*s*;*vs*;*es*⦈ ⇝-*i* ⦇*s'*;*vs'*;*es'*⦈
*store-typing s* $\mathcal{S}$
$\mathcal{S}$·*None* ⊨-*i vs*;*es* : *ts*
**shows** *store-typing s'* $\mathcal{S}$
**proof** −
**show** *?thesis*
**using** *store-preserved1*[*OF assms*(1,2), *of* - [] *ts None label* (*s-inst* $\mathcal{S}$!*i*)]
*s-type-unfold*[*OF assms*(3)]
**by** *fastforce*
**qed**

**lemma** *typeof-unop-testop*:
**assumes** $\mathcal{S}$·$\mathcal{C}$ ⊢ [$C *v*, $*e*] : (*ts* -> *ts'*)
(*e* = (*Unop-i t iop*)) ∨ (*e* = (*Unop-f t fop*)) ∨ (*e* = (*Testop t testop*))
**shows** (*typeof v*) = *t*
*e* = (*Unop-f t fop*) ⟹ *is-float-t t*
**proof** −

**have** $\mathcal{C} \vdash [C\ v,\ e] : (ts\ ->\ ts')$
**using** *unlift-b-e assms*(1)
**by** *simp*
**then obtain** $ts''$ **where** $ts''$-*def*:$\mathcal{C} \vdash [C\ v] : (ts\ ->\ ts'')\ \mathcal{C} \vdash [e] : (ts''\ ->\ ts')$
**using** *b-e-type-comp*[**where** *?e* = *e* **and** *?es* = $[C\ v]$]
**by** *fastforce*
**show** (*typeof v*) = *t e* = (*Unop-f t fop*) $\Longrightarrow$ *is-float-t t*
**using** *b-e-type-value*[*OF ts''-def*(1)] *assms*(2) *b-e-type-unop-testop*[*OF ts''-def*(2)]
**by** *simp-all*
**qed**

**lemma** *typeof-cvtop*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v,\ \$e] : (ts\ ->\ ts')$
*e* = *Cvtop t1 cvtop t sx*
**shows** (*typeof v*) = *t*
*cvtop* = *Convert* $\Longrightarrow$ (*t1* $\neq$ *t*) $\wedge$ ((*sx* = *None*) = ((*is-float-t t1* $\wedge$ *is-float-t t*) $\vee$ (*is-int-t t1* $\wedge$ *is-int-t t* $\wedge$ (*t-length t1* < *t-length t*))))
*cvtop* = *Reinterpret* $\Longrightarrow$ (*t1* $\neq$ *t*) $\wedge$ *t-length t1* = *t-length t*
**proof** −
**have** $\mathcal{C} \vdash [C\ v,\ e] : (ts\ ->\ ts')$
**using** *unlift-b-e assms*(1)
**by** *simp*
**then obtain** $ts''$ **where** $ts''$-*def*:$\mathcal{C} \vdash [C\ v] : (ts\ ->\ ts'')\ \mathcal{C} \vdash [e] : (ts''\ ->\ ts')$
**using** *b-e-type-comp*[**where** *?e* = *e* **and** *?es* = $[C\ v]$]
**by** *fastforce*
**show** (*typeof v*) = *t*
*cvtop* = *Convert* $\Longrightarrow$ (*t1* $\neq$ *t*) $\wedge$ (*sx* = *None*) = ((*is-float-t t1* $\wedge$ *is-float-t t*) $\vee$ (*is-int-t t1* $\wedge$ *is-int-t t* $\wedge$ (*t-length t1* < *t-length t*)))
*cvtop* = *Reinterpret* $\Longrightarrow$ (*t1* $\neq$ *t*) $\wedge$ *t-length t1* = *t-length t*
**using** *b-e-type-value*[*OF ts''-def*(1)] *b-e-type-cvtop*[*OF ts''-def*(2) *assms*(2)]
**by** *simp-all*
**qed**

**lemma** *types-preserved-unop-testop-cvtop*:
**assumes** $(\!|[\$C\ v,\ \$e]|\!) \rightsquigarrow (\!|[\$C\ v']|\!)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v,\ \$e] : (ts\ ->\ ts')$
(*e* = (*Unop-i t iop*)) $\vee$ (*e* = (*Unop-f t fop*)) $\vee$ (*e* = (*Testop t testop*)) $\vee$ (*e* = (*Cvtop t2 cvtop t sx*))
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v'] : (ts\ ->\ ts')$
**proof** −
**have** $\mathcal{C} \vdash [C\ v,\ e] : (ts\ ->\ ts')$
**using** *unlift-b-e assms*(2)
**by** *simp*
**then obtain** $ts''$ **where** $ts''$-*def*:$\mathcal{C} \vdash [C\ v] : (ts\ ->\ ts'')\ \mathcal{C} \vdash [e] : (ts''\ ->\ ts')$
**using** *b-e-type-comp*[**where** *?e* = *e* **and** *?es* = $[C\ v]$]
**by** *fastforce*
**have** $ts@[arity\text{-}1\text{-}result\ e] = ts'$ (*typeof v*) = *t*
**using** *b-e-type-value*[*OF ts''-def*(1)] *assms*(3) *b-e-type-unop-testop*(1)[*OF ts''-def*(2)]
*b-e-type-cvtop*(1)[*OF ts''-def*(2)]

```
    by (metis butlast-snoc, metis last-snoc)
  moreover
  have arity-1-result e = typeof (v')
    using assms(1,3)
    apply (cases rule: reduce-simple.cases)
            apply (simp-all add: arity-1-result-def wasm-deserialise-type t-cvt)
          apply (auto simp add: typeof-def)
    done
  hence C ⊢ [C v'] : ([] -> [arity-1-result e])
    using b-e-typing.const
    by metis
  ultimately
  show S·C ⊢ [$C v'] : (ts -> ts')
    using e-typing-s-typing.intros(1)
        b-e-typing.weakening[of C [C v'] [] [arity-1-result e] ts]
    by fastforce
qed

lemma typeof-binop-relop:
  assumes S·C ⊢ [$C v1, $C v2, $e] : (ts -> ts')
        e = Binop-i t iop ∨ e = Binop-f t fop ∨ e = Relop-i t irop ∨ e = Relop-f
t frop
  shows typeof v1 = t
       typeof v2 = t
       e = Binop-f t fop ⟹ is-float-t t
       e = Relop-f t frop ⟹ is-float-t t
proof −
  have C ⊢ [C v1, C v2, e] : (ts -> ts')
    using unlift-b-e assms(1)
    by simp
  then obtain ts'' where ts''-def:C ⊢ [C v1, C v2] : (ts -> ts'') C ⊢ [e] : (ts'' ->
ts')
    using b-e-type-comp[where ?e = e and ?es = [C v1, C v2]]
    by fastforce
  then obtain ts-id where ts-id-def:ts-id@[t,t] = ts'' ts' = ts-id @ [arity-2-result
e]
                                  e = Binop-f t fop ⟹ is-float-t t
                                  e = Relop-f t frop ⟹ is-float-t t
    using assms(2) b-e-type-binop-relop[of C e ts'' ts' t]
    by blast
  thus typeof v1 = t
      typeof v2 = t
      e = Binop-f t fop ⟹ is-float-t t
      e = Relop-f t frop ⟹ is-float-t t
    using ts''-def b-e-type-comp[of C [C v1] C v2 ts ts''] b-e-type-value2
    by fastforce+
qed

lemma types-preserved-binop-relop:
```

**assumes** $(\!|[\$C\ v1,\ \$C\ v2,\ \$e]|\!) \rightsquigarrow (\!|[\$C\ v']|\!)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v1,\ \$C\ v2,\ \$e] : (ts \text{ -> } ts')$
$e = Binop\text{-}i\ t\ iop \vee e = Binop\text{-}f\ t\ fop \vee e = Relop\text{-}i\ t\ irop \vee e = Relop\text{-}f\ t\ frop$
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v'] : (ts \text{ -> } ts')$
**proof** −
**have** $\mathcal{C} \vdash [C\ v1,\ C\ v2,\ e] : (ts \text{ -> } ts')$
**using** *unlift-b-e assms*(2)
**by** *simp*
**then obtain** $ts''$ **where** $ts''$-*def*:$\mathcal{C} \vdash [C\ v1,\ C\ v2] : (ts \text{ -> } ts'')\ \mathcal{C} \vdash [e] : (ts'' \text{ -> } ts')$
**using** *b-e-type-comp*[**where** *?e* = *e* **and** *?es* = $[C\ v1,\ C\ v2]$]
**by** *fastforce*
**then obtain** *ts-id* **where** *ts-id-def*:*ts-id*@[*t*,*t*] = $ts''$ $ts'$ = *ts-id* @ [*arity-2-result e*]
**using** *assms*(3) *b-e-type-binop-relop*[*of* $\mathcal{C}$ *e* $ts''$ $ts'$ *t*]
**by** *blast*
**hence** $\mathcal{C} \vdash [C\ v1] : (ts \text{ -> } ts\text{-}id@[t])$
**using** $ts''$-*def b-e-type-comp*[*of* $\mathcal{C}$ $[C\ v1]$ *C v2 ts* $ts''$] *b-e-type-value*
**by** *fastforce*
**hence** *ts*@[*arity-2-result e*] = $ts'$
**using** *b-e-type-value ts-id-def*(2)
**by** *fastforce*
**moreover**
**have** *arity-2-result e* = *typeof* $(v')$
**using** *assms*(1,3)
**by** (*cases rule*: *reduce-simple.cases*) (*auto simp add*: *arity-2-result-def typeof-def*)
**hence** $\mathcal{C} \vdash [C\ v'] : ([] \text{ -> } [arity\text{-}2\text{-}result\ e])$
**using** *b-e-typing.const*
**by** *metis*
**ultimately show** *?thesis*
**using** *e-typing-s-typing.intros*(1)
*b-e-typing.weakening*[*of* $\mathcal{C}$ $[C\ v']$ [] [*arity-2-result e*] *ts*]
**by** *fastforce*
**qed**

**lemma** *types-preserved-drop*:
**assumes** $(\!|[\$C\ v,\ \$e]|\!) \rightsquigarrow (\!|[]|\!)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v,\ \$e] : (ts \text{ -> } ts')$
$(e = (Drop))$
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [] : (ts \text{ -> } ts')$
**proof** −
**have** $\mathcal{C} \vdash [C\ v,\ e] : (ts \text{ -> } ts')$
**using** *unlift-b-e assms*(2)
**by** *simp*
**then obtain** $ts''$ **where** $ts''$-*def*:$\mathcal{C} \vdash [C\ v] : (ts \text{ -> } ts'')\ \mathcal{C} \vdash [e] : (ts'' \text{ -> } ts')$
**using** *b-e-type-comp*[**where** *?e* = *e* **and** *?es* = $[C\ v]$]
**by** *fastforce*
**hence** $ts'' = ts@[typeof\ v]$

**using** *b-e-type-value*
**by** *blast*
**hence** $ts = ts'$
**using** *ts''-def assms(3) b-e-type-drop*
**by** *blast*
**hence** $\mathcal{C} \vdash [] : (ts \text{ -> } ts')$
**using** *b-e-type-empty*
**by** *simp*
**thus** *?thesis*
**using** *e-typing-s-typing.intros(1)*
**by** *fastforce*
**qed**

**lemma** *types-preserved-select*:
**assumes** $(\!|[\$C\ v1,\ \$C\ v2,\ \$C\ vn,\ \$e]|\!) \rightsquigarrow (\!|[\$C\ v3]|\!)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v1,\ \$C\ v2,\ \$C\ vn,\ \$e] : (ts \text{ -> } ts')$
$(e = Select)$
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v3] : (ts \text{ -> } ts')$
**proof** −
**have** $\mathcal{C} \vdash [C\ v1,\ C\ v2,\ C\ vn,\ e] : (ts \text{ -> } ts')$
**using** *unlift-b-e assms(2)*
**by** *simp*
**then obtain** *t1s* **where** *t1s-def*:$\mathcal{C} \vdash [C\ v1,\ C\ v2,\ C\ vn] : (ts \text{ -> } t1s)$ $\mathcal{C} \vdash [e] : (t1s \text{ -> } ts')$
**using** *b-e-type-comp*[**where** *?e* = *e* **and** *?es* = $[C\ v1,\ C\ v2,\ C\ vn]$]
**by** *fastforce*
**then obtain** *t2s t* **where** *t2s-def*:$t1s = t2s\ @\ [t,\ t,\ (T\text{-}i32)]$ $ts' = t2s@[t]$
**using** *b-e-type-select*[*of* $\mathcal{C}$ *e t1s*] *assms*
**by** *fastforce*
**hence** $\mathcal{C} \vdash [C\ v1,\ C\ v2] : (ts \text{ -> } t2s@[t,t])$
**using** *t1s-def t2s-def b-e-type-value-list*[*of* $\mathcal{C}$ $[C\ v1,\ C\ v2]$ *vn ts t2s*@[*t*,*t*]]
**by** *fastforce*
**hence** *v2-t-def*:$\mathcal{C} \vdash [C\ v1] : (ts \text{ -> } t2s@[t])$ *typeof v2* = *t*
**using** *t1s-def t2s-def b-e-type-value-list*[*of* $\mathcal{C}$ $[C\ v1]$ *v2 ts t2s*@[*t*]]
**by** *fastforce*+
**hence** *v1-t-def*:*ts* = *t2s typeof v1* = *t*
**using** *b-e-type-value*
**by** *fastforce*+
**have** *typeof v3* = *t*
**using** *assms(1) v2-t-def(2) v1-t-def(2)*
**by** (*cases rule*: *reduce-simple.cases*, *simp-all*)
**hence** $\mathcal{C} \vdash [C\ v3] : (ts \text{ -> } ts')$
**using** *b-e-typing.const b-e-typing.weakening t2s-def(2) v1-t-def(1)*
**by** *fastforce*
**thus** *?thesis*
**using** *e-typing-s-typing.intros(1)*
**by** *fastforce*
**qed**

**lemma** *types-preserved-block*:
**assumes** $(|vs @ [\$Block\ (tn \text{ -> } tm)\ es]|) \rightsquigarrow (|[Label\ m\ []\ (vs @ (\$*\ es))]|)$
$\mathcal{S}\cdot\mathcal{C} \vdash vs @ [\$Block\ (tn \text{ -> } tm)\ es] : (ts \text{ -> } ts')$
*const-list vs*
*length vs* = *n*
*length tn* = *n*
*length tm* = *m*
**shows** $\mathcal{S}\cdot\mathcal{C} \vdash [Label\ m\ []\ (vs @ (\$*\ es))] : (ts \text{ -> } ts')$
**proof** −
**obtain** $\mathcal{C}'$ **where** *c-def*:$\mathcal{C}' = \mathcal{C}(|label := [tm] @ label\ \mathcal{C}|)$ **by** *blast*
**obtain** *ts''* **where** *ts''-def*:$\mathcal{S}\cdot\mathcal{C} \vdash vs : (ts \text{ -> } ts'')$ $\mathcal{S}\cdot\mathcal{C} \vdash [\$Block\ (tn \text{ -> } tm)\ es] : (ts'' \text{ -> } ts')$
**using** *assms*(2) *e-type-comp*[*of* $\mathcal{S}$ $\mathcal{C}$ *vs* $Block (tn -> tm) es ts ts'*]
**by** *fastforce*
**hence** $\mathcal{C} \vdash [Block\ (tn \text{ -> } tm)\ es] : (ts'' \text{ -> } ts')$
**using** *unlift-b-e*
**by** *auto*
**then obtain** *ts-c tfn tfm* **where** *ts-c-def*:$(tn \text{ -> } tm) = (tfn \text{ -> } tfm)$ $ts'' = ts\text{-}c@tfn$ $ts' = ts\text{-}c@tfm$ $(\mathcal{C}(|label := [tfm] @ label\ \mathcal{C}|) \vdash es : (tn \text{ -> } tm))$
**using** *b-e-type-block*[*of* $\mathcal{C}$ *Block* $(tn \text{ -> } tm)$ *es ts''* *ts'* $(tn \text{ -> } tm)$ *es*]
**by** *fastforce*
**hence** *tfn-l*:*length tfn* = *n*
**using** *assms*(5)
**by** *simp*
**obtain** *tvs'* **where** *tvs'-def*:*ts''* = *ts*@*tvs'* *length tvs'* = *n* $\mathcal{S}\cdot\mathcal{C}' \vdash vs : ([] \text{ -> } tvs')$
**using** *e-type-const-list assms*(3,4) *ts''-def*(1)
**by** *fastforce*
**hence** $\mathcal{S}\cdot\mathcal{C}' \vdash vs : ([] \text{ -> } tn)$ $\mathcal{S}\cdot\mathcal{C}' \vdash \$*es : (tn \text{ -> } tm)$
**using** *ts-c-def tvs'-def tfn-l ts''-def c-def e-typing-s-typing.intros*(1)
**by** *simp-all*
**hence** $\mathcal{S}\cdot\mathcal{C}' \vdash (vs @ (\$*\ es)) : ([] \text{ -> } tm)$ **using** *e-type-comp-conc*
**by** *simp*
**moreover**
**have** $\mathcal{S}\cdot\mathcal{C} \vdash [] : (tm \text{ -> } tm)$
**using** *b-e-type-empty*[*of* $\mathcal{C}$ [] []]
*e-typing-s-typing.intros*(1)[**where** *?b-es* = []]
*e-typing-s-typing.intros*(3)[*of* $\mathcal{S}$ $\mathcal{C}$ [] [] [] *tm*]
**by** *fastforce*
**ultimately**
**show** *?thesis*
**using** *e-typing-s-typing.intros*(7)[*of* $\mathcal{S}$ $\mathcal{C}$ [] *tm - vs* @ (\$* *es*) *m*]
*ts-c-def tvs'-def assms*(5,6) *e-typing-s-typing.intros*(3) *c-def*
**by** *fastforce*
**qed**

**lemma** *types-preserved-if*:
**assumes** $(|[\$C\ ConstInt32\ n, \$If\ tf\ e1s\ e2s]|) \rightsquigarrow (|[\$Block\ tf\ es']|)$
$\mathcal{S}\cdot\mathcal{C} \vdash [\$C\ ConstInt32\ n, \$If\ tf\ e1s\ e2s] : (ts \text{ -> } ts')$
**shows** $\mathcal{S}\cdot\mathcal{C} \vdash [\$Block\ tf\ es'] : (ts \text{ -> } ts')$

**proof** −
**have** $\mathcal{C} \vdash [C\ ConstInt32\ n,\ If\ tf\ e1s\ e2s] : (ts\ ->\ ts')$
**using** *unlift-b-e assms*(2)
**by** *fastforce*
**then obtain** *ts-i* **where** *ts-i-def*:$\mathcal{C} \vdash [C\ ConstInt32\ n] : (ts\ ->\ ts\text{-}i)\ \mathcal{C} \vdash [If\ tf\ e1s\ e2s] : (ts\text{-}i\ ->\ ts')$
**using** *b-e-type-comp*
**by** (*metis append-Cons append-Nil*)
**then obtain** *ts''* *tfn tfm* **where** *ts-def*:$tf = (tfn\ ->\ tfm)$
$ts\text{-}i = ts''@tfn\ @\ [T\text{-}i32]$
$ts' = ts''@tfm$
$(\mathcal{C}(|label := [tfm]\ @\ label\ \mathcal{C}|) \vdash e1s : tf)$
$(\mathcal{C}(|label := [tfm]\ @\ label\ \mathcal{C}|) \vdash e2s : tf)$
**using** *b-e-type-if*[*of* $\mathcal{C}$ *If tf e1s e2s*]
**by** *fastforce*
**have** $ts\text{-}i = ts\ @\ [(T\text{-}i32)]$
**using** *ts-i-def*(1) *b-e-type-value*
**unfolding** *typeof-def*
**by** *fastforce*
**moreover**
**have** $(\mathcal{C}(|label := [tfm]\ @\ label\ \mathcal{C}|) \vdash es' : (tfn\ ->\ tfm))$
**using** *assms*(1) *ts-def*(4,5) *ts-def*(1)
**by** (*cases rule*: *reduce-simple.cases*, *simp-all*)
**hence** $\mathcal{C} \vdash [Block\ tf\ es'] : (tfn\ ->\ tfm)$
**using** *ts-def*(1) *b-e-typing.block*[*of tf tfn tfm* $\mathcal{C}$ *es'*]
**by** *simp*
**ultimately**
**show** *?thesis*
**using** *ts-def*(2,3) *e-typing-s-typing.intros*(1,3)
**by** *fastforce*
**qed**

**lemma** *types-preserved-tee-local*:
**assumes** $(|[v,\ \$Tee\text{-}local\ i]|) \rightsquigarrow (|[v,\ v,\ \$Set\text{-}local\ i]|)$
$\mathcal{S}\cdot\mathcal{C} \vdash [v,\ \$Tee\text{-}local\ i] : (ts\ ->\ ts')$
*is-const v*
**shows** $\mathcal{S}\cdot\mathcal{C} \vdash [v,\ v,\ \$Set\text{-}local\ i] : (ts\ ->\ ts')$
**proof** −
**obtain** *bv* **where** *bv-def*:$v = \$C\ bv$
**using** *e-type-const-unwrap assms*(3)
**by** *fastforce*
**hence** $\mathcal{C} \vdash [C\ bv,\ Tee\text{-}local\ i] : (ts\ ->\ ts')$
**using** *unlift-b-e assms*(2)
**by** *fastforce*
**then obtain** *ts''* **where** *ts''-def*:$\mathcal{C} \vdash [C\ bv] : (ts\ ->\ ts'')\ \mathcal{C} \vdash [Tee\text{-}local\ i] : (ts''\ ->\ ts')$
**using** *b-e-type-comp*[*of* - $[C\ bv]$ *Tee-local i*]
**by** *fastforce*
**then obtain** *ts-c t* **where** *ts-c-def*:$ts'' = ts\text{-}c@[t]\ ts' = ts\text{-}c@[t]\ (local\ \mathcal{C})!i = t\ i$

$< length(local\ \mathcal{C})$
**using** *b-e-type-tee-local*[*of* $\mathcal{C}$ *Tee-local i ts'' ts' i*]
**by** *fastforce*
**hence** *t-bv*:$t$ = *typeof bv ts* = *ts-c*
**using** *b-e-type-value ts''-def*
**by** *fastforce+*
**have** $\mathcal{C} \vdash$ [*Set-local i*] : ([*t*,*t*] -> [*t*])
**using** *ts-c-def*(*3*,*4*) *b-e-typing.set-local*[*of i* $\mathcal{C}$ *t*]
*b-e-typing.weakening*[*of* $\mathcal{C}$ [*Set-local i*] [*t*] [] [*t*]]
**by** *fastforce*
**moreover**
**have** $\mathcal{C} \vdash$ [*C bv*] : ([*t*] -> [*t*,*t*])
**using** *t-bv b-e-typing.const*[*of* $\mathcal{C}$ *bv*] *b-e-typing.weakening*[*of* $\mathcal{C}$ [*C bv*] [] [*t*] [*t*]]
**by** *fastforce*
**hence** $\mathcal{C} \vdash$ [*C bv*, *C bv*] : ([] -> [*t*,*t*])
**using** *t-bv b-e-typing.const*[*of* $\mathcal{C}$ *bv*] *b-e-typing.composition*[*of* $\mathcal{C}$ [*C bv*] [] [*t*]]
**by** *fastforce*
**ultimately**
**have** $\mathcal{C} \vdash$ [*C bv*, *C bv*, *Set-local i*] : (*ts* -> *ts*@[*t*])
**using** *b-e-typing.composition b-e-typing.weakening*[*of* $\mathcal{C}$ [*C bv*, *C bv*, *Set-local i*]]
**by** *fastforce*
**thus** *?thesis*
**using** *t-bv*(*2*) *ts-c-def*(*2*) *bv-def e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**qed**

**lemma** *types-preserved-loop*:
**assumes** ⦇*vs* @ [$*Loop* (*t1s* -> *t2s*) *es*]⦈ ⇝ ⦇[*Label n* [$*Loop* (*t1s* -> *t2s*) *es*] (*vs* @ ($∗ *es*))]⦈
$\mathcal{S}$·$\mathcal{C}$ ⊢ *vs* @ [$*Loop* (*t1s* -> *t2s*) *es*] : (*ts* -> *ts'*)
*const-list vs*
*length vs* = *n*
*length t1s* = *n*
*length t2s* = *m*
**shows** $\mathcal{S}$·$\mathcal{C}$ ⊢ [*Label n* [$*Loop* (*t1s* -> *t2s*) *es*] (*vs* @ ($∗ *es*))] : (*ts* -> *ts'*)
**proof** −
**obtain** *ts''* **where** *ts''-def*:$\mathcal{S}$·$\mathcal{C}$ ⊢ *vs* : (*ts* -> *ts''*) $\mathcal{S}$·$\mathcal{C}$ ⊢ [$*Loop* (*t1s* -> *t2s*) *es*] : (*ts''* -> *ts'*)
**using** *assms*(*2*) *e-type-comp*
**by** *fastforce*
**then have** $\mathcal{C}$ ⊢ [*Loop* (*t1s* -> *t2s*) *es*] : (*ts''* -> *ts'*)
**using** *unlift-b-e assms*(*2*)
**by** *fastforce*
**then obtain** *ts-c tfn tfm* $\mathcal{C}'$ **where** *t-loop*:(*t1s* -> *t2s*) = (*tfn* -> *tfm*)
(*ts''* = *ts-c*@*tfn*)
(*ts'* = *ts-c*@*tfm*)
$\mathcal{C}'$ = $\mathcal{C}$⦇*label* := [*t1s*] @ *label* $\mathcal{C}$⦈
($\mathcal{C}'$ ⊢ *es* : (*tfn* -> *tfm*))

**using** *b-e-type-loop*[*of* $\mathcal{C}$ *Loop* (*t1s* -> *t2s*) *es ts'' ts'*]
**by** *fastforce*
**obtain** *tvs* **where** *tvs-def*:$ts'' = ts$ @ *tvs length vs* = *length tvs* $\mathcal{S}\cdot\mathcal{C}' \vdash$ *vs* : ([] -> *tvs*)
**using** *e-type-const-list assms*(*3*) *ts''-def*(*1*)
**by** *fastforce*
**then have** *tvs-eq*:*tvs* = *t1s tfn* = *t1s*
**using** *assms*(*4*,*5*) *t-loop*(*1*,*2*)
**by** *simp-all*
**have** $\mathcal{S}\cdot\mathcal{C} \vdash$ [$*Loop* (*t1s* -> *t2s*) *es*] : (*t1s* -> *t2s*)
**using** *t-loop b-e-typing.loop e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**moreover**
**have** $\mathcal{S}\cdot\mathcal{C}' \vdash$ $*es* : (*t1s* -> *t2s*)
**using** *t-loop e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**then have** $\mathcal{S}\cdot\mathcal{C}' \vdash$ *vs*@($*es*) : ([] -> *t2s*)
**using** *tvs-eq tvs-def*(*3*) *e-type-comp-conc*
**by** *blast*
**ultimately**
**have** $\mathcal{S}\cdot\mathcal{C} \vdash$ [*Label n* [$*Loop* (*t1s* -> *t2s*) *es*] (*vs* @ ($* *es*))] : ([] -> *t2s*)
**using** *e-typing-s-typing.intros*(*7*)[*of* $\mathcal{S}$ $\mathcal{C}$ [$*Loop* (*t1s* -> *t2s*) *es*] *t1s t2s vs* @ ($* *es*)]
*t-loop*(*4*) *assms*(*5*)
**by** *fastforce*
**then show** *?thesis*
**using** *t-loop e-typing-s-typing.intros*(*3*) *tvs-def*(*1*) *tvs-eq*(*1*)
**by** *fastforce*
**qed**

**lemma** *types-preserved-label-value*:
**assumes** (|[*Label n es0 vs*]|) $\rightsquigarrow$ (|*vs*|)
$\mathcal{S}\cdot\mathcal{C} \vdash$ [*Label n es0 vs*] : (*ts* -> *ts'*)
*const-list vs*
**shows** $\mathcal{S}\cdot\mathcal{C} \vdash$ *vs* : (*ts* -> *ts'*)
**proof** −
**obtain** *tls t2s* **where** *t2s-def*:($ts' = (ts@t2s)$)
($\mathcal{S}\cdot\mathcal{C} \vdash$ *es0* : (*tls* -> *t2s*))
($\mathcal{S}\cdot\mathcal{C}$(|*label* := [*tls*] @ (*label* $\mathcal{C}$)|) $\vdash$ *vs* : ([] -> *t2s*))
**using** *assms e-type-label*
**by** *fastforce*
**thus** *?thesis*
**using** *e-type-const-list*[*of vs* $\mathcal{S}$ $\mathcal{C}$(|*label* := [*tls*] @ (*label* $\mathcal{C}$)|) [] *t2s*]
*assms*(*3*) *e-typing-s-typing.intros*(*3*)
**by** *fastforce*
**qed**

**lemma** *types-preserved-br-if*:
**assumes** (|[$*C ConstInt32 n*, $*Br-if i*]|) $\rightsquigarrow$ (|*e*|)

$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ n, \$Br\text{-}if\ i] : (ts\ ->\ ts')$
$e = [\$Br\ i] \vee e = []$
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash e : (ts\ ->\ ts')$
**proof** −
**have** $\mathcal{C} \vdash [C\ ConstInt32\ n, Br\text{-}if\ i] : (ts\ ->\ ts')$
**using** *unlift-b-e assms*(2)
**by** *fastforce*
**then obtain** $ts''$ **where** $ts''\text{-}def{:}\mathcal{C} \vdash [C\ ConstInt32\ n] : (ts\ ->\ ts'')\ \mathcal{C} \vdash [Br\text{-}if\ i] : (ts''\ ->\ ts')$
**using** *b-e-type-comp*[*of* - $[C\ ConstInt32\ n]$ *Br-if i*]
**by** *fastforce*
**then obtain** *ts-c ts-b* **where** *ts-bc-def*:$i < length(label\ \mathcal{C})$
$ts'' = ts\text{-}c\ @\ ts\text{-}b\ @\ [T\text{-}i32]$
$ts' = ts\text{-}c\ @\ ts\text{-}b$
$(label\ \mathcal{C})!i = ts\text{-}b$
**using** *b-e-type-br-if*[*of* $\mathcal{C}$ *Br-if i ts'' ts' i*]
**by** *fastforce*
**hence** *ts-def*:$ts = ts\text{-}c\ @\ ts\text{-}b$
**using** $ts''\text{-}def(1)$ *b-e-type-value*
**by** *fastforce*
**show** *?thesis*
**using** *assms*(3)
**proof** (*rule disjE*)
**assume** $e = [\$Br\ i]$
**thus** *?thesis*
**using** *ts-def e-typing-s-typing.intros*(1) *b-e-typing.br ts-bc-def*
**by** *fastforce*
**next**
**assume** $e = []$
**thus** *?thesis*
**using** *ts-def b-e-type-empty ts-bc-def*(3)
*e-typing-s-typing.intros*(1)[*of* - [] $(ts\ ->\ ts')$]
**by** *fastforce*
**qed**
**qed**

**lemma** *types-preserved-br-table*:
**assumes** $(\!|[\$C\ ConstInt32\ c, \$Br\text{-}table\ is\ i]|\!) \rightsquigarrow (\!|[\$Br\ i']|\!)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ c, \$Br\text{-}table\ is\ i] : (ts\ ->\ ts')$
$(i' = (is\ !\ nat\text{-}of\text{-}int\ c) \wedge length\ is > nat\text{-}of\text{-}int\ c) \vee i' = i$
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$Br\ i'] : (ts\ ->\ ts')$
**proof** −
**have** $\mathcal{C} \vdash [C\ ConstInt32\ c, Br\text{-}table\ is\ i] : (ts\ ->\ ts')$
**using** *unlift-b-e assms*(2)
**by** *fastforce*
**then obtain** $ts''$ **where** $ts''\text{-}def{:}\mathcal{C} \vdash [C\ ConstInt32\ c] : (ts\ ->\ ts'')\ \mathcal{C} \vdash [Br\text{-}table\ is\ i] : (ts''\ ->\ ts')$
**using** *b-e-type-comp*[*of* - $[C\ ConstInt32\ c]$ *Br-table is i*]
**by** *fastforce*

**then obtain** *ts-l ts-c* **where** *ts-c-def*:*list-all* ($\lambda i.\ i < length(label\ \mathcal{C}) \wedge (label\ \mathcal{C})!i = ts\text{-}l$) (*is*@[*i*])
$$ts'' = ts\text{-}c\ @\ ts\text{-}l@[T\text{-}i32]$$
**using** *b-e-type-br-table*[*of* $\mathcal{C}$ *Br-table is i ts'' ts'*]
**by** *fastforce*
**hence** *ts-def*:*ts* = *ts-c* @ *ts-l*
**using** *ts''-def*(*1*) *b-e-type-value*
**by** *fastforce*
**have** $\mathcal{C} \vdash [Br\ i'] : (ts\ ->\ ts')$
**using** *assms*(*3*) *ts-c-def*(*1*,*2*) *b-e-typing.br*[*of i'* $\mathcal{C}$ *ts-l ts-c ts'*] *ts-def*
**unfolding** *list-all-length*
**by** (*fastforce simp add*: *less-Suc-eq nth-append*)
**thus** *?thesis*
**using** *e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**qed**

**lemma** *types-preserved-local-const*:
**assumes** $(\!|[Local\ n\ i\ vs\ es]|\!) \rightsquigarrow (\!|es|\!)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [Local\ n\ i\ vs\ es] : (ts\ ->\ ts')$
*const-list es*
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash es: (ts\ ->\ ts')$
**proof** −
**obtain** *tls* **where** $(\mathcal{S}{\cdot}((s\text{-}inst\ \mathcal{S})!i)(\!|local := (local\ ((s\text{-}inst\ \mathcal{S})!i))\ @\ (map\ typeof\ vs),\ return := Some\ tls|\!) \vdash es : ([]\ ->\ tls))$
$ts' = ts\ @\ tls$
**using** *e-type-local*[*OF assms*(*2*)]
**by** *blast*+
**moreover**
**then have** $\mathcal{S}{\cdot}\mathcal{C} \vdash es : ([]\ ->\ tls)$
**using** *assms*(*3*) *e-type-const-list*
**by** *fastforce*
**ultimately**
**show** *?thesis*
**using** *e-typing-s-typing.intros*(*3*)
**by** *fastforce*
**qed**

**lemma** *typing-map-typeof*:
**assumes** *ves* = $$∗ *vs*
$\mathcal{S}{\cdot}\mathcal{C} \vdash ves : ([]\ ->\ tvs)$
**shows** *tvs* = *map typeof vs*
**using** *assms*
**proof** (*induction ves arbitrary*: *vs tvs rule*: *List.rev-induct*)
**case** *Nil*
**hence** $\mathcal{C} \vdash [] : ([]\ ->\ tvs)$
**using** *unlift-b-e*
**by** *auto*
**thus** *?case*

```
    using Nil
    by auto
next
  case (snoc a ves)
  obtain vs' v' where vs'-def:ves @ [a] = $$* (vs'@[v']) vs = vs'@[v']
    using snoc(2)
    by (metis Nil-is-map-conv append-is-Nil-conv list.distinct(1) rev-exhaust)
  obtain tvs' where tvs'-def:S·C ⊢ ves: ([] -> tvs') S·C ⊢ [a] : (tvs' -> tvs)
    using snoc(3) e-type-comp
    by fastforce
  hence tvs' = map typeof vs'
    using snoc(1) vs'-def
    by fastforce
  moreover
  have is-const a
    using vs'-def
    unfolding is-const-def
    by auto
  then obtain t where t-def:tvs = tvs' @ [t] S·C ⊢ [a] : ([] -> [t])
    using tvs'-def(2)  e-type-const[of a S C tvs' tvs]
    by fastforce
  have a = $ C v'
    using vs'-def(1)
    by auto
  hence t = typeof v'
    using t-def unlift-b-e[of S C [C v'] ([] -> [t])] b-e-type-value[of C C v' [] [t] v']
    by fastforce
  ultimately
  show ?case
    using vs'-def t-def
    by simp
qed

lemma types-preserved-call-indirect-Some:
  assumes S·C ⊢ [$C ConstInt32 c, $Call-indirect j] : (ts -> ts')
          stab s i' (nat-of-int c) = Some cl
          stypes s i' j = tf
          cl-type cl = tf
          store-typing s S
          i' < length (inst s)
          C = (s-inst S ! i') (|local := local (s-inst S ! i') @ tvs, label := arb-labs,
return := arb-return|)
  shows S·C ⊢ [Callcl cl] : (ts -> ts')
proof −
  obtain t1s t2s where tf-def:tf = (t1s -> t2s)
    using tf.exhaust by blast
  obtain ts'' where ts''-def:C ⊢ [C ConstInt32 c] : (ts -> ts'')
                                C ⊢ [Call-indirect j] : (ts'' -> ts')
    using e-type-comp[of S C [$C ConstInt32 c] $Call-indirect j ts ts']
```

*assms*(*1*)
*unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*C ConstInt32 c*]]
*unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Call-indirect j*]]
**by** *fastforce*
**hence** *ts''* = *ts*@[(*T-i32*)]
**using** *b-e-type-value*
**unfolding** *typeof-def*
**by** *fastforce*
**moreover**
**have** *i'* < *length* (*s-inst* $\mathcal{S}$)
**using** *assms*(*5*,*6*) *store-typing-imp-inst-length-eq*
**by** *fastforce*
**hence** *stypes-eq*:*types-t* (*s-inst* $\mathcal{S}$ ! *i'*) = *types* (*inst s* ! *i'*)
**using** *store-typing-imp-inst-typing*[*OF assms*(*5*)] *store-typing-imp-inst-length-eq*[*OF assms*(*5*)]
**unfolding** *inst-typing.simps*
**by** *fastforce*
**obtain** *ts''a* **where** *ts''a-def*:*j* < *length* (*types-t* $\mathcal{C}$)
*ts''* = *ts''a* @ *t1s* @ [*T-i32*]
*ts'* = *ts''a* @ *t2s*
*types-t* $\mathcal{C}$ ! *j* = (*t1s* -> *t2s*)
**using** *b-e-type-call-indirect*[*OF ts''-def*(*2*), *of j*] *tf-def assms*(*3*,*7*) *stypes-eq*
**unfolding** *stypes-def*
**by** *fastforce*
**moreover**
**obtain** *tf'* **where** *tf'-def*:*cl-typing* $\mathcal{S}$ *cl tf'*
**using** *assms*(*2*,*5*,*6*) *stab-typed-some-imp-cl-typed*
**by** *blast*
**hence** *cl-typing* $\mathcal{S}$ *cl tf*
**using** *assms*(*4*)
**unfolding** *cl-typing.simps cl-type-def*
**by** *auto*
**hence** $\mathcal{S}$·$\mathcal{C}$ ⊢ [*Callcl cl*] : *tf*
**using** *e-typing-s-typing.intros*(*6*) *assms*(*6*,*7*) *ts''a-def*(*1*)
**by** *fastforce*
**ultimately**
**show** $\mathcal{S}$·$\mathcal{C}$ ⊢ [*Callcl cl*] : (*ts* -> *ts'*)
**using** *tf-def e-typing-s-typing.intros*(*3*)
**by** *auto*
**qed**

**lemma** *types-preserved-call-indirect-None*:
**assumes** $\mathcal{S}$·$\mathcal{C}$ ⊢ [$*C ConstInt32 c*, $*Call-indirect j*] : (*ts* -> *ts'*)
**shows** $\mathcal{S}$·$\mathcal{C}$ ⊢ [*Trap*] : (*ts* -> *ts'*)
**using** *e-typing-s-typing.intros*(*4*)
**by** *blast*

**lemma** *types-preserved-callcl-native*:
**assumes** $\mathcal{S}$·$\mathcal{C}$ ⊢ *ves* @ [*Callcl cl*] : (*ts* -> *ts'*)

*cl* = *Func-native i* (*t1s* -> *t2s*) *tfs es*
*ves* = $$* *vs*
*length vs* = *n*
*length tfs* = *k*
*length t1s* = *n*
*length t2s* = *m*
*n-zeros tfs* = *zs*
*store-typing s* $\mathcal{S}$
**shows** $\mathcal{S}$·$\mathcal{C}$ ⊢ [*Local m i* (*vs* @ *zs*) [$*Block* ([] -> *t2s*) *es*]] : (*ts* -> *ts'*)
**proof** −
**obtain** *ts''* **where** *ts''-def*:$\mathcal{S}$·$\mathcal{C}$ ⊢ *ves* : (*ts* -> *ts''*) $\mathcal{S}$·$\mathcal{C}$ ⊢ [*Callcl cl*] : (*ts''* -> *ts'*)
**using** *assms*(*1*) *e-type-comp*
**by** *fastforce*
**have** *ves-c*:*const-list ves*
**using** *is-const-list*[*OF assms*(*3*)]
**by** *simp*
**then obtain** *tvs* **where** *tvs-def*:*ts''* = *ts* @ *tvs*
*length t1s* = *length tvs*
$\mathcal{S}$·$\mathcal{C}$ ⊢ *ves* : ([] -> *tvs*)
**using** *ts''-def*(*1*) *e-type-const-list*[*of ves* $\mathcal{S}$ $\mathcal{C}$ *ts ts''*] *assms*
**by** *fastforce*
**obtain** *ts-c* $\mathcal{C}'$ **where** *ts-c-def*:(*ts''* = *ts-c* @ *t1s*)
(*ts'* = *ts-c* @ *t2s*)
*i* < *length* (*s-inst* $\mathcal{S}$)
$\mathcal{C}'$ = ((*s-inst* $\mathcal{S}$)!*i*)
($\mathcal{C}'$⦇*local* := (*local* $\mathcal{C}'$) @ *t1s* @ *tfs*, *label* := ([*t2s*] @ (*label* $\mathcal{C}'$)), *return* := *Some t2s*⦈ ⊢ *es* : ([] -> *t2s*))
**using** *e-type-callcl-native*[*OF ts''-def*(*2*) *assms*(*2*)]
**by** *fastforce*
**have** *inst-typing* $\mathcal{S}$ (*inst s* ! *i*) (*s-inst* $\mathcal{S}$ ! *i*)
**using** *store-typing-imp-inst-length-eq*[*OF assms*(*9*)] *store-typing-imp-inst-typing*[*OF assms*(*9*)]
*ts-c-def*(*3*)
**by** *simp*
**obtain** $\mathcal{C}''$ **where** *c''-def*:$\mathcal{C}''$ = $\mathcal{C}'$⦇*local* := (*local* $\mathcal{C}'$) @ *t1s* @ *tfs*, *return* := *Some t2s*⦈
**by** *blast*
**hence** $\mathcal{C}''$⦇*label* := ([*t2s*] @ (*label* $\mathcal{C}''$))⦈ = $\mathcal{C}'$⦇*local* := (*local* $\mathcal{C}'$) @ *t1s* @ *tfs*, *label* := ([*t2s*] @ (*label* $\mathcal{C}'$)), *return* := *Some t2s*⦈
**by** *fastforce*
**hence** $\mathcal{S}$·$\mathcal{C}''$ ⊢ [$*Block* ([] -> *t2s*) *es*] : ([] -> *t2s*)
**using** *ts-c-def b-e-typing.block*[*of* ([] -> *t2s*) [] *t2s* - *es*] *e-typing-s-typing.intros*(*1*)[*of* - [*Block* ([] -> *t2s*) *es*]]
**by** *fastforce*
**moreover**
**have** *t-eqs*:*ts* = *ts-c t1s* = *tvs*
**using** *tvs-def*(*1*,*2*) *ts-c-def*(*1*)
**by** *simp-all*
**have** *1*:*tfs* = *map typeof zs*

**using** *n-zeros-typeof assms(8)*
**by** *auto*
**have** *t1s = map typeof vs*
**using** *typing-map-typeof assms(3) tvs-def t-eqs*
**by** *fastforce*
**hence** *(t1s @ tfs) = map typeof (vs @ zs)*
**using** *1*
**by** *simp*
**ultimately**
**have** $\mathcal{S}$·*Some t2s* ⊩*-i (vs @ zs);([$Block ([] -> t2s) es]) : t2s*
**using** *e-typing-s-typing.intros(8) ts-c-def c''-def*
**by** *fastforce*
**thus** *?thesis*
**using** *e-typing-s-typing.intros(3,5) ts-c-def t-eqs(1) assms(2,7)*
**by** *fastforce*
**qed**

**lemma** *types-preserved-callcl-host-some*:
**assumes** $\mathcal{S}$·$\mathcal{C}$ ⊢ *ves @ [Callcl cl] : (ts -> ts')*
*cl = Func-host (t1s -> t2s) f*
*ves = $$* vcs*
*length vcs = n*
*length t1s = n*
*length t2s = m*
*host-apply s (t1s -> t2s) f vcs hs = Some (s', vcs')*
*store-typing s* $\mathcal{S}$
**shows** $\mathcal{S}$·$\mathcal{C}$ ⊢ *$$* vcs' : (ts -> ts')*
**proof** −
**obtain** *ts''* **where** *ts''-def:*$\mathcal{S}$·$\mathcal{C}$ ⊢ *ves : (ts -> ts'')* $\mathcal{S}$·$\mathcal{C}$ ⊢ *[Callcl cl] : (ts'' -> ts')*
**using** *assms(1) e-type-comp*
**by** *fastforce*
**have** *ves-c:const-list ves*
**using** *is-const-list[OF assms(3)]*
**by** *simp*
**then obtain** *tvs* **where** *tvs-def:ts'' = ts @ tvs*
*length t1s = length tvs*
$\mathcal{S}$·$\mathcal{C}$ ⊢ *ves : ([] -> tvs)*
**using** *ts''-def(1) e-type-const-list[of ves* $\mathcal{S}$ $\mathcal{C}$ *ts ts'']  assms*
**by** *fastforce*
**hence** *ts'' = ts @ t1s*
*ts' = ts @ t2s*
**using** *e-type-callcl-host[OF ts''-def(2) assms(2)]*
**by** *auto*
**moreover**
**hence** *list-all2 types-agree t1s vcs*
**using** *e-typing-imp-list-types-agree[***where** *?ts' = []] assms(3) tvs-def(1,3)*
**by** *fastforce*
**hence** $\mathcal{S}$·$\mathcal{C}$ ⊢ *$$* vcs' : ([] -> t2s)*
**using** *list-types-agree-imp-e-typing host-apply-respect-type[OF - assms(7)]*

**by** *fastforce*
**ultimately**
**show** *?thesis*
**using** *e-typing-s-typing.intros(3)*
**by** *fastforce*
**qed**

**lemma** *types-imp-concat*:
**assumes** $\mathcal{S}\cdot\mathcal{C} \vdash es$ @ $[e]$ @ $es' : (ts \text{ -> } ts')$
$\bigwedge tes\ tes'.\ ((\mathcal{S}\cdot\mathcal{C} \vdash [e] : (tes \text{ -> } tes')) \Longrightarrow (\mathcal{S}\cdot\mathcal{C} \vdash [e'] : (tes \text{ -> } tes')))$
**shows** $\mathcal{S}\cdot\mathcal{C} \vdash es$ @ $[e']$ @ $es' : (ts \text{ -> } ts')$
**proof** −
**obtain** $ts''$ **where** $\mathcal{S}\cdot\mathcal{C} \vdash es : (ts \text{ -> } ts'')$
$\mathcal{S}\cdot\mathcal{C} \vdash [e]$ @ $es' : (ts'' \text{ -> } ts')$
**using** *e-type-comp-conc1*[*of - - es* $[e]$ @ $es'$] *assms(1)*
**by** *fastforce*
**moreover**
**then obtain** $ts'''$ **where** $\mathcal{S}\cdot\mathcal{C} \vdash [e] : (ts'' \text{ -> } ts''')$ $\mathcal{S}\cdot\mathcal{C} \vdash es' : (ts''' \text{ -> } ts')$
**using** *e-type-comp-conc1*[*of - - [e] es' ts'' ts'*] *assms*
**by** *fastforce*
**ultimately**
**show** *?thesis*
**using** *assms(2) e-type-comp-conc*[*of - - es ts ts''* $[e']$ $ts'''$]
*e-type-comp-conc*[*of - - es* @ $[e']$ *ts ts'''*]
**by** *fastforce*
**qed**

**lemma** *type-const-return*:
**assumes** *Lfilled i lholed* (*vs* @ [$*Return*]) *LI*
(*return* $\mathcal{C}$) = *Some tcs*
*length tcs* = *length vs*
$\mathcal{S}\cdot\mathcal{C} \vdash LI : (ts \text{ -> } ts')$
*const-list vs*
**shows** $\mathcal{S}\cdot\mathcal{C}' \vdash vs : ([] \text{ -> } tcs)$
**using** *assms*
**proof** (*induction i arbitrary*: *ts ts' lholed* $\mathcal{C}$ *LI* $\mathcal{C}'$)
**case** *0*
**obtain** $vs'$ $es'$ **where** $LI = (vs'$ @ (*vs* @ [$*Return*]) @ $es')$
**using** *Lfilled.simps*[*of 0 lholed* (*vs* @ [$*Return*]) *LI*] *0(1)*
**by** *fastforce*
**then obtain** $ts''$ $ts'''$ **where** $\mathcal{S}\cdot\mathcal{C} \vdash vs' : (ts \text{ -> } ts'')$
$\mathcal{S}\cdot\mathcal{C} \vdash$ (*vs* @ [$*Return*]) $: (ts'' \text{ -> } ts''')$
$\mathcal{S}\cdot\mathcal{C} \vdash es' : (ts''' \text{ -> } ts')$
**using** *e-type-comp-conc2*[*of* $\mathcal{S}$ $\mathcal{C}$ $vs'$ (*vs* @ [$*Return*]) $es'$] *0(4)*
**by** *fastforce*
**then obtain** *ts-b* **where** *ts-b-def*:$\mathcal{S}\cdot\mathcal{C} \vdash vs : (ts'' \text{ -> } ts\text{-}b)$ $\mathcal{S}\cdot\mathcal{C} \vdash$ [$*Return*] : (*ts-b* -> $ts''')$
**using** *e-type-comp-conc1*
**by** *fastforce*

```
  then obtain ts-c where ts-c-def:ts-b = ts-c @ tcs (return C) = Some tcs
    using 0(2) b-e-type-return[of C] unlift-b-e[of S C [Return] ts-b -> ts''']
    by fastforce
  obtain tcs' where ts-b = ts'' @ tcs' length vs = length tcs' S·C' ⊢ vs : ([] ->
tcs')
    using ts-b-def(1) e-type-const-list 0(5)
    by fastforce
  thus ?case
    using 0(3) ts-c-def
    by simp
next
  case (Suc i)
  obtain vs' n l les les' LK where es-def:lholed = (LRec vs' n les l les')
                                   Lfilled i l (vs @ [$Return]) LK
                                   LI = (vs' @ [Label n les LK] @ les')
    using Lfilled.simps[of (Suc i) lholed (vs @ [$Return]) LI] Suc(2)
    by fastforce
  then obtain ts'' ts''' where S·C ⊢ [Label n les LK] : (ts'' -> ts''')
    using e-type-comp-conc2[of S C vs' [Label n les LK] les'] Suc(5)
    by fastforce
  then obtain tls t2s where
      ts''' = ts'' @ t2s
      length tls = n
      S·C ⊢ les : (tls -> t2s)
      S·C(|label := [tls] @ label C|) ⊢ LK : ([] -> t2s)
      return (C(|label := [tls] @ label C|)) = Some tcs
    using e-type-label[of S C n les LK ts'' ts'''] Suc(3)
    by fastforce
  then show ?case
    using Suc(1)[OF es-def(2) - assms(3) - assms(5)]
    by fastforce
qed

lemma types-preserved-return:
  assumes (|[Local n i vls LI]|) ⇝ (|ves|)
          S·C ⊢ [Local n i vls LI] : (ts -> ts')
          const-list ves
          length ves = n
          Lfilled j lholed (ves @ [$Return]) LI
  shows S·C ⊢ ves : (ts -> ts')
proof −
  obtain tls C' where l-def:i < length (s-inst S)
                      C' = ((s-inst S)!i)(|local := (local ((s-inst S)!i)) @ (map typeof
vls), return := Some tls|)
                      S·C' ⊢ LI : ([] -> tls)
                      ts' = ts @ tls
                      length tls = n
    using e-type-local[OF assms(2)]
    by blast
```

```
  hence S·C ⊢ ves : ([] -> tls)
    using type-const-return[OF assms(5) - - l-def(3)] assms(3−5)
    by fastforce
  thus ?thesis
    using e-typing-s-typing.intros(3) l-def(4)
    by fastforce
qed

lemma type-const-br:
  assumes Lfilled i lholed (vs @ [$Br (i+k)]) LI
          length (label C) > k
          (label C)!k = tcs
          length tcs = length vs
          S·C ⊢ LI : (ts -> ts')
          const-list vs
  shows S·C' ⊢ vs : ([] -> tcs)
  using assms
proof (induction i arbitrary: k ts ts' lholed C LI C')
  case 0
  obtain vs' es' where LI = (vs' @ (vs @ [$Br (0+k)]) @ es')
    using Lfilled.simps[of 0 lholed (vs @ [$Br (0 + k)]) LI] 0(1)
    by fastforce
  then obtain ts'' ts''' where S·C ⊢ vs' : (ts -> ts'')
                               S·C ⊢ (vs @ [$Br (0+k)]) : (ts'' -> ts''')
                               S·C ⊢ es' : (ts''' -> ts')
    using e-type-comp-conc2[of S C vs' (vs @ [$Br (0+k)]) es'] 0(5)
    by fastforce
  then obtain ts-b where ts-b-def:S·C ⊢ vs : (ts'' -> ts-b) S·C ⊢ [$Br (0+k)] :
(ts-b -> ts''')
    using e-type-comp-conc1
    by fastforce
  then obtain ts-c where ts-c-def:ts-b = ts-c @ tcs (label C)!k = tcs
    using 0(3) b-e-type-br[of C Br (0 + k)] unlift-b-e[of S C [Br (0 + k)] ts-b ->
ts''']
    by fastforce
  obtain tcs' where ts-b = ts'' @ tcs' length vs = length tcs' S·C' ⊢ vs : ([] ->
tcs')
    using ts-b-def(1) e-type-const-list 0(6)
    by fastforce
  thus ?case
    using 0(4) ts-c-def
    by simp
next
  case (Suc i k ts ts' lholed C LI)
  obtain vs' n l les les' LK where es-def:lholed = (LRec vs' n les l les')
                                   Lfilled i l (vs @ [$Br (i + (Suc k))]) LK
                                   LI = (vs' @ [Label n les LK] @ les')
    using Lfilled.simps[of (Suc i) lholed (vs @ [$Br ((Suc i) + k)]) LI] Suc(2)
    by fastforce
```

**then obtain** $ts''$ $ts'''$ **where** $\mathcal{S}{\cdot}\mathcal{C} \vdash [Label\ n\ les\ LK] : (ts''\ ->\ ts''')$
**using** *e-type-comp-conc2*[*of* $\mathcal{S}$ $\mathcal{C}$ $vs'$ $[Label\ n\ les\ LK]$ $les'$] *Suc*(6)
**by** *fastforce*
**moreover**
**then obtain** *lts* $\mathcal{C}''$ $ts''''$ **where** $\mathcal{S}{\cdot}\mathcal{C}'' \vdash LK : ([]\ ->\ ts'''')\ \mathcal{C}'' = \mathcal{C}(\!|label := [lts]$ @ $(label\ \mathcal{C})|\!)$
$length\ (label\ \mathcal{C}'') > (Suc\ k)$
$(label\ \mathcal{C}'')!(Suc\ k) = tcs$
**using** *e-type-label*[*of* $\mathcal{S}$ $\mathcal{C}$ *n les LK ts'' ts'''*] *Suc*(3,4)
**by** *fastforce*
**then show** *?case*
**using** *Suc*(1) *es-def*(2) *assms*(4,6)
**by** *fastforce*
**qed**

**lemma** *types-preserved-br*:
**assumes** $(|[Label\ n\ es0\ LI]|) \rightsquigarrow (|vs\ @\ es0|)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [Label\ n\ es0\ LI] : (ts\ ->\ ts')$
*const-list vs*
$length\ vs = n$
*Lfilled i lholed* $(vs\ @\ [\$Br\ i])$ *LI*
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash (vs\ @\ es0) : (ts\ ->\ ts')$
**proof** −
**obtain** *tls t2s* $\mathcal{C}'$ **where** *l-def*:$(ts' = (ts@t2s))$
$(\mathcal{S}{\cdot}\mathcal{C} \vdash es0 : (tls\ ->\ t2s))$
$\mathcal{C}' = \mathcal{C}(\!|label := [tls]\ @\ (label\ \mathcal{C})|\!)$
$length\ (label\ \mathcal{C}') > 0$
$(label\ \mathcal{C}')!0 = tls$
$length\ tls = n$
$(\mathcal{S}{\cdot}\mathcal{C}(\!|label := [tls]\ @\ (label\ \mathcal{C})|\!) \vdash LI : ([]\ ->\ t2s))$
**using** *e-type-label*[*of* $\mathcal{S}$ $\mathcal{C}$ *n es0 LI ts ts'*] *assms*(2)
**by** *fastforce*
**hence** $\mathcal{S}{\cdot}\mathcal{C} \vdash vs : ([]\ ->\ tls)$
**using** *assms*(3−5) *type-const-br*[*of i lholed vs 0 LI* $\mathcal{C}'$ *tls*]
**by** *fastforce*
**thus** *?thesis*
**using** *l-def*(1,2) *e-type-comp-conc e-typing-s-typing.intros*(3)
**by** *fastforce*
**qed**

**lemma** *store-local-label-empty*:
**assumes** $i < length\ (s\text{-}inst\ \mathcal{S})$
*store-typing s* $\mathcal{S}$
**shows** $label\ ((s\text{-}inst\ \mathcal{S})!i) = []\ local\ ((s\text{-}inst\ \mathcal{S})!i) = []$
**proof** −
**obtain** *insts* **where** *inst-typ*:*list-all2* $(inst\text{-}typing\ \mathcal{S})$ *insts* $(s\text{-}inst\ \mathcal{S})$
**using** *assms*(2)
**unfolding** *store-typing.simps*
**by** *auto*

```
  thus label ((s-inst S)!i) = []
    using assms(1)
    unfolding inst-typing.simps List.list-all2-conv-all-nth
    by fastforce
  show local ((s-inst S)!i) = []
    using assms(1) inst-typ
    unfolding inst-typing.simps List.list-all2-conv-all-nth
    by fastforce
qed

lemma types-preserved-b-e1:
  assumes (|es|) ⇝ (|es'|)
          store-typing s S
          S·C ⊢ es : (ts -> ts')
  shows S·C ⊢ es' : (ts -> ts')
  using assms(1)
proof (cases rule: reduce-simple.cases)
  case (unop-i32 c iop)
  thus ?thesis
    using assms(1,3) types-preserved-unop-testop-cvtop
    by simp
next
  case (unop-i64 c iop)
  thus ?thesis
    using assms(1, 3) types-preserved-unop-testop-cvtop
    by simp
next
  case (unop-f32 c fop)
  thus ?thesis
    using assms(1, 3) types-preserved-unop-testop-cvtop
    by simp
next
  case (unop-f64 c fop)
  thus ?thesis
    using assms(1, 3) types-preserved-unop-testop-cvtop
    by simp
next
  case (binop-i32-Some iop c1 c2 c)
  thus ?thesis
    using assms(1, 3) types-preserved-binop-relop
    by simp
next
  case (binop-i32-None iop c1 c2)
  thus ?thesis
    by (simp add: e-typing-s-typing.intros(4))
next
  case (binop-i64-Some iop c1 c2 c)
  thus ?thesis
    using assms(1, 3) types-preserved-binop-relop
```

**by** *simp*
**next**
**case** (*binop-i64-None iop c1 c2*)
**thus** *?thesis*
**by** (*simp add*: *e-typing-s-typing.intros*(*4*))
**next**
**case** (*binop-f32-Some fop c1 c2 c*)
**thus** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-binop-relop*
**by** *simp*
**next**
**case** (*binop-f32-None fop c1 c2*)
**thus** *?thesis*
**by** (*simp add*: *e-typing-s-typing.intros*(*4*))
**next**
**case** (*binop-f64-Some fop c1 c2 c*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-binop-relop*
**by** *simp*
**next**
**case** (*binop-f64-None fop c1 c2*)
**then show** *?thesis*
**by** (*simp add*: *e-typing-s-typing.intros*(*4*))
**next**
**case** (*testop-i32 c testop*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-unop-testop-cvtop*
**by** *simp*
**next**
**case** (*testop-i64 c testop*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-unop-testop-cvtop*
**by** *simp*
**next**
**case** (*relop-i32 c1 c2 iop*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-binop-relop*
**by** *simp*
**next**
**case** (*relop-i64 c1 c2 iop*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-binop-relop*
**by** *simp*
**next**
**case** (*relop-f32 c1 c2 fop*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-binop-relop*
**by** *simp*
**next**

```
  case (relop-f64 c1 c2 fop)
  then show ?thesis
    using assms(1, 3) types-preserved-binop-relop
    by simp
next
  case (convert-Some t1 v t2 sx v')
  then show ?thesis
    using assms(1, 3) types-preserved-unop-testop-cvtop
    by simp
next
  case (convert-None t1 v t2 sx)
  then show ?thesis
    using e-typing-s-typing.intros(4)
    by simp
next
  case (reinterpret t1 v t2)
  then show ?thesis
    using assms(1, 3) types-preserved-unop-testop-cvtop
    by simp
next
  case unreachable
  then show ?thesis
    using e-typing-s-typing.intros(4)
    by simp
next
  case nop
  then have C ⊢ [Nop] : (ts -> ts')
    using assms(3) unlift-b-e
    by simp
  then show ?thesis
    using nop b-e-typing.empty e-typing-s-typing.intros(1,3)
    apply (induction [Nop] ts -> ts' arbitrary: ts ts')
     apply simp-all
    apply (metis list.simps(8))
    apply blast
    done
next
  case (drop v)
  then show ?thesis
    using assms(1, 3) types-preserved-drop
    by simp
next
  case (select-false v1 v2)
  then show ?thesis
    using assms(1, 3) types-preserved-select
    by simp
next
  case (select-true n v1 v2)
  then show ?thesis
```

```
    using assms(1, 3) types-preserved-select
    by simp
next
  case (block vs n t1s t2s m es)
  then show ?thesis
    using assms(1, 3) types-preserved-block
    by simp
next
  case (loop vs n t1s t2s m es)
  then show ?thesis
    using assms(1, 3) types-preserved-loop
    by simp
next
  case (if-false tf e1s e2s)
  then show ?thesis
    using assms(1, 3) types-preserved-if
    by simp
next
  case (if-true n tf e1s e2s)
  then show ?thesis
    using assms(1, 3) types-preserved-if
    by simp
next
  case (label-const ts es)
  then show ?thesis
    using assms(1, 3) types-preserved-label-value
    by simp
next
  case (label-trap ts es)
  then show ?thesis
    by (simp add: e-typing-s-typing.intros(4))
next
  case (br vs n i lholed LI es)
  then show ?thesis
    using assms(1, 3) types-preserved-br
    by fastforce
next
  case (br-if-false n i)
  then show ?thesis
    using assms(1, 3) types-preserved-br-if
    by fastforce
next
  case (br-if-true n i)
  then show ?thesis
    using assms(1, 3) types-preserved-br-if
    by fastforce
next
  case (br-table is' c i')
  then show ?thesis
```

**using** *assms*(*1*, *3*) *types-preserved-br-table*
**by** *fastforce*
**next**
**case** (*br-table-length is' c i'*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-br-table*
**by** *fastforce*
**next**
**case** (*local-const i vs*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-local-const*
**by** *fastforce*
**next**
**case** (*local-trap i vs*)
**then show** *?thesis*
**by** (*simp add*: *e-typing-s-typing.intros*(*4*))
**next**
**case** (*return n j lholed es i vls*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-return*
**by** *fastforce*
**next**
**case** (*tee-local v i*)
**then show** *?thesis*
**using** *assms*(*1*, *3*) *types-preserved-tee-local*
**by** *simp*
**next**
**case** (*trap lholed*)
**then show** *?thesis*
**by** (*simp add*: *e-typing-s-typing.intros*(*4*))
**qed**

**lemma** *types-preserved-b-e*:
**assumes** (|*es*|) ⇝ (|*es'*|)
*store-typing s* $\mathcal{S}$
$\mathcal{S}$·*None* ⊩-*i vs*;*es* : *ts*
**shows** $\mathcal{S}$·*None* ⊩-*i vs*;*es'* : *ts*
**proof** −
**have** *i* < (*length* (*s-inst* $\mathcal{S}$))
**using** *assms*(*3*) *s-typing.cases*
**by** *blast*
**moreover**
**obtain** *tvs* $\mathcal{C}$ **where** *defs*: *tvs* = *map typeof vs* $\mathcal{C}$ = ((*s-inst* $\mathcal{S}$)!*i*)(|*local* := (*local* ((*s-inst* $\mathcal{S}$)!*i*) @ *tvs*), *return* := *None*|) $\mathcal{S}$·$\mathcal{C}$ ⊢ *es* : ([] -> *ts*)
**using** *assms*(*3*)
**unfolding** *s-typing.simps*
**by** *blast*
**have** $\mathcal{S}$·$\mathcal{C}$ ⊢ *es'* : ([] -> *ts*)
**using** *assms*(*1*,*2*) *defs*(*3*) *types-preserved-b-e1*

**by** *simp*
**ultimately show** *?thesis*
**using** *defs*
**unfolding** *s-typing.simps*
**by** *auto*
**qed**

**lemma** *types-preserved-store*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash$ [\$*C ConstInt32 k*, \$*C v*, \$*Store t tp a off*] : (*ts* -> *ts'*)
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash$ [] : (*ts* -> *ts'*)
*types-agree t v*
**proof** −
**obtain** *ts'' ts'''* **where** *ts-def*:$\mathcal{S}{\cdot}\mathcal{C} \vdash$ [\$*C ConstInt32 k*] : (*ts* -> *ts''*)
$\mathcal{S}{\cdot}\mathcal{C} \vdash$ [\$*C v*] : (*ts''* -> *ts'''*)
$\mathcal{S}{\cdot}\mathcal{C} \vdash$ [\$*Store t tp a off*] : (*ts'''* -> *ts'*)
**using** *assms e-type-comp-conc2*[*of* $\mathcal{S}$ $\mathcal{C}$ [\$*C ConstInt32 k*] [\$*C v*] [\$*Store t tp a off*]]
**by** *fastforce*
**then have** *ts''* = *ts*@[(*T-i32*)]
**using** *b-e-type-value*[*of* $\mathcal{C}$ *C ConstInt32 k ts ts''*]
*unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*C* (*ConstInt32 k*)] (*ts* -> *ts''*)]
**unfolding** *typeof-def*
**by** *fastforce*
**hence** *ts'''* = *ts*@[(*T-i32*), (*typeof v*)]
**using** *ts-def*(*2*) *b-e-type-value*[*of* $\mathcal{C}$ *C v ts'' ts'''*]
*unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*C v*] (*ts''* -> *ts'''*)]
**by** *fastforce*
**hence** *ts* = *ts'* *types-agree t v*
**using** *ts-def*(*3*) *b-e-type-store*[*of* $\mathcal{C}$ *Store t tp a off ts''' ts'*]
*unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Store t tp a off*] (*ts'''* -> *ts'*)]
**unfolding** *types-agree-def*
**by** *fastforce*+
**thus** $\mathcal{S}{\cdot}\mathcal{C} \vdash$ [] : (*ts* -> *ts'*) *types-agree t v*
**using** *b-e-type-empty*[*of* $\mathcal{C}$ *ts ts'*] *e-typing-s-typing.intros*(*1*)
**by** *fastforce*+
**qed**

**lemma** *types-preserved-current-memory*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash$ [\$*Current-memory*] : (*ts* -> *ts'*)
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash$ [\$*C ConstInt32 c*] : (*ts* -> *ts'*)
**proof** −
**have** *ts'* = *ts*@[*T-i32*]
**using** *assms b-e-type-current-memory unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Current-memory*]]
**by** *fastforce*
**thus** *?thesis*
**using** *b-e-typing.const*[*of* $\mathcal{C}$ *ConstInt32 c*] *e-typing-s-typing.intros*(*1*,*3*)
**unfolding** *typeof-def*
**by** *fastforce*
**qed**

**lemma** *types-preserved-grow-memory*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ c, \$Grow\text{-}memory] : (ts\ ->\ ts')$
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ c'] : (ts\ ->\ ts')$
**proof** −
**obtain** $ts''$ **where** $ts''\text{-}def{:}\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ c] : (ts\ ->\ ts'')$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$Grow\text{-}memory] : (ts''\ ->\ ts')$
**using** *e-type-comp assms*
**by** (*metis append-butlast-last-id butlast.simps*(2) *last.simps list.distinct*(1))
**have** $ts'' = ts@[(T\text{-}i32)]$
**using** *b-e-type-value*[*of* $\mathcal{C}$ *C ConstInt32 c ts ts'*]
*unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*C ConstInt32 c*]] *ts''-def*(1)
**unfolding** *typeof-def*
**by** *fastforce*
**moreover**
**hence** $ts'' = ts'$
**using** *ts''-def b-e-type-grow-memory*[*of - - ts'' ts'*] *unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Grow-memory*]]
**by** *fastforce*
**ultimately**
**show** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ c'] : (ts\ ->\ ts')$
**using** *e-typing-s-typing.intros*(1,3)
*b-e-typing.const*[*of* $\mathcal{C}$ *ConstInt32 c'*]
**unfolding** *typeof-def*
**by** *fastforce*
**qed**

**lemma** *types-preserved-set-global*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v, \$Set\text{-}global\ j] : (ts\ ->\ ts')$
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [] : (ts\ ->\ ts')$
*tg-t* (*global* $\mathcal{C}$ ! *j*) = *typeof v*
**proof** −
**obtain** $ts''$ **where** $ts''\text{-}def{:}\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v] : (ts\ ->\ ts'')$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$Set\text{-}global\ j] : (ts''\ ->\ ts')$
**using** *e-type-comp assms*
**by** (*metis append-butlast-last-id butlast.simps*(2) *last.simps list.distinct*(1))
**hence** $ts'' = ts@[typeof\ v]$
**using** *b-e-type-value unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*C v*]]
**by** *fastforce*
**hence** $ts = ts'$ *tg-t* (*global* $\mathcal{C}$ ! *j*) = *typeof v*
**using** *b-e-type-set-global ts''-def*(2) *unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Set-global j*]]
**by** *fastforce*+
**thus** $\mathcal{S}{\cdot}\mathcal{C} \vdash [] : (ts\ ->\ ts')$ *tg-t* (*global* $\mathcal{C}$ ! *j*) = *typeof v*
**using** *b-e-type-empty*[*of* $\mathcal{C}$ *ts ts'*] *e-typing-s-typing.intros*(1)
**by** *fastforce*+
**qed**

**lemma** *types-preserved-load*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ k, \$Load\ t\ tp\ a\ off] : (ts\ ->\ ts')$
*typeof v* = *t*

**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v] : (ts\ ->\ ts')$
**proof** −
**obtain** $ts''$ **where** $ts''\text{-}def{:}\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ ConstInt32\ k] : (ts\ ->\ ts'')$
$\mathcal{S}{\cdot}\mathcal{C} \vdash [\$Load\ t\ tp\ a\ off] : (ts''\ ->\ ts')$
**using** *e-type-comp assms*
**by** (*metis append-butlast-last-id butlast.simps*(2) *last.simps list.distinct*(1))
**hence** $ts'' = ts@[(T\text{-}i32)]$
**using** *b-e-type-value unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [$C$ *ConstInt32 k*]]
**unfolding** *typeof-def*
**by** *fastforce*
**hence** *ts-def*:$ts' = ts@[t]$ *load-store-t-bounds a* (*option-projl tp*) *t*
**using** $ts''\text{-}def(2)$ *b-e-type-load unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Load t tp a off*]]
**by** *fastforce*+
**moreover**
**hence** $\mathcal{C} \vdash [C\ v] : (ts\ ->\ ts@[t])$
**using** *assms*(2) *b-e-typing.const b-e-typing.weakening*
**by** *fastforce*
**ultimately**
**show** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v] : (ts\ ->\ ts')$
**using** *e-typing-s-typing.intros*(1)
**by** *fastforce*
**qed**

**lemma** *types-preserved-get-local*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$Get\text{-}local\ i] : (ts\ ->\ ts')$
*length vi* = *i*
(*local* $\mathcal{C}$) = *map typeof* (*vi* @ [*v*] @ *vs*)
**shows** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v] : (ts\ ->\ ts')$
**proof** −
**have** (*local* $\mathcal{C}$)!*i* = *typeof v*
**using** *assms*(2,3)
**by** (*metis* (*no-types*, *opaque-lifting*) *append-Cons length-map list.simps*(9) *map-append nth-append-length*)
**hence** $ts' = ts@[typeof\ v]$
**using** *assms*(1) *unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Get-local i*]] *b-e-type-get-local*
**by** *fastforce*
**thus** *?thesis*
**using** *b-e-typing.const e-typing-s-typing.intros*(1,3)
**by** *fastforce*
**qed**

**lemma** *types-preserved-set-local*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash [\$C\ v', \$Set\text{-}local\ i] : (ts\ ->\ ts')$
*length vi* = *i*
(*local* $\mathcal{C}$) = *map typeof* (*vi* @ [*v*] @ *vs*)
**shows** $(\mathcal{S}{\cdot}\mathcal{C} \vdash [] : (ts\ ->\ ts')) \wedge$ *map typeof* (*vi* @ [*v*] @ *vs*) = *map typeof* (*vi* @ [*v'*] @ *vs*)
**proof** −
**have** *v-type*:(*local* $\mathcal{C}$)!*i* = *typeof v*

**using** *assms*(*2*,*3*)
**by** (*metis* (*no-types*, *opaque-lifting*) *append-Cons length-map list.simps*(*9*) *map-append nth-append-length*)
**obtain** *ts''* **where** *ts''-def*:$\mathcal{S}\cdot\mathcal{C} \vdash [\$C\ v'] : (ts\ ->\ ts'')$
$\mathcal{S}\cdot\mathcal{C} \vdash [\$Set\text{-}local\ i] : (ts''\ ->\ ts')$
**using** *e-type-comp assms*
**by** (*metis append-butlast-last-id butlast.simps*(*2*) *last.simps list.distinct*(*1*))
**hence** $ts'' = ts@[typeof\ v']$
**using** *b-e-type-value unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ $[C\ v']$]
**by** *fastforce*
**hence** $typeof\ v = typeof\ v'$ $ts' = ts$
**using** *v-type b-e-type-set-local*[*of* $\mathcal{C}$ *Set-local i ts'' ts'*] *ts''-def*(*2*) *unlift-b-e*[*of* $\mathcal{S}$ $\mathcal{C}$ [*Set-local i*]]
**by** *fastforce*+
**thus** *?thesis*
**using** *b-e-type-empty*[*of* $\mathcal{C}$ *ts ts'*] *e-typing-s-typing.intros*(*1*)
**by** *fastforce*
**qed**

**lemma** *types-preserved-get-global*:
**assumes** $typeof\ (sglob\text{-}val\ s\ i\ j) = tg\text{-}t\ (global\ \mathcal{C}\ !\ j)$
$\mathcal{S}\cdot\mathcal{C} \vdash [\$Get\text{-}global\ j] : (ts\ ->\ ts')$
**shows** $\mathcal{S}\cdot\mathcal{C} \vdash [\$C\ sglob\text{-}val\ s\ i\ j] : (ts\ ->\ ts')$
**proof** −
**have** $ts' = ts@[tg\text{-}t\ (global\ \mathcal{C}\ !\ j)]$
**using** *b-e-type-get-global assms*(*2*) *unlift-b-e*[*of* - - [*Get-global j*]]
**by** *fastforce*
**thus** *?thesis*
**using** *b-e-typing.const*[*of* $\mathcal{C}$ *sglob-val s i j*] *assms*(*1*) *e-typing-s-typing.intros*(*1*,*3*)
**by** *fastforce*
**qed**

**lemma** *lholed-same-type*:
**assumes** *Lfilled k lholed es les*
*Lfilled k lholed es' les'*
$\mathcal{S}\cdot\mathcal{C} \vdash les : (ts\ ->\ ts')$
$\bigwedge arb\text{-}labs\ ts\ ts'.$
$\mathcal{S}\cdot(\mathcal{C}(\!|label := arb\text{-}labs@(label\ \mathcal{C})|\!)) \vdash es : (ts\ ->\ ts')$
$\Longrightarrow \mathcal{S}\cdot(\mathcal{C}(\!|label := arb\text{-}labs@(label\ \mathcal{C})|\!)) \vdash es' : (ts\ ->\ ts')$
**shows** $(\mathcal{S}\cdot\mathcal{C} \vdash les' : (ts\ ->\ ts'))$
**using** *assms*
**proof** (*induction arbitrary*: *ts ts' es' C les' rule*: *Lfilled.induct*)
**case** (*L0 vs lholed es' es ts ts' es''*)
**obtain** *ts'' ts'''* **where** $\mathcal{S}\cdot\mathcal{C} \vdash vs : (ts\ ->\ ts'')$
$\mathcal{S}\cdot\mathcal{C} \vdash es : (ts''\ ->\ ts''')$
$\mathcal{S}\cdot\mathcal{C} \vdash es' : (ts'''\ ->\ ts')$
**using** *e-type-comp-conc2 L0*(*4*)
**by** *blast*
**moreover**

**hence** ($\mathcal{S}$·$\mathcal{C}$ ⊢ *es''* : (*ts''* -> *ts'''*))
**using** *L0*(*5*)[*of* [] *ts''* *ts'''*]
**by** *fastforce*
**ultimately**
**have** ($\mathcal{S}$·$\mathcal{C}$ ⊢ *vs* @ *es''* @ *es'* : (*ts* -> *ts'*))
**using** *e-type-comp-conc*
**by** *fastforce*
**thus** *?case*
**using** *L0*(*2*,*3*) *Lfilled.simps*[*of 0 lholed es'' les'*]
**by** *fastforce*
**next**
**case** (*LN vs lholed n es' l es'' k es lfilledk t1s t2s es''' C les'*)
**obtain** *lfilledk'* **where** *l'-def*:*Lfilled k l es''' lfilledk' les'* = *vs* @ [*Label n es' lfilledk'*] @ *es''*
**using** *LN Lfilled.simps*[*of k+1 lholed es''' les'*]
**by** *fastforce*
**obtain** *ts' ts''* **where** *lab-def*:$\mathcal{S}$·$\mathcal{C}$ ⊢ *vs* : (*t1s* -> *ts'*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ [*Label n es' lfilledk*] : (*ts'* -> *ts''*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ *es''* : (*ts''* -> *t2s*)
**using** *e-type-comp-conc2*[*OF LN*(*6*)]
**by** *blast*
**obtain** *tls ts-c* $\mathcal{C}$*-int* **where** *int-def*: *ts''* = *ts'* @ *ts-c*
*length tls* = *n*
$\mathcal{S}$·$\mathcal{C}$ ⊢ *es'* : (*tls* -> *ts-c*)
$\mathcal{C}$*-int* = $\mathcal{C}$(|*label* := [*tls*] @ *label* $\mathcal{C}$|)
$\mathcal{S}$·$\mathcal{C}$*-int* ⊢ *lfilledk* : ([] -> *ts-c*)
**using** *e-type-label*[*OF lab-def*(*2*)]
**by** *blast*
**have** (⋀$\mathcal{C}'$ *arb-labs' ts ts'*.
$\mathcal{C}'$ = $\mathcal{C}$*-int*(|*label* := *arb-labs'* @ *label* $\mathcal{C}$*-int*|) ⟹
$\mathcal{S}$·$\mathcal{C}'$ ⊢ *es* : (*ts* -> *ts'*) ⟹
($\mathcal{S}$·$\mathcal{C}'$ ⊢ *es'''* : (*ts* -> *ts'*)))
**proof** −
**fix** $\mathcal{C}''$ *arb-labs'' tts tts'*
**assume** $\mathcal{C}''$ = $\mathcal{C}$*-int*(|*label* := *arb-labs''* @ *label* $\mathcal{C}$*-int*|)
$\mathcal{S}$·$\mathcal{C}''$ ⊢ *es* : (*tts* -> *tts'*)
**thus** ($\mathcal{S}$·$\mathcal{C}''$ ⊢ *es'''* : (*tts* -> *tts'*))
**using** *LN*(*7*)[*of arb-labs''* @ [*tls*] *tts tts'*] *int-def*(*4*)
**by** *fastforce*
**qed**
**hence** ($\mathcal{S}$·$\mathcal{C}$*-int* ⊢ *lfilledk'* : ([] -> *ts-c*))
**using** *LN*(*4*)[*OF l'-def*(*1*) *int-def*(*5*)]
**by** *fastforce*
**hence** ($\mathcal{S}$·$\mathcal{C}$ ⊢ [*Label n es' lfilledk'*] : (*ts'* -> *ts''*))
**using** *int-def e-typing-s-typing.intros*(*3*,*7*)
**by** (*metis append.right-neutral*)
**thus** *?case*
**using** *lab-def e-type-comp-conc l'-def*(*2*)
**by** *blast*

**qed**

**lemma** *types-preserved-e1*:
**assumes** $(\!|s;vs;es|\!) \rightsquigarrow_i (\!|s';vs';es'|\!)$
$store\text{-}typing\ s\ \mathcal{S}$
$tvs = map\ typeof\ vs$
$i < length\ (inst\ s)$
$\mathcal{C} = ((s\text{-}inst\ \mathcal{S})!i)(\!|local := (local\ ((s\text{-}inst\ \mathcal{S})!i)\ @\ tvs),\ label := arb\text{-}labs,$
$return := arb\text{-}return|\!)$
$\mathcal{S}{\cdot}\mathcal{C} \vdash es : (ts\ ->\ ts')$
**shows** $(\mathcal{S}{\cdot}\mathcal{C} \vdash es' : (ts\ ->\ ts')) \wedge (map\ typeof\ vs = map\ typeof\ vs')$
**using** *assms*
**proof** (*induction arbitrary*: *tvs* $\mathcal{C}$ *ts ts' arb-labs arb-return rule*: *reduce.induct*)
**case** (*basic e e' s vs i*)
**then show** *?case*
**using** *types-preserved-b-e1*[*OF basic*(*1*,*2*)]
**by** *fastforce*
**next**
**case** (*call s vs j i*)
**obtain** *ts'' tf1 tf2* **where** *l-func-t*: $length\ (func\text{-}t\ \mathcal{C}) > j$
$ts = ts''@tf1$
$ts' = ts''@tf2$
$((func\text{-}t\ \mathcal{C})!j) = (tf1\ ->\ tf2)$
**using** *b-e-type-call*[*of* $\mathcal{C}$ *Call j ts ts' j*] *call*(*5*)
*unlift-b-e*[*of - - [Call j] (ts -> ts')*]
**by** *fastforce*
**have** $i < length\ (s\text{-}inst\ \mathcal{S})$
**using** *call*(*3*) *store-typing-imp-inst-length-eq*[*OF call*(*1*)]
**by** *simp*
**moreover**
**have** $j < length\ (func\text{-}t\ (s\text{-}inst\ \mathcal{S}\ !\ i))$
**using** *l-func-t*(*1*) *call*(*4*)
**by** *simp*
**ultimately**
**have** *cl-typing* $\mathcal{S}$ (*sfunc s i j*) (*tf1 -> tf2*)
**using** *store-typing-imp-func-agree*[*OF call*(*1*)] *l-func-t*(*4*) *call*(*4*)
**by** *fastforce*
**thus** *?case*
**using** *e-typing-s-typing.intros*(*3*,*6*) *l-func-t*
**by** *fastforce*
**next**
**case** (*call-indirect-Some s i' c cl j tf vs*)
**show** *?case*
**using** *types-preserved-call-indirect-Some*[*OF call-indirect-Some*(*8*,*1*)]
*call-indirect-Some*(*2*,*3*,*4*,*6*,*7*)
**by** *fastforce*
**next**
**case** (*call-indirect-None s i c cl j vs*)
**thus** *?case*

**using** *e-typing-s-typing.intros*(*4*)
**by** *blast*
**next**
**case** (*callcl-native cl j t1s t2s ts es ves vcs n k m zs s vs i*)
**thus** *?case*
**using** *types-preserved-callcl-native*
**by** *fastforce*
**next**
**case** (*callcl-host-Some cl t1s t2s f ves vcs n m s hs s′ vcs′ vs i*)
**thus** *?case*
**using** *types-preserved-callcl-host-some*
**by** *fastforce*
**next**
**case** (*callcl-host-None cl t1s t2s f ves vcs n m s hs vs i*)
**thus** *?case*
**using** *e-typing-s-typing.intros*(*4*)
**by** *blast*
**next**
**case** (*get-local vi j s v vs i*)
**hence** *i* < *length* (*s-inst* $\mathcal{S}$)
**unfolding** *list-all2-conv-all-nth store-typing.simps*
**by** *fastforce*
**then have** *local* $\mathcal{C}$ = *tvs*
**using** *store-local-label-empty assms*(*2*) *get-local*
**by** *fastforce*
**then show** *?case*
**using** *types-preserved-get-local get-local*
**by** *fastforce*
**next**
**case** (*set-local vi j s v vs v′ i*)
**hence** *i* < *length* (*s-inst* $\mathcal{S}$)
**unfolding** *list-all2-conv-all-nth store-typing.simps*
**by** *fastforce*
**hence** *local* $\mathcal{C}$ = *tvs*
**using** *store-local-label-empty assms*(*2*) *set-local*
**by** *fastforce*
**thus** *?case*
**using** *set-local types-preserved-set-local*
**by** *simp*
**next**
**case** (*get-global s vs j i*)
**have** *length* (*global* $\mathcal{C}$) > *j*
**using** *b-e-type-get-global get-global*(*5*) *unlift-b-e*[*of - - [Get-global j] (ts -> ts′)*]
**by** *fastforce*
**hence** *glob-agree* (*sglob s i j*) ((*global* $\mathcal{C}$)!*j*)
**using** *get-global*(*3*,*4*) *store-typing-imp-glob-agree*[*OF get-global*(*1*)] *store-typing-imp-inst-length-eq*[*OF get-global*(*1*)]
**by** *fastforce*
**hence** *typeof* (*g-val* (*sglob s i j*)) = *tg-t* (*global* $\mathcal{C}$ ! *j*)

**unfolding** *glob-agree-def*
**by** *simp*
**thus** *?case*
**using** *get-global*(*5*) *types-preserved-get-global*
**unfolding** *glob-agree-def sglob-val-def*
**by** *fastforce*
**next**
**case** (*set-global s i j v s' vs*)
**then show** *?case*
**using** *types-preserved-set-global*
**by** *fastforce*
**next**
**case** (*load-Some s i j m k off t bs vs a*)
**then show** *?case*
**using** *types-preserved-load*(*1*) *wasm-deserialise-type*
**by** *blast*
**next**
**case** (*load-None s i j m k off t vs a*)
**then show** *?case*
**using** *e-typing-s-typing.intros*(*4*)
**by** *blast*
**next**
**case** (*load-packed-Some s i j m sx k off tp bs vs t a*)
**then show** *?case*
**using** *types-preserved-load*(*1*) *wasm-deserialise-type*
**by** *blast*
**next**
**case** (*load-packed-None s i j m sx k off tp vs t a*)
**then show** *?case*
**using** *e-typing-s-typing.intros*(*4*)
**by** *blast*
**next**
**case** (*store-Some t v s i j m k off mem' vs a*)
**then show** *?case*
**using** *types-preserved-store*
**by** *blast*
**next**
**case** (*store-None t v s i j m k off vs a*)
**then show** *?case*
**using** *e-typing-s-typing.intros*(*4*)
**by** *blast*
**next**
**case** (*store-packed-Some t v s i j m k off tp mem' vs a*)
**then show** *?case*
**using** *types-preserved-store*
**by** *blast*
**next**
**case** (*store-packed-None t v s i j m k off tp vs a*)
**then show** *?case*

```
    using e-typing-s-typing.intros(4)
    by blast
next
  case (current-memory s i j m n vs)
  then show ?case
    using types-preserved-current-memory
    by fastforce
next
  case (grow-memory s i j m n c mem' vs)
  then show ?case
    using types-preserved-grow-memory
    by fastforce
next
  case (grow-memory-fail s i j m n vs c)
  thus ?case
    using types-preserved-grow-memory
    by blast
next
  case (label s vs es i s' vs' es' k lholed les les')
  {
    fix C' arb-labs' ts ts'
    assume local-assms:C' = C(|label := arb-labs'@(label C), return := (return C)|)
    hence (S·C' ⊢ es : (ts -> ts')) ⟹ (S·C' ⊢ es' : (ts -> ts')) ∧ map typeof vs =
map typeof vs'
      using label(4)[OF label(5,6,7)] label(8)
      by fastforce
    hence (S·C(|label := arb-labs'@(label C)|) ⊢ es : (ts -> ts'))
            ⟹ (S·C(|label := arb-labs'@(label C)|) ⊢ es' : (ts -> ts')) ∧
                map typeof vs = map typeof vs'
      using local-assms
      by simp
  }
  hence ⋀arb-labs' ts ts'. S·C(|label := arb-labs'@(label C)|) ⊢ es : (ts -> ts')
                          ⟹ (S·C(|label := arb-labs'@(label C)|) ⊢ es' : (ts -> ts'))
      map typeof vs = map typeof vs'
    using types-exist-lfilled[OF label(2,9)]
    by auto
  thus ?case
    using lholed-same-type[OF label(2,3,9)]
    by fastforce
next
  case (local s vls es i s' vs' es' vs n j)
  obtain C' tls where es-def:i < length (s-inst S)
                      length tls = n
                      C' = (s-inst S ! i) (|local := local(s-inst S ! i) @ map typeof
vls, label := label (s-inst S ! i), return := Some tls|)
                      S·C' ⊢ es : ([] -> tls)
                      ts' = ts @ tls
    using e-type-local[OF local(7)]
```

```
    by fastforce
  moreover
  obtain ts'' where ts' = ts@ts'' (S·(Some ts'') ⊩-i vls;es : ts'')
    using e-type-local-shallow local(7)
    by fastforce
  moreover
  have inst-typing S ((inst s)!i) ((s-inst S)!i) i < length (inst s)
    using local es-def(1)
    unfolding store-typing.simps list-all2-conv-all-nth
    by fastforce+
  ultimately
  have S·C' ⊢ es' : ([] -> tls) map typeof vls = map typeof vs'
     using local(2)[OF local(3) - - - es-def(4), of map typeof vls Some tls label
(s-inst S ! i)]
    by fastforce+
  hence S·(Some tls) ⊩- i vs';es' : tls
    using e-typing-s-typing.intros(8) es-def(1,3)
    by fastforce
  thus ?case
    using e-typing-s-typing.intros(3,5) es-def(2,5)
    by fastforce
qed

lemma types-preserved-e:
  assumes (|s;vs;es|) ~>-i (|s';vs';es'|)
          store-typing s S
          S·None ⊩-i vs;es : ts
  shows S·None ⊩-i vs';es' : ts
  using assms
proof −
  have i < (length (s-inst S))
    using assms(3) s-typing.cases
    by blast
  moreover
  hence i-bound:i < length (inst s)
    using assms(2)
    unfolding list-all2-conv-all-nth store-typing.simps
    by fastforce
  obtain tvs C where defs: tvs = map typeof vs
                         C = ((s-inst S)!i)(|local := (local ((s-inst S)!i) @ tvs), label
:= (label ((s-inst S)!i)), return := None|)
                         S·C ⊢ es : ([] -> ts)
    using assms(3)
    unfolding s-typing.simps
    by fastforce
  have (S·C ⊢ es' : ([] -> ts)) ∧ (map typeof vs = map typeof vs')
    using types-preserved-e1[OF assms(1,2) defs(1) i-bound defs(2,3)]
    by simp
  ultimately show ?thesis
```

```
    using defs
    unfolding s-typing.simps
    by auto
qed
```

## 6.2 Progress

```
lemma const-list-no-progress:
  assumes const-list es
  shows ¬(⟦s;vs;es⟧) ↝- i (⟦s';vs';es'⟧)
proof −
  {
    assume (⟦s;vs;es⟧) ↝- i (⟦s';vs';es'⟧)
    hence False
      using assms
    proof (induction rule: reduce.induct)
      case (basic e e' s vs i)
      thus ?thesis
      proof (induction rule: reduce-simple.induct)
        case (trap es lholed)
        show ?case
          using trap(2)
        proof (cases rule: Lfilled.cases)
          case (L0 vs es')
          thus ?thesis
            using trap(3) list-all-append const-list-cons-last(2)[of vs Trap]
            unfolding const-list-def
            by (simp add: is-const-def)
        next
          case (LN vs n es' l es'' k lfilledk)
          thus ?thesis
            by (simp add: is-const-def)
        qed
      qed (fastforce simp add: const-list-cons-last(2) is-const-def const-list-def)+
    next
      case (label s vs es i s' vs' es' k lholed les les')
      show ?case
        using label(2)
      proof (cases rule: Lfilled.cases)
        case (L0 vs es')
        thus ?thesis
          using label(4,5) list-all-append
          unfolding const-list-def
          by fastforce
      next
        case (LN vs n es' l es'' k lfilledk)
        thus ?thesis
          using label(4,5)
          unfolding const-list-def
```

```
        by (simp add: is-const-def)
    qed
  qed (fastforce simp add: const-list-cons-last(2) is-const-def const-list-def)+
 }
 thus ?thesis
  by blast
qed

lemma empty-no-progress:
 assumes es = []
 shows ¬(|s;vs;es|) ↝- i (|s';vs';es'|)
proof −
 {
  assume (|s;vs;es|) ↝- i (|s';vs';es'|)
  hence False
   using assms
  proof (induction rule: reduce.induct)
   case (basic e e' s vs i)
   thus ?thesis
   proof (induction rule: reduce-simple.induct)
    case (trap es lholed)
    thus ?case
     using Lfilled.simps[of 0 lholed [Trap] es]
     by auto
   qed auto
  next
   case (label s vs es i s' vs' es' k lholed les les')
   thus ?case
      using Lfilled.simps[of k lholed es []]
      by auto
  qed auto
 }
 thus ?thesis
  by blast
qed

lemma trap-no-progress:
 assumes es = [Trap]
 shows ¬(|s;vs;es|) ↝- i (|s';vs';es'|)
proof −
 {
  assume (|s;vs;es|) ↝- i (|s';vs';es'|)
  hence False
   using assms
  proof (induction rule: reduce.induct)
   case (basic e e' s vs i)
   thus ?case
   by (induction rule: reduce-simple.induct) auto
  next
```

```
      case (label s vs es i s' vs' es' k lholed les les')
      show ?case
        using label(2)
        proof (cases rule: Lfilled.cases)
          case (L0 vs es')
          show ?thesis
            using L0(2) label(1,4,5) empty-no-progress
            by (auto simp add: Cons-eq-append-conv)
        next
          case (LN vs n es' l es'' k' lfilledk)
          show ?thesis
            using LN(2) label(5)
            by (simp add: Cons-eq-append-conv)
        qed
    qed auto
  }
  thus ?thesis
    by blast
qed

lemma terminal-no-progress:
  assumes const-list es ∨ es = [Trap]
  shows ¬(⟦s;vs;es⟧) ↝- i (⟦s';vs';es'⟧)
  using const-list-no-progress trap-no-progress assms
  by blast

lemma progress-L0:
  assumes (⟦s;vs;es⟧) ↝- i (⟦s';vs';es'⟧)
          const-list cs
  shows (⟦s;vs;cs@es@es-c⟧) ↝- i (⟦s';vs';cs@es'@es-c⟧)
proof −
  have ⋀es. Lfilled 0 (LBase cs es-c) es (cs@es@es-c)
    using Lfilled.intros(1)[of cs (LBase cs es-c) es-c] assms(2)
    unfolding const-list-def
    by fastforce
  thus ?thesis
    using reduce.intros(23) assms(1)
    by blast
qed

lemma progress-L0-left:
  assumes (⟦s;vs;es⟧) ↝- i (⟦s';vs';es'⟧)
          const-list cs
  shows (⟦s;vs;cs@es⟧) ↝- i (⟦s';vs';cs@es'⟧)
  using assms progress-L0[where ?es-c = []]
  by fastforce

lemma progress-L0-trap:
  assumes const-list cs
```

```
        cs ≠ [] ∨ es ≠ []
  shows ∃ a. (|s;vs;cs@[Trap]@es|) ↝- i (|s;vs;[Trap]|)
proof −
  have cs @ [Trap] @ es ≠ [Trap]
    using assms(2)
    by (cases cs = []) (auto simp add: append-eq-Cons-conv)
  thus ?thesis
    using reduce.intros(1) assms(2) reduce-simple.trap
          Lfilled.intros(1)[OF assms(1), of - es [Trap]]
    by blast
qed

lemma progress-LN:
  assumes (Lfilled j lholed [$Br (j+k)] es)
          S·C ⊢ es : ([] -> ts)
          (label C)!k = tvs
  shows ∃ lholed' vs C'. (Lfilled j lholed' (vs@[$Br (j+k)]) es)
                    ∧ (S·C' ⊢ vs : ([] -> tvs))
                    ∧ const-list vs
  using assms
proof (induction [$Br (j+k)] es arbitrary: k C ts rule: Lfilled.induct)
  case (L0 vs lholed es')
  obtain ts' ts'' where ts-def:S·C ⊢ vs : ([] -> ts')
                                S·C ⊢ [$Br k] : (ts' -> ts'')
                                S·C ⊢ es' : (ts'' -> ts)
    using e-type-comp-conc2[OF L0(3)]
    by fastforce
  obtain ts-c where ts' = ts-c @ tvs
    using b-e-type-br[of C Br k ts' ts''] L0(3,4) ts-def(2) unlift-b-e
    by fastforce
  then obtain vs1 vs2 where vs-def:S·C ⊢ vs1 : ([] -> ts-c)
                                  S·C ⊢ vs2 : (ts-c -> (ts-c@tvs))
                                  vs = vs1@vs2
                                  const-list vs1
                                  const-list vs2
    using e-type-const-list-cons[OF L0(1)] ts-def(1)
    by fastforce
  hence S·C ⊢ vs2 : ([] -> tvs)
    using e-type-const-list by blast
  thus ?case
    using Lfilled.intros(1)[OF vs-def(4), of - es' vs2@[$Br k]] vs-def(3,5)
    by fastforce
next
  case (LN vs lholed n es' l es'' j lfilledk)
  obtain t1s t2s where ts-def:S·C ⊢ vs : ([] -> t1s)
                               S·C ⊢ [Label n es' lfilledk] : (t1s -> t2s)
                               S·C ⊢ es'' : (t2s -> ts)
  using e-type-comp-conc2[OF LN(5)]
  by fastforce
```

**obtain** *ts′ ts-l* **where** *ts-l-def*:$\mathcal{S}$·$\mathcal{C}$⦇*label* := [*ts′*] @ *label* $\mathcal{C}$⦈ ⊢ *lfilledk* : ([] -> *ts-l*)
**using** *e-type-label*[*OF ts-def*(*2*)]
**by** *fastforce*
**obtain** *lholed′ vs′ C′* **where** *lfilledk-def*:*Lfilled j lholed′* (*vs′* @ [$*Br* (*j* + (*1* + *k*))]) *lfilledk*
$\mathcal{S}$·$\mathcal{C}$′ ⊢ *vs′* : ([] -> *tvs*)
*const-list vs′*
**using** *LN*(*4*)[*OF* - *ts-l-def*, *of 1* + *k*] *LN*(*5*,*6*)
**by** *fastforce*
**thus** *?case*
**using** *Lfilled.intros*(*2*)[*OF LN*(*1*) - *lfilledk-def*(*1*)]
**by** *fastforce*
**qed**

**lemma** *progress-LN-return*:
**assumes** (*Lfilled j lholed* [$*Return*] *es*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ *es* : ([] -> *ts*)
(*return* $\mathcal{C}$) = *Some tvs*
**shows** ∃ *lholed′ vs C′*. (*Lfilled j lholed′* (*vs*@[$*Return*]) *es*)
∧ ($\mathcal{S}$·$\mathcal{C}$′ ⊢ *vs* : ([] -> *tvs*))
∧ *const-list vs*
**using** *assms*
**proof** (*induction* [$*Return*] *es arbitrary*: *k* $\mathcal{C}$ *ts rule*: *Lfilled.induct*)
**case** (*L0 vs lholed es′*)
**obtain** *ts′ ts′′* **where** *ts-def*:$\mathcal{S}$·$\mathcal{C}$ ⊢ *vs* : ([] -> *ts′*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ [$*Return*] : (*ts′* -> *ts′′*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ *es′* : (*ts′′* -> *ts*)
**using** *e-type-comp-conc2*[*OF L0*(*3*)]
**by** *fastforce*
**obtain** *ts-c* **where** *ts′* = *ts-c* @ *tvs*
**using** *b-e-type-return*[*of* $\mathcal{C}$ *Return ts′ ts′′*] *L0*(*3*,*4*) *ts-def*(*2*) *unlift-b-e*
**by** *fastforce*
**then obtain** *vs1 vs2* **where** *vs-def*:$\mathcal{S}$·$\mathcal{C}$ ⊢ *vs1* : ([] -> *ts-c*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ *vs2* : (*ts-c* -> (*ts-c*@*tvs*))
*vs* = *vs1*@*vs2*
*const-list vs1*
*const-list vs2*
**using** *e-type-const-list-cons*[*OF L0*(*1*)] *ts-def*(*1*)
**by** *fastforce*
**hence** $\mathcal{S}$·$\mathcal{C}$ ⊢ *vs2* : ([] -> *tvs*)
**using** *e-type-const-list* **by** *blast*
**thus** *?case*
**using** *Lfilled.intros*(*1*)[*OF vs-def*(*4*), *of* - *es′ vs2*@[$*Return*]] *vs-def*(*3*,*5*)
**by** *fastforce*
**next**
**case** (*LN vs lholed n es′ l es′′ j lfilledk*)
**obtain** *t1s t2s* **where** *ts-def*:$\mathcal{S}$·$\mathcal{C}$ ⊢ *vs* : ([] -> *t1s*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ [*Label n es′ lfilledk*] : (*t1s* -> *t2s*)
$\mathcal{S}$·$\mathcal{C}$ ⊢ *es′′* : (*t2s* -> *ts*)

```
  using e-type-comp-conc2[OF LN(5)]
  by fastforce
  obtain ts' ts-l where ts-l-def:S·C⟦label := [ts'] @ label C⟧ ⊢ lfilledk : ([] -> ts-l)
    using e-type-label[OF ts-def(2)]
    by fastforce
  obtain lholed' vs' C' where lfilledk-def:Lfilled j lholed' (vs' @ [$Return]) lfilledk
                                        S·C' ⊢ vs' : ([] -> tvs)
                                        const-list vs'
    using LN(4)[OF ts-l-def] LN(6)
    by fastforce
  thus ?case
    using Lfilled.intros(2)[OF LN(1) - lfilledk-def(1)]
    by fastforce
qed

lemma progress-LN1:
  assumes (Lfilled j lholed [$Br (j+k)] es)
          S·C ⊢ es : (ts -> ts')
  shows length (label C) > k
  using assms
proof (induction [$Br (j+k)] es arbitrary: k C ts ts' rule: Lfilled.induct)
  case (L0 vs lholed es')
  obtain ts'' ts''' where ts-def:S·C ⊢ vs : (ts -> ts'')
                          S·C ⊢ [$Br k] : (ts'' -> ts''')
                          S·C ⊢ es' : (ts''' -> ts')
    using e-type-comp-conc2[OF L0(3)]
    by fastforce
  thus ?case
    using b-e-type-br(1)[of - Br k ts'' ts'''] unlift-b-e
    by fastforce
next
  case (LN vs lholed n es' l es'' k' lfilledk)
  obtain t1s t2s where ts-def:S·C ⊢ vs : (ts -> t1s)
                       S·C ⊢ [Label n es' lfilledk] : (t1s -> t2s)
                       S·C ⊢ es'' : (t2s -> ts')
  using e-type-comp-conc2[OF LN(5)]
  by fastforce
  obtain ts'' ts-l where ts-l-def:S·C⟦label := [ts''] @ label C⟧ ⊢ lfilledk : ([] -> ts-l)
    using e-type-label[OF ts-def(2)]
    by fastforce
  thus ?case
    using LN(4)[of 1+k]
    by fastforce
qed

lemma progress-LN2:
  assumes (Lfilled j lholed e1s lfilled)
  shows ∃ lfilled'. (Lfilled j lholed e2s lfilled')
  using assms
```

**proof** (*induction rule*: *Lfilled.induct*)
**case** (*L0 vs lholed es' es*)
**thus** *?case*
**using** *Lfilled.intros*(*1*)
**by** *fastforce*
**next**
**case** (*LN vs lholed n es' l es'' k es lfilledk*)
**thus** *?case*
**using** *Lfilled.intros*(*2*)
**by** *fastforce*
**qed**

**lemma** *const-of-const-list*:
**assumes** *length cs* = *1*
*const-list cs*
**shows** ∃ *v*. *cs* = [$*C v*]
**using** *e-type-const-unwrap assms*
**unfolding** *const-list-def list-all-length*
**by** (*metis append-butlast-last-id append-self-conv2 gr-zeroI last-conv-nth length-butlast length-greater-0-conv less-numeral-extra*(*1*,*4*) *zero-less-diff*)

**lemma** *const-of-i32*:
**assumes** *const-list cs*
*S*·*C* ⊢ *cs* : ([] -> [(*T-i32*)])
**shows** ∃ *c*. *cs* = [$*C ConstInt32 c*]
**proof** −
**obtain** *v* **where** *cs* = [$*C v*]
**using** *const-of-const-list assms*(*1*) *e-type-const-list*[*OF assms*]
**by** *fastforce*
**moreover**
**hence** *C* ⊢ [*C v*] : ([] -> [(*T-i32*)])
**using** *assms*(*2*) *unlift-b-e*
**by** *fastforce*
**hence** ∃ *c*. *v* = *ConstInt32 c*
**proof** (*induction* [*C v*] ([] -> [(*T-i32*)]) *rule*: *b-e-typing.induct*)
**case** (*const C*)
**then show** *?case*
**unfolding** *typeof-def*
**by** (*cases v*, *auto*)
**qed** *auto*
**ultimately**
**show** *?thesis*
**by** *fastforce*
**qed**

**lemma** *const-of-i64*:
**assumes** *const-list cs*
*S*·*C* ⊢ *cs* : ([] -> [(*T-i64*)])
**shows** ∃ *c*. *cs* = [$*C ConstInt64 c*]

```
proof −
  obtain v where cs = [$C v]
    using const-of-const-list assms(1) e-type-const-list[OF assms]
    by fastforce
  moreover
  hence C ⊢ [C v] : ([] -> [(T-i64)])
    using assms(2) unlift-b-e
    by fastforce
  hence ∃ c. v = ConstInt64 c
  proof (induction [C v] ([] -> [(T-i64)]) rule: b-e-typing.induct)
    case (const C)
    then show ?case
      unfolding typeof-def
      by (cases v, auto)
  qed auto
  ultimately
  show ?thesis
    by fastforce
qed

lemma const-of-f32:
  assumes const-list cs
          S·C ⊢ cs : ([] -> [T-f32])
  shows ∃ c. cs = [$C ConstFloat32 c]
proof −
  obtain v where cs = [$C v]
    using const-of-const-list assms(1) e-type-const-list[OF assms]
    by fastforce
  moreover
  hence C ⊢ [C v] : ([] -> [T-f32])
    using assms(2) unlift-b-e
    by fastforce
  hence ∃ c. v = ConstFloat32 c
  proof (induction [C v] ([] -> [T-f32]) rule: b-e-typing.induct)
    case (const C)
    then show ?case
      unfolding typeof-def
      by (cases v, auto)
  qed auto
  ultimately
  show ?thesis
    by fastforce
qed

lemma const-of-f64:
  assumes const-list cs
          S·C ⊢ cs : ([] -> [T-f64])
  shows ∃ c. cs = [$C ConstFloat64 c]
proof −
```

**obtain** $v$ **where** $cs = [\$C\ v]$
**using** *const-of-const-list assms(1) e-type-const-list*[*OF assms*]
**by** *fastforce*
**moreover**
**hence** $\mathcal{C} \vdash [C\ v] : ([] \text{ -> } [T\text{-}f64])$
**using** *assms(2) unlift-b-e*
**by** *fastforce*
**hence** $\exists c.\ v = ConstFloat64\ c$
**proof** (*induction* $[C\ v]$ $([] \text{ -> } [T\text{-}f64])$ *rule*: *b-e-typing.induct*)
**case** (*const* $\mathcal{C}$)
**then show** *?case*
**unfolding** *typeof-def*
**by** (*cases v*, *auto*)
**qed** *auto*
**ultimately**
**show** *?thesis*
**by** *fastforce*
**qed**

**lemma** *progress-unop-testop-i*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash cs : ([] \text{ -> } [t])$
*is-int-t t*
*const-list cs*
$e = Unop\text{-}i\ t\ iop \vee e = Testop\ t\ testop$
**shows** $\exists a\ s'\ vs'\ es'.\ (\!|s;vs;cs@([\$e])|\!) \rightsquigarrow\text{-}i\ (\!|s';vs';es'|\!)$
**using** *assms(2)*
**proof** (*cases t*)
**case** *T-i32*
**thus** *?thesis*
**using** *const-of-i32*[*OF assms(3)*] *assms*(1,4)
*reduce.intros*(1)[*OF reduce-simple.intros*(1)] *reduce.intros*(1)[*OF reduce-simple.intros*(13)]
**by** *fastforce*
**next**
**case** *T-i64*
**thus** *?thesis*
**using** *const-of-i64*[*OF assms(3)*] *assms*(1,4)
*reduce.intros*(1)[*OF reduce-simple.intros*(2)] *reduce.intros*(1)[*OF reduce-simple.intros*(14)]
**by** *fastforce*
**qed** (*simp-all add*: *is-int-t-def*)

**lemma** *progress-unop-f*:
**assumes** $\mathcal{S}{\cdot}\mathcal{C} \vdash cs : ([] \text{ -> } [t])$
*is-float-t t*
*const-list cs*
$e = Unop\text{-}f\ t\ iop$
**shows** $\exists a\ s'\ vs'\ es'.\ (\!|s;vs;cs@([\$e])|\!) \rightsquigarrow\text{-}i\ (\!|s';vs';es'|\!)$
**using** *assms(2)*

**proof** (*cases t*)
**case** *T-f32*
**thus** *?thesis*
**using** *const-of-f32*[*OF assms*(*3*)] *assms*(*1*,*4*)
*reduce.intros*(*1*)[*OF reduce-simple.intros*(*3*)] *reduce.intros*(*1*)[*OF reduce-simple.intros*(*13*)]
**by** *fastforce*
**next**
**case** *T-f64*
**thus** *?thesis*
**using** *const-of-f64*[*OF assms*(*3*)] *assms*(*1*,*4*)
*reduce.intros*(*1*)[*OF reduce-simple.intros*(*4*)] *reduce.intros*(*1*)[*OF reduce-simple.intros*(*14*)]
**by** *fastforce*
**qed** (*simp-all add*: *is-float-t-def*)

**lemma** *const-list-split-2*:
**assumes** *const-list cs*
$\mathcal{S}{\cdot}\mathcal{C} \vdash cs : ([] \to [t1, t2])$
**shows** $\exists\, c1\ c2.\ (\mathcal{S}{\cdot}\mathcal{C} \vdash [c1] : ([] \to [t1]))$
$\wedge\ (\mathcal{S}{\cdot}\mathcal{C} \vdash [c2] : ([] \to [t2]))$
$\wedge\ cs = [c1, c2]$
$\wedge$ *const-list* $[c1]$
$\wedge$ *const-list* $[c2]$
**proof** −
**have** *l-cs*:*length cs* = *2*
**using** *assms e-type-const-list*[*OF assms*]
**by** *simp*
**then obtain** *c1 c2* **where** *cs*!*0* = *c1 cs*!*1* = *c2*
**by** *fastforce*
**hence** *cs* = [*c1*] @ [*c2*]
**using** *assms e-type-const-conv-vs typing-map-typeof*
**by** *fastforce*
**thus** *?thesis*
**using** *assms e-type-comp*[*of* $\mathcal{S}$ $\mathcal{C}$ [*c1*] *c2*] *e-type-const*[*of c2* $\mathcal{S}$ $\mathcal{C}$ - [*t1*,*t2*]]
**unfolding** *const-list-def*
**by** *fastforce*
**qed**

**lemma** *const-list-split-3*:
**assumes** *const-list cs*
$\mathcal{S}{\cdot}\mathcal{C} \vdash cs : ([] \to [t1, t2, t3])$
**shows** $\exists\, c1\ c2\ c3.\ (\mathcal{S}{\cdot}\mathcal{C} \vdash [c1] : ([] \to [t1]))$
$\wedge\ (\mathcal{S}{\cdot}\mathcal{C} \vdash [c2] : ([] \to [t2]))$
$\wedge\ (\mathcal{S}{\cdot}\mathcal{C} \vdash [c3] : ([] \to [t3]))$
$\wedge\ cs = [c1, c2, c3]$
**proof** −
**have** *l-cs*:*length cs* = *3*
**using** *assms e-type-const-list*[*OF assms*]

```
    by simp
  then obtain c1 c2 c3 where cs!0 = c1 cs!1 = c2 cs!2 = c3
    by fastforce
  hence cs = [c1] @ [c2] @ [c3]
    using assms e-type-const-conv-vs typing-map-typeof
    by fastforce
  thus ?thesis
    using assms e-type-comp-conc2[of 𝒮 𝒞 [c1] [c2] [c3] [] [t1,t2,t3]]
          e-type-const[of c1] e-type-const[of c2] e-type-const[of c3]
    unfolding const-list-def
    by fastforce
qed

lemma progress-binop-relop-i:
  assumes 𝒮·𝒞 ⊢ cs : ([] -> [t, t])
          is-int-t t
          const-list cs
          e = Binop-i t iop ∨ e = Relop-i t irop
  shows ∃ a s' vs' es'. (|s;vs;cs@([$e])|) ↪-i (|s';vs';es'|)
  using assms(2)
proof (cases t)
  case (T-i32)
  hence cs-def:∃ c1 c2. cs = [$C ConstInt32 c1,$C ConstInt32 c2]
    using const-list-split-2[OF assms(3,1)] assms(3) const-of-i32
    unfolding const-list-def
    by blast
  show ?thesis
  proof (cases e = Binop-i t iop)
    case True
    obtain c1 c2 where cs = [$C ConstInt32 c1,$C ConstInt32 c2]
      using cs-def
      by blast
    thus ?thesis
      apply (cases app-binop-i iop c1 c2)
     apply (metis reduce-simple.intros(6) reduce.intros(1) T-i32 True append-Cons
append-Nil)
     apply (metis reduce-simple.intros(5) reduce.intros(1) T-i32 True append-Cons
append-Nil)
      done
  next
    case False
    thus ?thesis
    using reduce-simple.intros(15) assms(4) reduce.intros(1) cs-def T-i32
    by fastforce
  qed
next
  case (T-i64)
  hence cs-def:∃ c1 c2. cs = [$C ConstInt64 c1,$C ConstInt64 c2]
    using const-list-split-2[OF assms(3,1)] assms(3) const-of-i64
```

```
    unfolding const-list-def
    by blast
  show ?thesis
  proof (cases e = Binop-i t iop)
    case True
    obtain c1 c2 where cs = [$C ConstInt64 c1,$C ConstInt64 c2]
      using cs-def
      by blast
    thus ?thesis
      apply (cases app-binop-i iop c1 c2)
     apply (metis reduce-simple.intros(8) reduce.intros(1) T-i64 True append-Cons
append-Nil)
     apply (metis reduce-simple.intros(7) reduce.intros(1) T-i64 True append-Cons
append-Nil)
      done
  next
    case False
    thus ?thesis
    using reduce-simple.intros(16) assms(4) reduce.intros(1) cs-def T-i64
    by fastforce
  qed
qed (simp-all add: is-int-t-def)

lemma progress-binop-relop-f:
  assumes S·C ⊢ cs : ([] -> [t, t])
          is-float-t t
          const-list cs
          e = Binop-f t fop ∨ e = Relop-f t frop
  shows ∃ a s' vs' es'. (|s;vs;cs@([$e])|) ↪-i (|s';vs';es'|)
  using assms(2)
proof (cases t)
  case T-f32
  hence cs-def:∃ c1 c2. cs = [$C ConstFloat32 c1,$C ConstFloat32 c2]
    using const-list-split-2[OF assms(3,1)] assms(3) const-of-f32
    unfolding const-list-def
    by blast
  show ?thesis
  proof (cases e = Binop-f t fop)
    case True
    obtain c1 c2 where cs-def:cs = [$C ConstFloat32 c1,$C ConstFloat32 c2]
      using cs-def
      by blast
    thus ?thesis
      apply (cases app-binop-f fop c1 c2)
          apply (metis reduce-simple.intros(10) reduce.intros(1) T-f32 True ap-
pend-Cons append-Nil)
     apply (metis reduce-simple.intros(9) reduce.intros(1) T-f32 True append-Cons
append-Nil)
    done
```

```
  next
    case False
    thus ?thesis
    using reduce-simple.intros(17) assms(4) reduce.intros(1) cs-def T-f32
    by fastforce
  qed
next
  case T-f64
  hence cs-def:∃ c1 c2. cs = [$C ConstFloat64 c1,$C ConstFloat64 c2]
    using const-list-split-2[OF assms(3,1)] assms(3) const-of-f64
    unfolding const-list-def
    by blast
  show ?thesis
  proof (cases e = Binop-f t fop)
    case True
    obtain c1 c2 where cs = [$C ConstFloat64 c1,$C ConstFloat64 c2]
      using cs-def
      by blast
    thus ?thesis
      apply (cases app-binop-f fop c1 c2)
          apply (metis reduce-simple.intros(12) reduce.intros(1) T-f64 True ap-
pend-Cons append-Nil)
     apply (metis reduce-simple.intros(11) reduce.intros(1) T-f64 True append-Cons
append-Nil)
     done
  next
    case False
    thus ?thesis
      using reduce-simple.intros(18) assms(4) reduce.intros(1) cs-def T-f64
    by fastforce
  qed
qed (simp-all add: is-float-t-def)

lemma progress-b-e:
  assumes C ⊢ b-es : (ts -> ts')
          S·C ⊢ cs : ([] -> ts)
          (⋀lholed. ¬(Lfilled 0 lholed [$Return] (cs@($∗b-es))))
          ⋀ i lholed. ¬(Lfilled 0 lholed [$Br (i)] (cs@($∗b-es)))
          const-list cs
          ¬ const-list ($∗ b-es)
          i < length (s-inst S)
          length (local C) = length (vs)
          Option.is-none (memory C) = Option.is-none (inst.mem ((inst s)!i))
  shows ∃ a s' vs' es'. (|s;vs;cs@($∗b-es)|) ↝-i (|s';vs';es'|)
  using assms
proof (induction b-es (ts -> ts') arbitrary: ts ts' cs rule: b-e-typing.induct)
  case (const C v)
  then show ?case
    unfolding const-list-def is-const-def
```

```
    by simp
next
  case (unop-i t C uu)
  thus ?case
    using progress-unop-testop-i[OF unop-i(2,1)]
    by fastforce
next
  case (unop-f t C uv)
  thus ?case
    using progress-unop-f[OF unop-f(2,1,5)]
    by fastforce
next
  case (binop-i t C uw)
  thus ?case
    using progress-binop-relop-i[OF binop-i(2,1)]
    by fastforce
next
  case (binop-f t C ux)
  thus ?case
    using progress-binop-relop-f[OF binop-f(2,1,5)]
    by fastforce
next
  case (testop t C uy)
  thus ?case
    using progress-unop-testop-i[OF testop(2,1)]
    by fastforce
next
  case (relop-i t C uz)
  thus ?case
    using progress-binop-relop-i[OF relop-i(2,1)]
    by fastforce
next
  case (relop-f t C va)
  thus ?case
    using progress-binop-relop-f[OF relop-f(2,1,5)]
    by fastforce
next
  case (convert t1 t2 sx C)
  obtain v where cs-def:cs = [$ C v] typeof v = t2
   using const-typeof const-of-const-list[OF - convert(6)] e-type-const-list[OF con-
vert(6,3)]
    by fastforce
  thus ?case
  proof (cases cvt t1 sx v)
    case None
    thus ?thesis
      using reduce.intros(1)[OF reduce-simple.convert-None[OF - None]] cs-def
      unfolding types-agree-def
      by fastforce
```

```
  next
    case (Some a)
    thus ?thesis
      using reduce.intros(1)[OF reduce-simple.convert-Some[OF - Some]] cs-def
      unfolding types-agree-def
      by fastforce
  qed
next
  case (reinterpret t1 t2 C)
  obtain v where cs-def:cs = [$ C v] typeof v = t2
    using const-typeof const-of-const-list[OF - reinterpret(6)] e-type-const-list[OF
reinterpret(6,3)]
    by fastforce
  thus ?case
    using reduce.intros(1)[OF reduce-simple.reinterpret]
    unfolding types-agree-def
    by fastforce
next
  case (unreachable C ts ts')
  thus ?case
   using reduce.intros(1)[OF reduce-simple.unreachable] progress-L0[OF - unreach-
able(4)]
    by fastforce
next
  case (nop C)
  thus ?case
    using reduce.intros(1)[OF reduce-simple.nop] progress-L0[OF - nop(4)]
    by fastforce
next
  case (drop C t)
  obtain v where cs = [$C v]
    using const-of-const-list drop(4) e-type-const-list[OF drop(4,1)]
    by fastforce
  thus ?case
    using reduce.intros(1)[OF reduce-simple.drop] progress-L0[OF - drop(4)]
    by fastforce
next
  case (select C t)
  obtain v1 v2 v3 where cs-def:S·C ⊢ [$ C v3] : ([] -> [T-i32])
                        cs = [$C v1, $C v2, $ C v3]
    using const-list-split-3[OF select(4,1)] select(4)
    unfolding const-list-def
    by (metis list-all-simps(1) e-type-const-unwrap)
  obtain c3 where c-def:v3 = ConstInt32 c3
    using cs-def select(4) const-of-i32[OF - cs-def(1)]
    unfolding const-list-def
    by fastforce
   have ∃ a s' vs' es'. (|s;vs;[$C v1, $C v2, $ C ConstInt32 c3, $Select]|) ↝-i
(|s';vs';es'|)
```

```
  proof (cases int-eq c3 0)
    case True
    thus ?thesis
      using reduce.intros(1)[OF reduce-simple.select-false]
      by fastforce
  next
    case False
    thus ?thesis
      using reduce.intros(1)[OF reduce-simple.select-true]
      by fastforce
  qed
  thus ?case
    using c-def cs-def
    by fastforce
next
  case (block tf tn tm C es)
  show ?case
    using reduce-simple.block[OF block(7), of - tn tm - es]
          e-type-const-list[OF block(7,4)] reduce.intros(1) block(1)
    by fastforce
next
  case (loop tf tn tm C es)
  show ?case
    using reduce-simple.loop[OF loop(7), of - tn tm - es]
          e-type-const-list[OF loop(7,4)] reduce.intros(1) loop(1)
    by fastforce
next
  case (if-wasm tf tn tm C es1 es2)
  obtain c1s c2s where cs-def:S·C ⊢ c1s : ([] -> tn)
                       S·C ⊢ c2s : ([] -> [T-i32])
                       const-list c1s
                       const-list c2s
                       cs = c1s @ c2s
    using e-type-const-list-cons[OF if-wasm(9,6)] e-type-const-list
    by fastforce
  obtain c where c-def: c2s = [$ C (ConstInt32 c)]
    using const-of-i32 cs-def
    by fastforce
  have ∃ a s' vs' es'. (|s;vs;[$ C (ConstInt32 c), $ If tf es1 es2]|) ↝-i (|s';vs';es'|)
  proof (cases int-eq c 0)
    case True
    thus ?thesis
      using reduce.intros(1)[OF reduce-simple.if-false]
      by fastforce
  next
    case False
    thus ?thesis
      using reduce.intros(1)[OF reduce-simple.if-true]
      by fastforce
```

```
  qed
  thus ?case
    using c-def cs-def progress-L0
    by fastforce
next
  case (br i C ts t1s t2s)
  thus ?case
    using Lfilled.intros(1)[OF br(6), of - [] [$Br i]]
    by fastforce
next
  case (br-if j C ts)
  obtain cs1 cs2 where cs-def:S·C ⊢ cs1 : ([] -> ts)
                       S·C ⊢ cs2 : ([] -> [T-i32])
                       const-list cs1
                       const-list cs2
                       cs = cs1 @ cs2
    using e-type-const-list-cons[OF br-if(6,3)] e-type-const-list
    by fastforce
  obtain c where c-def:cs2 = [$C ConstInt32 c]
    using const-of-i32[OF cs-def(4,2)]
    by blast
  have ∃ a s' vs' es'. (|s;vs;cs2@($* [Br-if j])|) ↝-i (|s';vs';es'|)
  proof (cases int-eq c 0)
    case True
    thus ?thesis
      using c-def reduce.intros(1)[OF reduce-simple.br-if-false]
      by fastforce
  next
    case False
    thus ?thesis
      using c-def reduce.intros(1)[OF reduce-simple.br-if-true]
      by fastforce
  qed
  thus ?case
    using cs-def(5) progress-L0[OF - cs-def(3), of s vs cs2 @ ($* [Br-if j]) - - - -
[]]
    by fastforce
next
  case (br-table C ts is i' t1s t2s)
  obtain cs1 cs2 where cs-def:S·C ⊢ cs1 : ([]-> (t1s @ ts))
                       S·C ⊢ cs2 : ([] -> [T-i32])
                       const-list cs1
                       const-list cs2
                       cs = cs1 @ cs2
    using e-type-const-list-cons[OF br-table(5), of S C (t1s @ ts) [T-i32]]
          e-type-const-list[of - S C t1s @ ts (t1s @ ts) @ [T-i32]]
          br-table(2,5)
    unfolding const-list-def
    by fastforce
```

```
  obtain c where c-def:cs2 = [$C ConstInt32 c]
    using const-of-i32[OF cs-def(4,2)]
    by blast
  have ∃ a s' vs' es'. (|s;vs;[$C ConstInt32 c, $Br-table is i']|) ↪-i (|s';vs';es'|)
  proof (cases (nat-of-int c) < length is)
    case True
    show ?thesis
      using reduce.intros(1)[OF reduce-simple.br-table[OF True]]
      by fastforce
  next
    case False
    hence length is ≤ nat-of-int c
      by fastforce
    thus ?thesis
      using reduce.intros(1)[OF reduce-simple.br-table-length]
      by fastforce
  qed
  thus ?case
    using c-def cs-def progress-L0
    by fastforce
next
  case (return C ts t1s t2s)
  thus ?case
    using Lfilled.intros(1)[OF return(5), of - [] [$Return]]
    by fastforce
next
  case (call j C)
  show ?case
    using progress-L0[OF reduce.intros(2) call(6)]
    by fastforce
next
  case (call-indirect j C t1s t2s)
  obtain cs1 cs2 where cs-def:S·C ⊢ cs1 : ([]-> t1s)
                       S·C ⊢ cs2 : ([] -> [T-i32])
                       const-list cs1
                       const-list cs2
                       cs = cs1 @ cs2
    using e-type-const-list-cons[OF call-indirect(7), of S C t1s [T-i32]]
          e-type-const-list[of - S C t1s t1s @ [T-i32]]
          call-indirect(4)
    by fastforce
  obtain c where c-def:cs2 = [$C ConstInt32 c]
    using cs-def(2,4) const-of-i32
    by fastforce
  consider
    (1) ∃ cl tf. stab s i (nat-of-int c) = Some cl ∧ stypes s i j = tf ∧ cl-type cl = tf
  | (2) ∃ cl. stab s i (nat-of-int c) = Some cl ∧ stypes s i j ≠ cl-type cl
  | (3) stab s i (nat-of-int c) = None
    by (metis option.collapse)
```

```
  hence ∃ a s' vs' es'. (|s;vs;[$C ConstInt32 c, $Call-indirect j]|) ↝-i (|s';vs';es'|)
  proof (cases)
    case 1
    thus ?thesis
      using reduce.intros(3)
      by blast
  next
    case 2
    thus ?thesis
      using reduce.intros(4)
      by blast
  next
    case 3
    thus ?thesis
      using reduce.intros(4)
      by blast
  qed
  then show ?case
    using c-def cs-def progress-L0
    by fastforce
next
  case (get-local j C t)
  obtain v vj vj' where v-def:v = vs ! j vj = (take j vs) vj' = (drop (j+1) vs)
    by blast
  have j-def:j < length vs
    using get-local(1,9)
    by simp
  hence vj-len:length vj = j
    using v-def(2)
    by fastforce
  hence vs = vj @ [v] @ vj'
    using v-def id-take-nth-drop j-def
    by fastforce
  thus ?case
    using progress-L0[OF reduce.intros(8)[OF vj-len, of s v vj'] get-local(6)]
    by fastforce
next
  case (set-local j C t)
  obtain v vj vj' where v-def:v = vs ! j vj = (take j vs) vj' = (drop (j+1) vs)
    by blast
  obtain v' where cs-def: cs = [$C v']
    using const-of-const-list set-local(3,6) e-type-const-list
    by fastforce
  have j-def:j < length vs
    using set-local(1,9)
    by simp
  hence vj-len:length vj = j
    using v-def(2)
    by fastforce
```

```
  hence vs = vj @ [v] @ vj'
    using v-def id-take-nth-drop j-def
    by fastforce
  thus ?case
    using reduce.intros(9)[OF vj-len, of s v vj' v' i] cs-def
    by fastforce
next
  case (tee-local i C t)
  obtain v where cs = [$C v]
    using const-of-const-list tee-local(3,6) e-type-const-list
    by fastforce
  thus ?case
    using reduce.intros(1)[OF reduce-simple.tee-local] tee-local(6)
    unfolding const-list-def
    by fastforce
next
  case (get-global j C t)
  thus ?case
    using reduce.intros(10)[of s vs j i] progress-L0
    by fastforce
next
  case (set-global j C t)
  obtain v where cs = [$C v]
    using const-of-const-list set-global(4,7) e-type-const-list
    by fastforce
  thus ?case
    using reduce.intros(11)[of s i j v - vs]
    by fastforce
next
  case (load C n a tp-sx t off)
  obtain c where c-def: cs = [$C ConstInt32 c]
    using const-of-i32 load(3,6) e-type-const-unwrap
    unfolding const-list-def
    by fastforce
  obtain j where mem-some:smem-ind s i = Some j
    using load(1,10)
    unfolding smem-ind-def
    by fastforce
  have ∃ a' s' vs' es'. (|s;vs;[$C ConstInt32 c, $Load t tp-sx a off]|) ↪-i (|s';vs';es'|)
  proof (cases tp-sx)
    case None
    note tp-none = None
    show ?thesis
    proof (cases load ((mem s)!j) (nat-of-int c) off (t-length t))
      case None
      show ?thesis
        using reduce.intros(13)[OF mem-some - None, of vs] tp-none load(2)
        by fastforce
    next
```

```
      case (Some a)
      show ?thesis
        using reduce.intros(12)[OF mem-some - Some, of vs] tp-none load(2)
        by fastforce
    qed
  next
    case (Some a)
    obtain tp sx where tp-some:tp-sx = Some (tp, sx)
      using Some
      by fastforce
    show ?thesis
   proof (cases load-packed sx ((mem s)!j) (nat-of-int c) off (tp-length tp) (t-length
t))
      case None
      show ?thesis
        using reduce.intros(15)[OF mem-some - None, of vs] tp-some load(2)
        by fastforce
    next
      case (Some a)
      show ?thesis
        using reduce.intros(14)[OF mem-some - Some, of vs] tp-some load(2)
        by fastforce
    qed
  qed
  then show ?case
    using c-def progress-L0
    by fastforce
next
  case (store C n a tp t off)
  obtain cs' v where cs-def:S·C ⊢ [cs'] : ([] -> [T-i32])
                     S·C ⊢ [$ C v] : ([] -> [t])
                     cs = [cs',$ C v]
    using const-list-split-2[OF store(6,3)] e-type-const-unwrap
    unfolding const-list-def
    by fastforce
  have t-def:typeof v = t
    using cs-def(2) b-e-type-value[OF unlift-b-e[of S C [C v] ([] -> [t])]]
    by fastforce
  obtain j where mem-some:smem-ind s i = Some j
    using store(1,10)
    unfolding smem-ind-def
    by fastforce
  obtain c where c-def:cs' = $C ConstInt32 c
    using const-of-i32[OF - cs-def(1)] cs-def(3) store(6)
    unfolding const-list-def
    by fastforce
   have ∃a' s' vs' es'. (|s;vs;[$C ConstInt32 c, $C v, $Store t tp a off]|) ↪-i
(|s';vs';es'|)
  proof (cases tp)
```

```
    case None
    note tp-none = None
    show ?thesis
    proof (cases store (s.mem s ! j) (nat-of-int c) off (bits v) (t-length t))
      case None
      show ?thesis
       using reduce.intros(17)[OF - mem-some - None, of vs] t-def tp-none store(2)
        unfolding types-agree-def
        by fastforce
    next
      case (Some a)
      show ?thesis
       using reduce.intros(16)[OF - mem-some - Some, of vs] t-def tp-none store(2)
        unfolding types-agree-def
        by fastforce
    qed
  next
    case (Some a)
    note tp-some = Some
    show ?thesis
    proof (cases store-packed (s.mem s ! j) (nat-of-int c) off (bits v) (tp-length a))
      case None
      show ?thesis
          using reduce.intros(19)[OF - mem-some - None, of t vs] t-def tp-some
store(2)
        unfolding types-agree-def
        by fastforce
    next
      case (Some a)
      show ?thesis
          using reduce.intros(18)[OF - mem-some - Some, of t vs] t-def tp-some
store(2)
        unfolding types-agree-def
        by fastforce
    qed
  qed
  then show ?case
    using c-def cs-def progress-L0
    by fastforce
next
  case (current-memory C n)
  obtain j where mem-some:smem-ind s i = Some j
    using current-memory(1,9)
    unfolding smem-ind-def
    by fastforce
  thus ?case
    using progress-L0[OF reduce.intros(20)[OF mem-some] current-memory(5), of
- - vs []]
    by fastforce
```

```
next
  case (grow-memory C n)
  obtain c where c-def:cs = [$C ConstInt32 c]
    using const-of-i32 grow-memory(2,5)
    by fastforce
  obtain j where mem-some:smem-ind s i = Some j
    using grow-memory(1,9)
    unfolding smem-ind-def
    by fastforce
  show ?case
    using reduce.intros(22)[OF mem-some, of -] c-def
    by fastforce
next
  case (empty C)
  thus ?case
    unfolding const-list-def
    by simp
next
  case (composition C es t1s t2s e t3s)
  consider (1) ¬ const-list ($* es) | (2) const-list ($* es) ¬ const-list ($*[e])
    using composition(9)
    unfolding const-list-def
    by fastforce
  thus ?case
  proof (cases)
    case 1
    have (⋀lholed. ¬ Lfilled 0 lholed [$Return] (cs @ ($* es)))
         (⋀i lholed. ¬ Lfilled 0 lholed [$Br i] (cs @ ($* es)))
    proof safe
      fix lholed
      assume Lfilled 0 lholed [$Return] (cs @ ($* es))
      hence ∃lholed'. Lfilled 0 lholed' [$Return] (cs @ ($* es @ [e]))
      proof (cases rule: Lfilled.cases)
        case (L0 vs es')
        thus ?thesis
          using Lfilled.intros(1)[of vs - es'@ ($*[e]) [$Return]]
          by (metis append.assoc map-append)
      qed simp
      thus False
        using composition(6)
        by simp
    next
      fix i lholed
      assume Lfilled 0 lholed [$Br i] (cs @ ($* es))
      hence ∃lholed'. Lfilled 0 lholed' [$Br i] (cs @ ($* es @ [e]))
      proof (cases rule: Lfilled.cases)
        case (L0 vs es')
        thus ?thesis
          using Lfilled.intros(1)[of vs - es'@ ($*[e]) [$Br i]]
```

```
        by (metis append.assoc map-append)
      qed simp
      thus False
        using composition(7)
        by simp
    qed
    thus ?thesis
        using composition(2)[OF composition(5) - - composition(8) 1 composi-
tion(10,11,12)] progress-L0[of s vs (cs @ ($* es)) i - - - [] $*[e]]
      unfolding const-list-def
      by fastforce
  next
    case 2
    hence const-list (cs@($* es))
      using composition(8)
      unfolding const-list-def
      by simp
    moreover
    have S·C ⊢ (cs@($* es)) : ([] -> t2s)
    using composition(5) e-typing-s-typing.intros(1)[OF composition(1)] e-type-comp-conc
      by fastforce
    ultimately
    show ?thesis
    using composition(4)[of (cs@($* es))] 2(2) composition(6,7) composition(10−)
      by fastforce
  qed
next
  case (weakening C es t1s t2s ts)
  obtain cs1 cs2 where cs-def:S·C ⊢ cs1 : ([] -> ts)
                       S·C ⊢ cs2 : ([] -> t1s)
                       cs = cs1 @ cs2
                       const-list cs1
                       const-list cs2
    using e-type-const-list-cons[OF weakening(6,3)] e-type-const-list[of - S C ts ts
@ t1s]
    by fastforce
  have (⋀lholed. ¬ Lfilled 0 lholed [$Return] (cs2 @ ($* es)))
       (⋀i lholed. ¬ Lfilled 0 lholed [$Br i] (cs2 @ ($* es)))
  proof safe
    fix lholed
    assume Lfilled 0 lholed [$Return] (cs2 @ ($* es))
    hence ∃ lholed'. Lfilled 0 lholed' [$Return] (cs1 @ cs2 @ ($* es))
    proof (cases rule: Lfilled.cases)
      case (L0 vs es')
      thus ?thesis
        using Lfilled.intros(1)[of cs1 @ vs - es' [$Return]] cs-def(4)
        unfolding const-list-def
        by fastforce
    qed simp
```

```
    thus False
      using weakening(4) cs-def(3)
      by simp
  next
    fix i lholed
    assume Lfilled 0 lholed [$Br i] (cs2 @ ($* es))
    hence ∃ lholed'. Lfilled 0 lholed' [$Br i] (cs1 @ cs2 @ ($* es))
    proof (cases rule: Lfilled.cases)
      case (L0 vs es')
      thus ?thesis
        using Lfilled.intros(1)[of cs1 @ vs - es' [$Br i]] cs-def(4)
        unfolding const-list-def
        by fastforce
    qed simp
    thus False
      using weakening(5) cs-def(3)
      by simp
  qed
  hence ∃ a s' vs' es'. (|s;vs;cs2@($*es)|) ↪-i (|s';vs';es'|)
    using weakening(2)[OF cs-def(2) - - cs-def(5) weakening(7)] weakening(8−)
    by fastforce
  thus ?case
    using progress-L0[OF - cs-def(4), of s vs cs2 @ ($* es) i - - - []] cs-def(3)
    by fastforce
qed

lemma progress-e:
  assumes S·None ⊩-i vs;cs-es : ts'
          ⋀ k lholed. ¬(Lfilled k lholed [$Return] cs-es)
          ⋀ i k lholed. (Lfilled k lholed [$Br (i)] cs-es) ⟹ i < k
          cs-es ≠ [Trap]
          ¬ const-list (cs-es)
          store-typing s S
  shows ∃ a s' vs' es'. (|s;vs;cs-es|) ↪-i (|s';vs';es'|)
proof −
  fix C cs es ts-c
  have prems1:
      S·C ⊢ es : (ts-c -> ts') ⟹
       S·C ⊢ cs-es : ([] -> ts') ⟹
       cs-es = cs@es ⟹
       const-list cs ⟹
       S·C ⊢ cs : ([] -> ts-c) ⟹
       (⋀ k lholed. ¬(Lfilled k lholed [$Return] cs-es)) ⟹
       (⋀ i k lholed. (Lfilled k lholed [$Br (i)] cs-es) ⟹ i < k) ⟹
       cs-es ≠ [Trap] ⟹
       ¬ const-list (cs-es) ⟹
       store-typing s S ⟹
       i < length (s-inst S) ⟹
       length (local C) = length (vs) ⟹
```

```
    Option.is-none (memory C) = Option.is-none (inst.mem ((inst s)!i)) ⟹
      ∃ a s' vs' cs-es'. (|s;vs;cs-es|) ↝-i (|s';vs';cs-es'|)
 and prems2:
    S·None ⊩-i vs;cs-es : ts' ⟹
    (⋀ k lholed. ¬(Lfilled k lholed [$Return] cs-es)) ⟹
    (⋀ i k lholed. (Lfilled k lholed [$Br (i)] cs-es) ⟹ i < k) ⟹
    cs-es ≠ [Trap] ⟹
    ¬ const-list (cs-es) ⟹
    store-typing s S ⟹
      ∃ a s' vs' cs-es'. (|s;vs;cs-es|) ↝-i (|s';vs';cs-es'|)
proof (induction arbitrary: vs ts-c ts' i cs-es cs rule: e-typing-s-typing.inducts)
  case (1 C b-es tf S)
  hence C ⊢ b-es : (ts-c -> ts')
    using e-type-comp-conc1[of S C cs ($* b-es) [] ts'] unlift-b-e
    by (metis e-type-const-conv-vs typing-map-typeof)
  then show ?case
    using progress-b-e[OF - 1(5) - - 1(4)] 1(3,4,9) list-all-append 1
    unfolding const-list-def
    by fastforce
next
  case (2 S C es t1s t2s e t3s)
  show ?case
  proof (cases const-list es)
    case True
    hence const-list (cs@es)
      using 2(7)
      unfolding const-list-def
      by simp
    moreover
    have ∃ ts''. (S·C ⊢ (cs @ es) : ([] -> ts''))
      using 2(5,6)
      by (metis append.assoc e-type-comp-conc1)
    ultimately
    show ?thesis
      using 2(4)[OF 2(5) - - - 2(9,10,11,12,13,14,15), of (cs@es)] 2(6,16)
      by fastforce
  next
    case False
    hence ¬const-list (cs@es)
      unfolding const-list-def
      by simp
    moreover
    have ∃ ts''. (S·C ⊢ (cs @ es) : ([] -> ts''))
      using 2(5,6)
      by (metis append.assoc e-type-comp-conc1)
    moreover
    have ⋀k lholed. ¬ Lfilled k lholed [$Return] (cs @ es)
    proof −
      {
```

```
      assume ∃k lholed. Lfilled k lholed [$Return] (cs @ es)
       then obtain k lholed where local-assms:Lfilled k lholed [$Return] (cs @
es)
        by blast
      hence ∃lholed'. Lfilled k lholed' [$Return] (cs @ es @ [e])
      proof (cases rule: Lfilled.cases)
        case (L0 vs es')
        obtain lholed' where lholed' = LBase vs (es'@[e])
          by blast
        thus ?thesis
          using L0
          by (metis Lfilled.intros(1) append.assoc)
      next
        case (LN vs ts es' l es'' k lfilledk)
        obtain lholed' where lholed' = LRec vs ts es' l (es''@[e])
          by blast
        thus ?thesis
          using LN
          by (metis Lfilled.intros(2) append.assoc)
      qed
      hence False
        using 2(6,9)
        by blast
    }
    thus ⋀k lholed. ¬ Lfilled k lholed [$Return] (cs @ es)
      by blast
  qed
  moreover
  have ⋀i k lholed.  Lfilled k lholed [$Br i] (cs @ es) ⟹ i < k
  proof −
    {
      assume ∃i k lholed.  Lfilled k lholed [$Br i] (cs @ es) ∧ ¬(i < k)
       then obtain i k lholed where local-assms:Lfilled k lholed [$Br i] (cs @
es) ¬(i < k)
        by blast
      hence ∃lholed'.  Lfilled k lholed' [$Br i] (cs @ es @ [e]) ∧ ¬(i < k)
      proof (cases rule: Lfilled.cases)
        case (L0 vs es')
        obtain lholed' where lholed' = LBase vs (es'@[e])
          by blast
        thus ?thesis
          using L0 local-assms(2)
          by (metis Lfilled.intros(1) append.assoc)
      next
        case (LN vs ts es' l es'' k lfilledk)
        obtain lholed' where lholed' = LRec vs ts es' l (es''@[e])
          by blast
        thus ?thesis
          using LN local-assms(2)
```

```
        by (metis Lfilled.intros(2) append.assoc)
      qed
      hence False
        using 2(6,10)
        by blast
    }
    thus ⋀i k lholed. Lfilled k lholed [$Br i] (cs @ es) ⟹ i < k
      by blast
  qed
  moreover
  note preds = calculation
  show ?thesis
  proof (cases cs @ es = [Trap])
    case True
    thus ?thesis
      using reduce-simple.trap[of - (LBase [] [e])]
            Lfilled.intros(1)[of [] LBase [] [e] [e] cs @ es]
            reduce.intros(1) 2(6,11)
      unfolding const-list-def
      by (metis append.assoc append-Nil list.pred-inject(1))
  next
    case False
    thus ?thesis
      using 2(3)[OF - - 2(7,8) - - - -  2(13,14,15)] preds 2(6,16)
            progress-L0[of s vs (cs @ es) - - - - [] [e]]
      unfolding const-list-def
      by (metis append.assoc append-Nil list.pred-inject(1))
  qed
 qed
next
 case (3 S C es t1s t2s ts)
 thus ?case
   by fastforce
next
 case (4 S C)
 have cs-es-def:Lfilled 0 (LBase cs []) [Trap] cs-es
   using Lfilled.intros(1)[OF 4(3), of - [] [Trap]] 4(2)
   by fastforce
 thus ?case
   using reduce-simple.trap[OF 4(7) cs-es-def] reduce.intros(1)
   by blast
next
case (5 S ts j vls es n C)
 consider (1) (⋀k lholed. ¬ Lfilled k lholed [$Return] es)
            (⋀k lholed i. (Lfilled k lholed [$Br i] es) ⟹ i < k)
            es ≠ [Trap]
            ¬ const-list es
        | (2) ∃k lholed. Lfilled k lholed [$Return] es
        | (3) const-list es ∨ (es = [Trap])
```

```
        | (4) ∃ k lholed i. (Lfilled k lholed [$Br i] es) ∧ i ≥ k
    using not-le-imp-less
    by blast
  thus ?case
  proof (cases)
    case 1
    obtain s' vs'' a where temp1:(|s;vls;es|) ↝- j (|s';vs'';a|)
      using 5(3)[OF 1(1) - 1(3,4) 5(12)] 1(2)
      by fastforce
    show ?thesis
      using reduce.intros(24)[OF temp1, of vs] progress-L0[where ?cs = cs, OF
- 5(6)] 5(5)
      by fastforce
  next
    case 2
    then obtain k lholed where local-assms:(Lfilled k lholed [$Return] es)
      by blast
   then obtain lholed' vs' C' where lholed'-def:(Lfilled k lholed' (vs'@[$Return])
es)
                                                  S·C' ⊢ vs' : ([] -> ts)
                                                  const-list vs'
      using progress-LN-return[OF local-assms, of S - ts ts] s-type-unfold[OF
5(1)]
      by fastforce
    hence temp1:∃ a. (|[Local n j vls es]|) ↝ (|vs'|)
      using reduce-simple.return[OF lholed'-def(3)]
            e-type-const-list[OF lholed'-def(3,2)] 5(2)
      by fastforce
    show ?thesis
      using temp1 progress-L0[OF reduce.intros(1) 5(6)] 5(5)
      by fastforce
  next
    case 3
    then consider (1) const-list es | (2) es = [Trap]
      by blast
    hence temp1:∃ a. (|s;vs;[Local n j vls es]|) ↝- i (|s;vs;es|)
    proof (cases)
      case 1
      have length es = length ts
        using s-type-unfold[OF 5(1)] e-type-const-list[OF 1]
        by fastforce
      thus ?thesis
        using reduce-simple.local-const[OF 1] reduce.intros(1) 5(2)
        by fastforce
    next
      case 2
      thus ?thesis
        using reduce-simple.local-trap reduce.intros(1)
        by fastforce
```

```
    qed
    thus ?thesis
      using progress-L0[where ?cs = cs, OF - 5(6)] 5(5)
      by fastforce
  next
    case 4
    then obtain k' lholed' i' where temp1:Lfilled k' lholed' [$Br (k'+i')] es
      using le-Suc-ex
      by blast
     obtain C' where c-def:C' = ((s-inst S)!j)(|local := (local ((s-inst S)!j)) @
(map typeof vls), return := Some ts|)
      by blast
    hence  es-def:S·C' ⊢ es : ([] -> ts) j < length (s-inst S)
      using 5(1) s-type-unfold
      by fastforce+
    hence length (label C') = 0
      using c-def store-local-label-empty 5(12)
      by fastforce
    thus ?thesis
      using progress-LN1[OF temp1 es-def(1)]
      by linarith
  qed
next
  case (6 S cl tf C)
  obtain ts'' where ts''-def:S·C ⊢ cs : ([] -> ts'') S·C ⊢ [Callcl cl] : (ts'' -> ts')
    using 6(2,3) e-type-comp-conc1
    by fastforce
  obtain ts-c t1s t2s where cl-def:(ts'' = ts-c @ t1s)
                                   (ts' = ts-c @ t2s)
                                   cl-type cl = (t1s -> t2s)
    using e-type-callcl[OF ts''-def(2)]
    by fastforce
  obtain vs1 vs2 where vs-def:S·C ⊢ vs1 : ([] -> ts-c)
                              S·C ⊢ vs2 : (ts-c -> ts-c @ t1s)
                              cs = vs1 @ vs2
                              const-list vs1
                              const-list vs2
    using e-type-const-list-cons[OF 6(4)] ts''-def(1) cl-def(1)
    by fastforce
  have l:(length vs2) = (length t1s)
    using e-type-const-list vs-def(2,5)
    by fastforce
  show ?case
  proof (cases cl)
    case (Func-native x11 x12 x13 x14)
    hence func-native-def:cl = Func-native x11 (t1s -> t2s) x13 x14
      using cl-def(3)
      unfolding cl-type-def
      by simp
```

```
      have ∃ a a'. (|s;vs;vs2 @ [Callcl cl]|) ↪- i (|s;vs;a|)
      using reduce.intros(5)[OF func-native-def] e-type-const-conv-vs[OF vs-def(5)]
l
        unfolding n-zeros-def
        by fastforce
      thus ?thesis
        using progress-L0 vs-def(3,4) 6(3)
        by fastforce
    next
      case (Func-host x21 x22)
      hence func-host-def:cl = Func-host (t1s -> t2s) x22
        using cl-def(3)
        unfolding cl-type-def
        by simp
      obtain vcs where vcs-def:vs2 = $$* vcs
        using e-type-const-conv-vs[OF vs-def(5)]
        by blast
      fix hs
      have ∃ s' a a'. (|s;vs;vs2 @ [Callcl cl]|) ↪- i (|s';vs;a|)
      proof (cases host-apply s (t1s -> t2s) x22 vcs hs)
        case None
        thus ?thesis
          using reduce.intros(7)[OF func-host-def] l vcs-def
          by fastforce
      next
        case (Some a)
        then obtain s' vcs' where ha-def:host-apply s (t1s -> t2s) x22 vcs hs =
Some (s', vcs')
          by (metis surj-pair)
        have list-all2 types-agree t1s vcs
          using e-typing-imp-list-types-agree vs-def(2,4) vcs-def
          by simp
        thus ?thesis
          using reduce.intros(6)[OF func-host-def - - - - ha-def] l vcs-def
                host-apply-respect-type[OF - ha-def]
          by fastforce
      qed
      thus ?thesis
        using vs-def(3,4) 6(3) progress-L0
        by fastforce
    qed
  next
    case (7 S C e0s ts t2s es n)
    consider (1) (⋀k lholed. ¬ Lfilled k lholed [$Return] es)
                 (⋀k lholed i. (Lfilled k lholed [$Br i] es) ⟹ i < k)
                 es ≠ [Trap]
                 ¬ const-list es
           | (2) ∃ k lholed. Lfilled k lholed [$Return] es
           | (3) const-list es ∨ (es = [Trap])
```

```
        | (4) ∃ k lholed i. (Lfilled k lholed [$Br i] es) ∧ i = k
        | (5) ∃ k lholed i. (Lfilled k lholed [$Br i] es) ∧ i > k
    using linorder-neqE-nat
    by blast
  thus ?case
  proof (cases)
    case 1
    have temp1:es = [] @ es const-list []
      unfolding const-list-def
      by auto
    have temp2:S·C(|label := [ts] @ label C|) ⊢ [] : ([] -> [])
      using b-e-typing.empty e-typing-s-typing.intros(1)
      by fastforce
    have ∃ s' vs' a. (|s;vs;es|) ↝- i (|s';vs';a|)
      using 7(5)[OF 7(2), of [] [], OF temp1 temp2 1(1) - 1(3,4) 7(14,15)]
          1(2) 7(16,17)
      unfolding const-list-def
      by fastforce
    then obtain s' vs' a where red-def:(|s;vs;es|) ↝- i (|s';vs';a|)
      by blast
    have temp4:⋀es. Lfilled 0 (LBase [] []) es es
      using Lfilled.intros(1)[of [] (LBase [] []) []]
      unfolding const-list-def
      by fastforce
   hence temp5:Lfilled 1 (LRec cs n e0s (LBase [] []) []) es (cs@[Label n e0s es])
     using Lfilled.intros(2)[of cs (LRec cs n e0s (LBase [] []) []) n e0s (LBase []
[]) [] 0 es es] 7(8)
      unfolding const-list-def
      by fastforce
    have temp6:Lfilled 1 (LRec cs n e0s (LBase [] []) []) a (cs@[Label n e0s a])
      using temp4 Lfilled.intros(2)[of cs (LRec cs n e0s (LBase [] []) []) n e0s
(LBase [] []) [] 0 a a] 7(8)
      unfolding const-list-def
      by fastforce
    show ?thesis
      using reduce.intros(23)[OF - temp5 temp6] 7(7) red-def
      by fastforce
  next
    case 2
    then obtain k lholed where (Lfilled k lholed [$Return] es)
      by blast
   hence (Lfilled (k+1) (LRec cs n e0s lholed []) [$Return] (cs@[Label n e0s es]))
      using Lfilled.intros(2) 7(8)
      by fastforce
    thus ?thesis
      using 7(10)[of k+1] 7(7)
    by fastforce
  next
    case 3
```

```
    hence temp1:∃ a. (|s;vs;[Label n e0s es]|) ↝- i (|s;vs;es|)
      using reduce-simple.label-const reduce-simple.label-trap reduce.intros(1)
      by fastforce
    show ?thesis
      using progress-L0[OF - 7(8)] 7(7) temp1
      by fastforce
  next
    case 4
    then obtain k lholed where lholed-def:(Lfilled k lholed [$Br (k+0)] es)
      by fastforce
   then obtain lholed' vs' C' where lholed'-def:(Lfilled k lholed' (vs'@[$Br (k)])
es)
                                                  S·C' ⊢ vs' : ([] -> ts)
                                                  const-list vs'
      using progress-LN[OF lholed-def 7(2), of ts]
      by fastforce
    have ∃ es' a. (|[Label n e0s es]|) ↝ (|vs'@e0s|)
      using reduce-simple.br[OF lholed'-def(3) - lholed'-def(1)] 7(3)
          e-type-const-list[OF lholed'-def(3,2)]
      by fastforce
    hence ∃ es' a. (|s;vs;[Label n e0s es]|) ↝- i (|s;vs;es'|)
      using reduce.intros(1)
      by fastforce
    thus ?thesis
      using progress-L0 7(7,8)
      by fastforce
  next
    case 5
    then obtain i k lholed where lholed-def:(Lfilled k lholed [$Br i] es) i > k
      using less-imp-add-positive
      by blast
    have k1-def:Lfilled (k+1) (LRec cs n e0s lholed []) [$Br i] cs-es
      using 7(7) Lfilled.intros(2)[OF 7(8) - lholed-def(1), of - n e0s []]
      by fastforce
    thus ?thesis
      using 7(11)[OF k1-def] lholed-def(2)
      by simp
  qed
next
  case (8 i S tvs vs C rs es ts)
  have length (local C) = length vs
    using 8(2,3) store-local-label-empty[OF 8(1,11)]
    by fastforce
  moreover
  have Option.is-none (memory C) = Option.is-none (inst.mem ((inst s)!i))
    using store-mem-exists[OF 8(1,11)] 8(3)
    by simp
  ultimately show ?case
    using 8(6)[OF 8(4) - - - 8(7,8,9,10,11,1)]
```

```
        e-typing-s-typing.intros(1)[OF b-e-typing.empty[of C]]
    unfolding const-list-def
    by fastforce
  qed
  show ?thesis
    using prems2[OF assms]
    by fastforce
qed

lemma progress-e1:
  assumes S·None ⊩-i vs;es : ts
  shows ¬(Lfilled k lholed [$Return] es)
proof −
  {
    assume ∃ k lholed. (Lfilled k lholed [$Return] es)
    then obtain k lholed where local-assms:(Lfilled k lholed [$Return] es)
      by blast
    obtain C where c-def:i < length (s-inst S)
                C = ((s-inst S)!i)(|local := (local ((s-inst S)!i)) @ (map typeof vs),
return := None|)
                (S·C ⊢ es : ([] -> ts))
      using assms s-type-unfold
      by fastforce
    have ∃ rs. return C = Some rs
      using local-assms c-def(3)
    proof (induction [$Return] es arbitrary: C ts rule: Lfilled.induct)
      case (L0 vs lholed es')
      thus ?case
      using e-type-comp-conc2[OF L0(3)] unlift-b-e[of S C [Return]] b-e-type-return
        by fastforce
    next
      case (LN vs lholed tls es' l es'' k lfilledk)
      thus ?case
        using e-type-comp-conc2[OF LN(5)] e-type-label[of S C tls es' lfilledk]
        by fastforce
    qed
    hence False
      using c-def(2)
      by fastforce
  }
  thus ⋀ k lholed. ¬(Lfilled k lholed [$Return] es)
    by blast
qed

lemma progress-e2:
  assumes S·None ⊩-i vs;es : ts
        store-typing s S
  shows (Lfilled k lholed [$Br (j)] es) ⟹ j < k
proof −
```

**{**
**assume** $(\exists\, i\ k\ lholed.\ (Lfilled\ k\ lholed\ [\$Br\ (i)]\ es) \wedge i \geq k)$
**then obtain** *j k lholed* **where** *local-assms*:$(Lfilled\ k\ lholed\ [\$Br\ (k{+}j)]\ es)$
**by** (*metis le-iff-add*)
**obtain** $\mathcal{C}$ **where** *c-def*:$i < length\ (s\text{-}inst\ \mathcal{S})$
$\mathcal{C} = ((s\text{-}inst\ \mathcal{S})!i)(\!|local := (local\ ((s\text{-}inst\ \mathcal{S})!i)) @ (map\ typeof\ vs),$
$return := None|\!)$
$(\mathcal{S}{\cdot}\mathcal{C} \vdash es : ([] \to ts))$
**using** *assms s-type-unfold*
**by** *fastforce*
**have** $j < length\ (label\ \mathcal{C})$
**using** *progress-LN1*[*OF local-assms c-def*(*3*)]
**by** −
**hence** *False*
**using** *store-local-label-empty*(*1*)[*OF c-def*(*1*) *assms*(*2*)] *c-def*(*2*)
**by** *fastforce*
**}**
**thus** $(\bigwedge j\ k\ lholed.\ (Lfilled\ k\ lholed\ [\$Br\ (j)]\ es) \Longrightarrow j < k)$
**by** *fastforce*
**qed**

**lemma** *progress-e3*:
**assumes** $\mathcal{S}{\cdot}None \vdash$-*i vs*;*cs-es* : *ts*′
*cs-es* ≠ [*Trap*]
¬ *const-list* (*cs-es*)
*store-typing s* $\mathcal{S}$
**shows** $\exists\, a\ s'\ vs'\ es'.\ (\!|s;vs;cs\text{-}es|\!) \rightsquigarrow$-*i* $(\!|s';vs';es'|\!)$
**using** *assms progress-e progress-e1 progress-e2*
**by** *fastforce*

**end**

# 7 Soundness Theorems

**theory** *Wasm-Soundness* **imports** *Main Wasm-Properties* **begin**

**theorem** *preservation*:
**assumes** ⊢-*i s*;*vs*;*es* : *ts*
$(\!|s;vs;es|\!) \rightsquigarrow$-*i* $(\!|s';vs';es'|\!)$
**shows** ⊢-*i s*′;*vs*′;*es*′ : *ts*
**proof** −
**obtain** $\mathcal{S}$ **where** *store-typing s* $\mathcal{S}$ $\mathcal{S}{\cdot}None \vdash$-*i vs*;*es* : *ts*
**using** *assms*(*1*) *config-typing.simps*
**by** *blast*
**hence** *store-typing s*′ $\mathcal{S}$ $\mathcal{S}{\cdot}None \vdash$-*i vs*′;*es*′ : *ts*
**using** *assms*(*2*) *store-preserved types-preserved-e*
**by** *simp-all*
**thus** *?thesis*
**using** *config-typing.intros*

**by** *blast*
**qed**

**theorem** *progress*:
**assumes** $\vdash$-*i* *s*;*vs*;*es* : *ts*
**shows** *const-list es* $\vee$ *es* = [*Trap*] $\vee$ ($\exists$ *a s' vs' es'*. ($\!|$*s*;*vs*;*es*$|\!$) $\rightsquigarrow$-*i* ($\!|$*s'*;*vs'*;*es'*$|\!$))
**proof** −
**obtain** $\mathcal{S}$ **where** *store-typing s* $\mathcal{S}$ $\mathcal{S}$·*None* $\models$-*i* *vs*;*es* : *ts*
**using** *assms config-typing.simps*
**by** *blast*
**thus** *?thesis*
**using** *progress-e3*
**by** *blast*
**qed**

**end**

# 8 Augmented Type Syntax for Concrete Checker

**theory** *Wasm-Checker-Types* **imports** *Wasm HOL−Library.Sublist* **begin**

**datatype** *ct* =
*TAny*
| *TSome t*

**datatype** *checker-type* =
*TopType ct list*
| *Type t list*
| *Bot*

**definition** *to-ct-list* :: *t list* ⇒ *ct list* **where**
*to-ct-list ts* = *map TSome ts*

**fun** *ct-eq* :: *ct* ⇒ *ct* ⇒ *bool* **where**
*ct-eq* (*TSome t*) (*TSome t'*) = (*t* = *t'*)
| *ct-eq TAny* - = *True*
| *ct-eq* - *TAny* = *True*

**definition** *ct-list-eq* :: *ct list* ⇒ *ct list* ⇒ *bool* **where**
*ct-list-eq ct1s ct2s* = *list-all2 ct-eq ct1s ct2s*

**definition** *ct-prefix* :: *ct list* ⇒ *ct list* ⇒ *bool* **where**
*ct-prefix xs ys* = ($\exists$ *as bs*. *ys* = *as*@*bs* ∧ *ct-list-eq as xs*)

**definition** *ct-suffix* :: *ct list* ⇒ *ct list* ⇒ *bool* **where**
*ct-suffix xs ys* = ($\exists$ *as bs*. *ys* = *as*@*bs* ∧ *ct-list-eq bs xs*)

**lemma** *ct-eq-commute*:
**assumes** *ct-eq x y*

**shows** *ct-eq y x*
**using** *assms*
**by** (*metis ct-eq.elims*(*3*) *ct-eq.simps*(*1*))

**lemma** *ct-eq-flip*: $ct\text{-}eq^{-1-1} = ct\text{-}eq$
**using** *ct-eq-commute*
**by** *fastforce*

**lemma** *ct-eq-common-tsome*: *ct-eq x y* = (∃ *t*. *ct-eq x* (*TSome t*) ∧ *ct-eq* (*TSome t*) *y*)
**by** (*metis ct-eq.elims*(*3*) *ct-eq.simps*(*1*))

**lemma** *ct-list-eq-commute*:
**assumes** *ct-list-eq xs ys*
**shows** *ct-list-eq ys xs*
**using** *assms ct-eq-commute List.List.list.rel-flip ct-eq-flip*
**unfolding** *ct-list-eq-def*
**by** *fastforce*

**lemma** *ct-list-eq-refl*: *ct-list-eq xs xs*
**unfolding** *ct-list-eq-def*
**by** (*metis ct-eq.elims*(*3*) *ct-eq.simps*(*1*) *list-all2-refl*)

**lemma** *ct-list-eq-length*:
**assumes** *ct-list-eq xs ys*
**shows** *length xs* = *length ys*
**using** *assms list-all2-lengthD*
**unfolding** *ct-list-eq-def*
**by** *blast*

**lemma** *ct-list-eq-concat*:
**assumes** *ct-list-eq xs ys*
*ct-list-eq xs′ ys′*
**shows** *ct-list-eq* (*xs*@*xs′*) (*ys*@*ys′*)
**using** *assms*
**unfolding** *ct-list-eq-def*
**by** (*simp add*: *list-all2-appendI*)

**lemma** *ct-list-eq-ts-conv-eq*:
*ct-list-eq* (*to-ct-list ts*) (*to-ct-list ts′*) = (*ts* = *ts′*)
**unfolding** *ct-list-eq-def to-ct-list-def*
*list-all2-map1 list-all2-map2*
*ct-eq.simps*(*1*)
**by** (*simp add*: *list-all2-eq*)

**lemma** *ct-list-eq-exists*: ∃ *ys*. *ct-list-eq xs* (*to-ct-list ys*)
**proof** (*induction xs*)
**case** *Nil*
**thus** *?case*

```
    unfolding ct-list-eq-def to-ct-list-def
    by (simp)
next
  case (Cons a xs)
  thus ?case
    unfolding ct-list-eq-def to-ct-list-def
    apply (cases a)
     apply (metis ct-eq.simps(3) ct-eq-commute list.rel-intros(2) list.simps(9))
    apply (metis ct-eq.simps(1) list.rel-intros(2) list.simps(9))
    done
qed

lemma ct-list-eq-common-tsome-list:
  ct-list-eq xs ys = (∃ zs. ct-list-eq xs (to-ct-list zs) ∧ ct-list-eq (to-ct-list zs) ys)
proof (induction ys arbitrary: xs)
  case Nil
  thus ?case
    unfolding ct-list-eq-def to-ct-list-def
    by simp
next
  case (Cons a ys)
  show ?case
  proof (safe)
    assume assms:ct-list-eq xs (a # ys)
    then obtain x' xs' where xs-def:xs = x'#xs'
      by (meson ct-list-eq-def list-all2-Cons2)
    then obtain zs where zs-def:ct-eq x' a
                                ct-list-eq xs' (to-ct-list zs) ∧ ct-list-eq (to-ct-list zs) ys
      using Cons[of xs'] assms list-all2-Cons
      unfolding ct-list-eq-def
      by fastforce
    obtain z where ct-eq x' (TSome z) ct-eq (TSome z) a
      using ct-eq-common-tsome[of x' a] zs-def(1)
      by fastforce
   hence ct-list-eq (x'#xs') (to-ct-list (z#zs)) ∧ ct-list-eq (to-ct-list (z#zs)) (a #
ys)
      using zs-def(2) list-all2-Cons
      unfolding ct-list-eq-def to-ct-list-def
      by simp
    thus ∃ zs. ct-list-eq xs (to-ct-list zs) ∧ ct-list-eq (to-ct-list zs) (a # ys)
      using xs-def
      by fastforce
  next
    fix zs
    assume assms:ct-list-eq xs (to-ct-list zs) ct-list-eq (to-ct-list zs) (a # ys)
    then obtain x' xs' z' zs' where xs = x'#xs'
                                    zs = z'#zs'
                                    ct-list-eq xs' (to-ct-list zs')
                                    ct-list-eq (to-ct-list zs') (ys)
```

**using** *list-all2-Cons2*
**unfolding** *ct-list-eq-def to-ct-list-def list-all2-map1 list-all2-map2*
**by** (*metis* (*no-types*, *lifting*))
**thus** *ct-list-eq xs* (*a # ys*)
**using** *assms Cons ct-list-eq-def to-ct-list-def ct-eq-common-tsome*
**by** (*metis list.simps*(*9*) *list-all2-Cons*)
**qed**
**qed**

**lemma** *ct-list-eq-cons-ct-list*:
**assumes** *ct-list-eq* (*to-ct-list as*) (*xs @ ys*)
**shows** ∃ *bs bs′*. *as* = *bs @ bs′* ∧ *ct-list-eq* (*to-ct-list bs*) *xs* ∧ *ct-list-eq* (*to-ct-list bs′*) *ys*
**using** *assms*
**proof** (*induction xs arbitrary*: *as*)
**case** *Nil*
**thus** *?case*
**by** (*metis append-Nil ct-list-eq-ts-conv-eq list.simps*(*8*) *to-ct-list-def*)
**next**
**case** (*Cons a xs*)
**thus** *?case*
**unfolding** *ct-list-eq-def to-ct-list-def list-all2-map1*
**by** (*meson list-all2-append2*)
**qed**

**lemma** *ct-list-eq-cons-ct-list1*:
**assumes** *ct-list-eq* (*to-ct-list as*) (*xs* @ (*to-ct-list ys*))
**shows** ∃ *bs*. *as* = *bs @ ys* ∧ *ct-list-eq* (*to-ct-list bs*) *xs*
**using** *ct-list-eq-cons-ct-list*[*OF assms*] *ct-list-eq-ts-conv-eq*
**by** *fastforce*

**lemma** *ct-list-eq-shared*:
**assumes** *ct-list-eq xs* (*to-ct-list as*)
*ct-list-eq ys* (*to-ct-list as*)
**shows** *ct-list-eq xs ys*
**using** *assms ct-list-eq-def*
**by** (*meson ct-list-eq-common-tsome-list ct-list-eq-commute*)

**lemma** *ct-list-eq-take*:
**assumes** *ct-list-eq xs ys*
**shows** *ct-list-eq* (*take n xs*) (*take n ys*)
**using** *assms list-all2-takeI*
**unfolding** *ct-list-eq-def*
**by** *blast*

**lemma** *ct-prefixI* [*intro?*]:
**assumes** *ys* = *as @ zs*
*ct-list-eq as xs*
**shows** *ct-prefix xs ys*

**using** *assms*
**unfolding** *ct-prefix-def*
**by** *blast*

**lemma** *ct-prefixE* [*elim?*]:
**assumes** *ct-prefix xs ys*
**obtains** *as zs* **where** *ys* = *as* @ *zs ct-list-eq as xs*
**using** *assms*
**unfolding** *ct-prefix-def*
**by** *blast*

**lemma** *ct-prefix-snoc* [*simp*]: *ct-prefix xs* (*ys* @ [*y*]) = (*ct-list-eq xs* (*ys*@[*y*]) ∨ *ct-prefix xs ys*)
**proof** (*safe*)
**assume** *ct-prefix xs* (*ys* @ [*y*]) ¬ *ct-prefix xs ys*
**thus** *ct-list-eq xs* (*ys* @ [*y*])
**unfolding** *ct-prefix-def ct-list-eq-def*
**by** (*metis butlast-append butlast-snoc ct-eq-flip list.rel-flip*)
**next**
**assume** *ct-list-eq xs* (*ys* @ [*y*])
**thus** *ct-prefix xs* (*ys* @ [*y*])
**using** *ct-list-eq-commute ct-prefixI*
**by** *fastforce*
**next**
**assume** *ct-prefix xs ys*
**thus** *ct-prefix xs* (*ys* @ [*y*])
**using** *append-assoc*
**unfolding** *ct-prefix-def*
**by** *blast*
**qed**

**lemma** *ct-prefix-nil*:*ct-prefix* [] *xs*
¬*ct-prefix* (*x* # *xs*) []
**by** (*simp-all add*: *ct-prefix-def ct-list-eq-def*)

**lemma** *Cons-ct-prefix-Cons*[*simp*]: *ct-prefix* (*x* # *xs*) (*y* # *ys*) = ((*ct-eq x y*) ∧ *ct-prefix xs ys*)
**proof** (*safe*)
**assume** *ct-prefix* (*x* # *xs*) (*y* # *ys*)
**thus** *ct-eq x y*
**unfolding** *ct-prefix-def ct-list-eq-def*
**by** (*metis ct-eq-commute hd-append2 list.sel*(*1*) *list.simps*(*3*) *list-all2-Cons2*)
**next**
**assume** *ct-prefix* (*x* # *xs*) (*y* # *ys*)
**thus** *ct-prefix xs ys*
**unfolding** *ct-prefix-def ct-list-eq-def*
**by** (*metis list.rel-distinct*(*1*) *list.sel*(*3*) *list-all2-Cons2 tl-append2*)
**next**
**assume** *ct-eq x y ct-prefix xs ys*

**thus** *ct-prefix* (*x* # *xs*) (*y* # *ys*)
**unfolding** *ct-prefix-def ct-list-eq-def*
**by** (*metis* (*full-types*) *append-Cons ct-list-eq-commute ct-list-eq-def list.rel-inject*(*2*))
**qed**

**lemma** *ct-prefix-code* [*code*]:
*ct-prefix* [] *xs* = *True*
*ct-prefix* (*x* # *xs*) [] = *False*
*ct-prefix* (*x* # *xs*) (*y* # *ys*) = ((*ct-eq x y*) ∧ *ct-prefix xs ys*)
**by** (*simp-all add*: *ct-prefix-nil*)

**lemma** *ct-suffix-to-ct-prefix* [*code*]: *ct-suffix xs ys* = *ct-prefix* (*rev xs*) (*rev ys*)
**unfolding** *ct-suffix-def ct-prefix-def ct-list-eq-def*
**by** (*metis list-all2-rev1 rev-append rev-rev-ident*)

**lemma** *inj-TSome*: *inj TSome*
**by** (*meson ct.inject injI*)

**lemma** *to-ct-list-append*:
**assumes** *to-ct-list ts* = *as*@*bs*
**shows** ∃ *as'*. *to-ct-list as'* = *as*
∃ *bs'*. *to-ct-list bs'* = *bs*
**using** *assms*
**proof** (*induct as arbitrary*: *ts*)
**fix** *ts*
**assume** *to-ct-list ts* = [] @ *bs*
**thus** ∃ *as'*. *to-ct-list as'* = []
∃ *bs'*. *to-ct-list bs'* = *bs*
**unfolding** *to-ct-list-def*
**by** *auto*
**next**
**case** (*Cons a as*)
**fix** *ts*
**assume** *local-assms*:*to-ct-list ts* = (*a* # *as*) @ *bs*
**then obtain** *t' ts'* **where** *ts* = *t'*#*ts'*
**unfolding** *to-ct-list-def*
**by** *auto*
**thus** ∃ *as'*. *to-ct-list as'* = *a* # *as*
∃ *as'*. *to-ct-list as'* = *bs*
**using** *Cons local-assms*
**unfolding** *to-ct-list-def*
**apply** *simp-all*
**apply** (*metis list.simps*(*9*))
**apply** *blast*
**done**
**qed**

**lemma** *ct-suffixI* [*intro?*]:
**assumes** *ys* = *as* @ *zs*

*ct-list-eq zs xs*
**shows** *ct-suffix xs ys*
**using** *assms*
**unfolding** *ct-suffix-def*
**by** *blast*

**lemma** *ct-suffixE* [*elim?*]:
**assumes** *ct-suffix xs ys*
**obtains** *as zs* **where** *ys* = *as* @ *zs ct-list-eq zs xs*
**using** *assms*
**unfolding** *ct-suffix-def*
**by** *blast*

**lemma** *ct-suffix-nil*: *ct-suffix* [] *ts*
**unfolding** *ct-suffix-def*
**using** *ct-list-eq-refl*
**by** *auto*

**lemma** *ct-suffix-refl*: *ct-suffix ts ts*
**unfolding** *ct-suffix-def*
**using** *ct-list-eq-refl*
**by** *auto*

**lemma** *ct-suffix-length*:
**assumes** *ct-suffix ts ts′*
**shows** *length ts* ≤ *length ts′*
**using** *assms list-all2-lengthD*
**unfolding** *ct-suffix-def ct-list-eq-def*
**by** *fastforce*

**lemma** *ct-suffix-take*:
**assumes** *ct-suffix ts ts′*
**shows** *ct-suffix* ((*take* (*length ts* − *n*) *ts*)) ((*take* (*length ts′* − *n*) *ts′*))
**using** *assms ct-list-eq-take append-eq-conv-conj*
**unfolding** *ct-suffix-def*
**proof** −
**assume** ∃ *as bs*. *ts′* = *as* @ *bs* ∧ *ct-list-eq bs ts*
**then obtain** *ccs* :: *ct list* **and** *ccsa* :: *ct list* **where**
*f1*: *ts′* = *ccs* @ *ccsa* ∧ *ct-list-eq ccsa ts*
**by** *moura*
**then have** *f2*: *length ccsa* = *length ts*
**by** (*meson ct-list-eq-length*)
**have** ⋀*n*. *ct-list-eq* (*take n ccsa*) (*take n ts*)
**using** *f1* **by** (*meson ct-list-eq-take*)
**then show** ∃ *cs csa*. *take* (*length ts′* − *n*) *ts′* = *cs* @ *csa* ∧ *ct-list-eq csa* (*take* (*length ts* − *n*) *ts*)
**using** *f2 f1* **by** *auto*
**qed**

**lemma** *ct-suffix-ts-conv-suffix*:
  *ct-suffix* (*to-ct-list ts*) (*to-ct-list ts'*) = *suffix ts ts'*
**proof** *safe*
  **assume** *ct-suffix* (*to-ct-list ts*) (*to-ct-list ts'*)
  **then obtain** *as bs* **where** *to-ct-list ts'* = (*to-ct-list as*) @ (*to-ct-list bs*)
                        *ct-list-eq* (*to-ct-list bs*) (*to-ct-list ts*)
    **using** *to-ct-list-append*
    **unfolding** *ct-suffix-def*
    **by** *metis*
  **thus** *suffix ts ts'*
    **using** *ct-list-eq-ts-conv-eq*
    **unfolding** *ct-suffix-def to-ct-list-def suffix-def*
    **by** (*metis map-append*)
**next**
  **assume** *suffix ts ts'*
  **thus** *ct-suffix* (*to-ct-list ts*) (*to-ct-list ts'*)
    **using** *ct-list-eq-ts-conv-eq*
    **unfolding** *ct-suffix-def to-ct-list-def suffix-def*
    **by** (*metis map-append*)
**qed**

**lemma** *ct-suffix-exists*: ∃ *ts-c*. *ct-suffix x1* (*to-ct-list ts-c*)
  **using** *ct-list-eq-commute ct-list-eq-exists ct-suffix-def*
  **by** *fastforce*

**lemma** *ct-suffix-ct-list-eq-exists*:
  **assumes** *ct-suffix x1 x2*
  **shows** ∃ *ts-c*. *ct-suffix x1* (*to-ct-list ts-c*) ∧ *ct-list-eq* (*to-ct-list ts-c*) *x2*
**proof** −
  **obtain** *as bs* **where** *x2-def*:*x2* = *as* @ *bs ct-list-eq x1 bs*
    **using** *assms ct-list-eq-commute*
    **unfolding** *ct-suffix-def*
    **by** *blast*
  **then obtain** *ts-as ts-bs* **where** *ct-list-eq as* (*to-ct-list ts-as*)
                                *ct-list-eq x1* (*to-ct-list ts-bs*)
                                *ct-list-eq* (*to-ct-list ts-bs*) *bs*
    **using** *ct-list-eq-common-tsome-list*[*of x1 bs*] *ct-list-eq-exists*
    **by** *fastforce*
  **thus** *?thesis*
    **using** *x2-def ct-list-eq-commute*
    **unfolding** *ct-suffix-def to-ct-list-def*
    **by** (*metis ct-list-eq-def list-all2-appendI map-append*)
**qed**

**lemma** *ct-suffix-cons-ct-list*:
  **assumes** *ct-suffix* (*xs*@*ys*) (*to-ct-list zs*)
  **shows** ∃ *as bs*. *zs* = *as*@*bs* ∧ *ct-list-eq ys* (*to-ct-list bs*) ∧ *ct-suffix xs* (*to-ct-list as*)
**proof** −

**obtain** *as bs* **where** *to-ct-list zs* = (*to-ct-list as*) @ (*to-ct-list bs*)
*ct-list-eq* (*to-ct-list bs*) (*xs* @ *ys*)
**using** *assms to-ct-list-append*[*of zs*]
**unfolding** *ct-suffix-def*
**by** *blast*
**thus** *?thesis*
**using** *assms ct-list-eq-cons-ct-list*[*of bs xs ys*]
**unfolding** *ct-suffix-def*
**by** (*metis append.assoc ct-list-eq-commute ct-list-eq-ts-conv-eq map-append to-ct-list-def*)
**qed**

**lemma** *ct-suffix-cons-ct-list1*:
**assumes** *ct-suffix* (*xs*@(*to-ct-list ys*)) (*to-ct-list zs*)
**shows** ∃ *as*. *zs* = *as*@*ys* ∧ *ct-suffix xs* (*to-ct-list as*)
**using** *ct-suffix-cons-ct-list*[*OF assms*] *ct-list-eq-ts-conv-eq*
**by** *fastforce*

**lemma** *ct-suffix-cons2*:
**assumes** *ct-suffix* (*xs*) (*ys*@*zs*)
*length xs* = *length zs*
**shows** *ct-list-eq xs zs*
**using** *assms*
**by** (*metis append-eq-append-conv ct-list-eq-commute ct-list-eq-def ct-suffix-def list-all2-lengthD*)

**lemma** *ct-suffix-imp-ct-list-eq*:
**assumes** *ct-suffix xs ys*
**shows** *ct-list-eq* (*drop* (*length ys* − *length xs*) *ys*) *xs*
**using** *assms ct-list-eq-def list-all2-lengthD*
**unfolding** *ct-suffix-def*
**by** *fastforce*

**lemma** *ct-suffix-extend-ct-list-eq*:
**assumes** *ct-suffix xs ys*
*ct-list-eq xs′ ys′*
**shows** *ct-suffix* (*xs*@*xs′*) (*ys*@*ys′*)
**using** *assms*
**unfolding** *ct-suffix-def ct-list-eq-def*
**by** (*meson append.assoc ct-list-eq-commute ct-list-eq-def list-all2-appendI*)

**lemma** *ct-suffix-extend-any1*:
**assumes** *ct-suffix xs ys*
*length xs* < *length ys*
**shows** *ct-suffix* (*TAny*#*xs*) *ys*
**proof** −
**obtain** *as bs* **where** *ys-def*:*ys* = *as*@*bs*
*ct-list-eq bs xs*
**using** *assms*(*1*) *ct-suffix-def*
**by** *fastforce*

**hence** *length as > 0*
**using** *list-all2-lengthD assms(2)*
**unfolding** *ct-list-eq-def*
**by** *fastforce*
**then obtain** *as' a* **where** *as-def:as = as'@[a]*
**by** (*metis append-butlast-last-id length-greater-0-conv*)
**hence** *ct-list-eq* (*a#bs*) (*TAny#xs*)
**using** *ys-def*
**by** (*meson ct-eq.simps(2) ct-list-eq-commute ct-list-eq-def list.rel-intros(2)*)
**thus** *?thesis*
**using** *as-def ys-def ct-suffix-def*
**by** *fastforce*
**qed**

**lemma** *ct-suffix-singleton-any*: *ct-suffix* [*TAny*] [*t*]
**using** *ct-suffix-extend-ct-list-eq*[*of* [] [] [*TAny*] [*t*]] *ct-suffix-nil*
**by** (*simp add*: *ct-list-eq-def*)

**lemma** *ct-suffix-cons-it*: *ct-suffix xs* (*xs'@xs*)
**using** *ct-list-eq-refl ct-suffix-def*
**by** *blast*

**lemma** *ct-suffix-singleton*:
**assumes** *length cts > 0*
**shows** *ct-suffix* [*TAny*] *cts*
**proof** −
**have** ⋀*c*. *ct-prefix* [*TAny*] [*c*]
**using** *ct-suffix-singleton-any ct-suffix-to-ct-prefix* **by** *force*
**then show** *?thesis*
**by** (*metis* (*no-types*) *Suc-leI append-butlast-last-id assms butlast.simps(2) ct-list-eq-commute*
*ct-prefix-nil(2) ct-prefix-snoc ct-suffix-def impossible-Cons*
*length-Cons*
*list.size(3)*)
**qed**

**lemma** *ct-suffix-less*:
**assumes** *ct-suffix* (*xs@xs'*) *ys*
**shows** *ct-suffix xs' ys*
**using** *assms*
**unfolding** *ct-suffix-def*
**by** (*metis append-eq-appendI ct-list-eq-def list-all2-append2*)

**lemma** *ct-suffix-unfold-one*: *ct-suffix* (*xs@*[*x*]) (*ys@*[*y*]) = ((*ct-eq x y*) ∧ *ct-suffix*
*xs ys*)
**using** *ct-prefix-code(3)*
**by** (*simp add*: *ct-suffix-to-ct-prefix*)

**lemma** *ct-suffix-shared*:
**assumes** *ct-suffix cts* (*to-ct-list ts*)

*ct-suffix cts′ (to-ct-list ts)*
**shows** *ct-suffix cts cts′ ∨ ct-suffix cts′ cts*
**proof** (*cases length cts > length cts′*)
**case** *True*
**obtain** *as bs* **where** *cts-def*:*ts = as@bs*
*ct-list-eq cts (to-ct-list bs)*
**using** *assms*(*1*) *ct-suffix-def to-ct-list-def*
**by** (*metis append-Nil ct-suffix-cons-ct-list*)
**obtain** *as′ bs′* **where** *cts′-def*:*ts = as′@bs′*
*ct-list-eq cts′ (to-ct-list bs′)*
**using** *assms*(*2*) *ct-suffix-def to-ct-list-def*
**by** (*metis append-Nil ct-suffix-cons-ct-list*)
**obtain** *ct1s ct2s* **where** *cts = ct1s@ct2s*
*length ct2s = length cts′*
**using** *True*
**by** (*metis add-diff-cancel-right′ append-take-drop-id length-drop less-imp-le-nat nat-le-iff-add*)
**show** *?thesis*
**proof** −
**obtain** *tts* :: *t list* ⇒ *ct list* ⇒ *ct list* ⇒ *t list* **and** *ttsa* :: *t list* ⇒ *ct list* ⇒ *ct list* ⇒ *t list* **where**
*∀ x0 x1 x2. (∃ v3 v4. x0 = v3 @ v4 ∧ ct-list-eq x1 (to-ct-list v4) ∧ ct-suffix x2 (to-ct-list v3)) = (x0 = tts x0 x1 x2 @ ttsa x0 x1 x2 ∧ ct-list-eq x1 (to-ct-list (ttsa x0 x1 x2)) ∧ ct-suffix x2 (to-ct-list (tts x0 x1 x2)))*
**by** *moura*
**then have** *f1*: *as′ @ bs′ = tts (as′ @ bs′) ct2s ct1s @ ttsa (as′ @ bs′) ct2s ct1s ∧ ct-list-eq ct2s (to-ct-list (ttsa (as′ @ bs′) ct2s ct1s)) ∧ ct-suffix ct1s (to-ct-list (tts (as′ @ bs′) ct2s ct1s))*
**using** *assms*(*1*) ‹*cts = ct1s @ ct2s*› *cts′-def*(*1*) *ct-suffix-cons-ct-list* **by** *force*
**then have** *ct-list-eq cts′ (to-ct-list (ttsa (as′ @ bs′) ct2s ct1s))*
**by** (*metis* ‹*ct-suffix cts′ (to-ct-list ts)*› ‹*length ct2s = length cts′*› *cts′-def*(*1*) *ct-list-eq-length ct-suffix-cons2 map-append to-ct-list-def*)
**then show** *?thesis*
**using** *f1* **by** (*metis* ‹*cts = ct1s @ ct2s*› *ct-list-eq-shared ct-suffix-def*)
**qed**
**next**
**case** *False*
**hence** *len*:*length cts′ ≥ length cts*
**by** *linarith*
**obtain** *as bs* **where** *cts-def*:*ts = as@bs*
*ct-list-eq cts (to-ct-list bs)*
**using** *assms*(*1*) *ct-suffix-def to-ct-list-def*
**by** (*metis append-Nil ct-suffix-cons-ct-list*)
**obtain** *as′ bs′* **where** *cts′-def*:*ts = as′@bs′*
*ct-list-eq cts′ (to-ct-list bs′)*
**using** *assms*(*2*) *ct-suffix-def to-ct-list-def*
**by** (*metis append-Nil ct-suffix-cons-ct-list*)
**obtain** *ct1s ct2s* **where** *cts′ = ct1s@ct2s*
*length ct2s = length cts*

```
    using len
    by (metis add-diff-cancel-right' append-take-drop-id length-drop nat-le-iff-add)
  show ?thesis
  proof −
    obtain tts :: t list ⇒ ct list ⇒ ct list ⇒ t list and ttsa :: t list ⇒ ct list ⇒ ct
list ⇒ t list where
      ∀ x0 x1 x2. (∃ v3 v4. x0 = v3 @ v4 ∧ ct-list-eq x1 (to-ct-list v4) ∧ ct-suffix
x2 (to-ct-list v3)) = (x0 = tts x0 x1 x2 @ ttsa x0 x1 x2 ∧ ct-list-eq x1 (to-ct-list
(ttsa x0 x1 x2)) ∧ ct-suffix x2 (to-ct-list (tts x0 x1 x2)))
      by moura
    then have f1: as @ bs = tts (as @ bs) ct2s ct1s @ ttsa (as @ bs) ct2s ct1s ∧
ct-list-eq ct2s (to-ct-list (ttsa (as @ bs) ct2s ct1s)) ∧ ct-suffix ct1s (to-ct-list (tts
(as @ bs) ct2s ct1s))
      using assms(2) ‹cts' = ct1s @ ct2s› cts-def(1) ct-suffix-cons-ct-list by force
    then have ct-list-eq cts (to-ct-list (ttsa (as @ bs) ct2s ct1s))
      by (metis ‹ct-suffix cts (to-ct-list ts)› ‹length ct2s = length cts› cts-def(1)
ct-list-eq-length ct-suffix-cons2 map-append to-ct-list-def)
    then show ?thesis
      using f1 by (metis ‹cts' = ct1s @ ct2s› ct-list-eq-shared ct-suffix-def)
  qed
qed

fun checker-type-suffix::checker-type ⇒ checker-type ⇒ bool where
  checker-type-suffix (Type ts) (Type ts') = suffix ts ts'
| checker-type-suffix (Type ts) (TopType cts) = ct-suffix (to-ct-list ts) cts
| checker-type-suffix (TopType cts) (Type ts) = ct-suffix cts (to-ct-list ts)
| checker-type-suffix - - = False

fun consume :: checker-type ⇒ ct list ⇒ checker-type where
  consume (Type ts) cons = (if ct-suffix cons (to-ct-list ts)
                            then Type (take (length ts − length cons) ts)
                            else Bot)
| consume (TopType cts) cons = (if ct-suffix cons cts
                                then TopType (take (length cts − length cons) cts)
                                else (if ct-suffix cts cons
                                      then TopType []
                                      else Bot))
| consume - - = Bot

fun produce :: checker-type ⇒ checker-type ⇒ checker-type where
  produce (TopType ts) (Type ts') = TopType (ts@(to-ct-list ts'))
| produce (Type ts) (Type ts') = Type (ts@ts')
| produce (Type ts') (TopType ts) = TopType ts
| produce (TopType ts') (TopType ts) = TopType ts
| produce - - = Bot

fun type-update :: checker-type ⇒ ct list ⇒ checker-type ⇒ checker-type where
  type-update curr-type cons prods = produce (consume curr-type cons) prods
```

```
fun select-return-top :: [ct list] ⇒ ct ⇒ ct ⇒ checker-type where
  select-return-top ts ct1 TAny = TopType ((take (length ts − 3) ts) @ [ct1])
| select-return-top ts TAny ct2 = TopType ((take (length ts − 3) ts) @ [ct2])
| select-return-top ts (TSome t1) (TSome t2) = (if (t1 = t2)
                                                 then (TopType ((take (length ts − 3) ts)
@ [TSome t1]))
                                                 else Bot)

fun type-update-select :: checker-type ⇒ checker-type where
  type-update-select (Type ts) = (if (length ts ≥ 3 ∧ (ts!(length ts−2)) = (ts!(length
ts−3)))
                                  then consume (Type ts) [TAny, TSome T-i32]
                                  else Bot)
| type-update-select (TopType ts) = (case length ts of
                                       0 ⇒ TopType [TAny]
                                     | Suc 0 ⇒ type-update (TopType ts) [TSome T-i32]
(TopType [TAny])
                                     | Suc (Suc 0) ⇒ consume (TopType ts) [TSome
T-i32]
                                     | - ⇒ type-update (TopType ts) [TAny, TAny,
TSome T-i32]
                                                 (select-return-top ts (ts!(length ts−2))
(ts!(length ts−3))))
| type-update-select - = Bot

fun c-types-agree :: checker-type ⇒ t list ⇒ bool where
  c-types-agree (Type ts) ts′ = (ts = ts′)
| c-types-agree (TopType ts) ts′ = ct-suffix ts (to-ct-list ts′)
| c-types-agree Bot - = False

lemma consume-type:
  assumes consume (Type ts) ts′ = c-t
          c-t ≠ Bot
  shows ∃ ts′′. ct-list-eq (to-ct-list ts) ((to-ct-list ts′′)@ts′) ∧ c-t = Type ts′′
proof −
  {
   assume a1: (if ct-suffix ts′ (map TSome ts) then Type (take (length ts − length
ts′) ts) else Bot) = c-t
    assume a2: c-t ≠ Bot
    obtain ccs :: ct list ⇒ ct list ⇒ ct list and ccsa :: ct list ⇒ ct list ⇒ ct list
where
      f3: ∀ cs csa. ¬ ct-suffix cs csa ∨ csa = ccs cs csa @ ccsa cs csa ∧ ct-list-eq
(ccsa cs csa) cs
      using ct-suffixE by moura
    have f4: ct-suffix ts′ (map TSome ts)
      using a2 a1 by metis
    then have f5: ct-list-eq (ccsa ts′ (map TSome ts)) ts′
      using f3 by blast
     have f6: take (length (map TSome ts) − length (ccsa ts′ (map TSome ts)))
```

```
(map TSome ts) @ ccsa ts' (map TSome ts) = map TSome ts
      using f4 f3 by (metis (full-types) suffixI suffix-take)
    have ⋀cs. ct-list-eq (cs @ ccsa ts' (map TSome ts)) (cs @ ts')
      using f5 ct-list-eq-concat ct-list-eq-refl by blast
    then have ∃tsa. ct-list-eq (map TSome ts) (map TSome tsa @ ts') ∧ c-t =
Type tsa
      using f6 f5 f4 a1 by (metis (no-types) ct-list-eq-length length-map take-map)
  }
  thus ?thesis
    using assms to-ct-list-def
    by simp
qed

lemma consume-top-geq:
  assumes consume (TopType ts) ts' = c-t
          length ts ≥ length ts'
          c-t ≠ Bot
  shows (∃as bs. ts = as@bs ∧ ct-list-eq bs ts' ∧ c-t = TopType as)
proof −
  consider (1) ct-suffix ts' ts
         | (2) ¬ct-suffix ts' ts ct-suffix ts ts'
         | (3) ¬ct-suffix ts' ts ¬ct-suffix ts ts'
    by blast
  thus ?thesis
  proof (cases)
    case 1
    hence TopType (take (length ts − length ts') ts) = c-t
      using assms
      by simp
    thus ?thesis
      using assms(2) 1 ct-list-eq-def
      unfolding ct-suffix-def
    by (metis (no-types, lifting) append-eq-append-conv append-take-drop-id diff-diff-cancel
length-drop list-all2-lengthD)
  next
    case 2
    thus ?thesis
      using assms append-eq-append-conv ct-list-eq-commute
      unfolding ct-suffix-def
      by (metis append.left-neutral ct-suffix-def ct-suffix-length le-antisym)
  next
    case 3
    thus ?thesis
      using assms
      by auto
  qed
qed

lemma consume-top-leq:
```

**assumes** *consume* (*TopType ts*) *ts′* = *c-t*
*length ts* ≤ *length ts′*
*c-t* ≠ *Bot*
**shows** *c-t* = *TopType* []
**using** *assms append-eq-conv-conj*
**by** *fastforce*

**lemma** *consume-type-type*:
**assumes** *consume xs cons* = (*Type t-int*)
**shows** ∃ *tn*. *xs* = *Type tn*
**using** *assms*
**apply** (*cases xs*)
**apply** *simp-all*
**apply** (*metis checker-type.distinct*(*1*) *checker-type.distinct*(*5*))
**done**

**lemma** *produce-type-type*:
**assumes** *produce xs cons* = (*Type tm*)
**shows** ∃ *tn*. *xs* = *Type tn*
**apply** (*cases xs*; *cases cons*)
**using** *assms*
**apply** *simp-all*
**done**

**lemma** *consume-weaken-type*:
**assumes** *consume* (*Type tn*) *cons* = (*Type t-int*)
**shows** *consume* (*Type* (*ts*@*tn*)) *cons* = (*Type* (*ts*@*t-int*))
**proof** −
**obtain** *ts′* **where** *ct-list-eq* (*to-ct-list tn*) (*to-ct-list ts′* @ *cons*) ∧ *Type t-int* = *Type ts′*
**using** *consume-type*[*OF assms*]
**by** *blast*
**have** *cond*:*ct-suffix cons* (*to-ct-list tn*)
**using** *assms*
**by** (*simp*, *metis checker-type.distinct*(*5*))
**hence** *res*:*t-int* = *take* (*length tn* − *length cons*) *tn*
**using** *assms*
**by** *simp*
**have** *ct-suffix cons* (*to-ct-list* (*ts*@*tn*))
**using** *cond*
**unfolding** *to-ct-list-def*
**by** (*metis append-assoc ct-suffix-def map-append*)
**moreover**
**have** *ts*@*t-int* = *take* (*length* (*ts*@*tn*) − *length cons*) (*ts*@*tn*)
**using** *res take-append cond ct-suffix-length to-ct-list-def*
**by** *fastforce*
**ultimately**
**show** *?thesis*
**by** *simp*

**qed**

**lemma** *produce-weaken-type*:
**assumes** *produce* (*Type tn*) *cons* = (*Type tm*)
**shows** *produce* (*Type* (*ts*@*tn*)) *cons* = (*Type* (*ts*@*tm*))
**using** *assms*
**by** (*cases cons*, *simp-all*)

**lemma** *produce-nil*: *produce ts* (*Type* []) = *ts*
**using** *to-ct-list-def*
**by** (*cases ts*, *simp-all*)

**lemma** *c-types-agree-id*: *c-types-agree* (*Type ts*) *ts*
**by** *simp*

**lemma** *c-types-agree-top1*: *c-types-agree* (*TopType* []) *ts*
**using** *ct-suffix-ts-conv-suffix to-ct-list-def*
**by** (*simp add*: *ct-suffix-nil*)

**lemma** *c-types-agree-top2*:
**assumes** *ct-list-eq ts* (*to-ct-list ts''*)
**shows** *c-types-agree* (*TopType ts*) (*ts'*@*ts''*)
**using** *assms ct-list-eq-commute ct-suffix-def to-ct-list-def*
**by** *auto*

**lemma** *c-types-agree-imp-ct-list-eq*:
**assumes** *c-types-agree* (*TopType cts*) *ts*
**shows** ∃ *ts' ts''*. (*ts* = *ts'*@*ts''*) ∧ *ct-list-eq cts* (*to-ct-list ts''*)
**using** *assms ct-suffix-def to-ct-list-def*
**by** (*simp*, *metis ct-list-eq-commute ct-list-eq-ts-conv-eq ct-suffix-ts-conv-suffix suffixE*
*to-ct-list-append*(*2*))

**lemma** *c-types-agree-not-bot-exists*:
**assumes** *ts* ≠ *Bot*
**shows** ∃ *ts-c*. *c-types-agree ts ts-c*
**using** *assms ct-suffix-exists*
**by** (*cases ts*, *simp-all*)

**lemma** *consume-c-types-agree*:
**assumes** *consume* (*Type ts*) *cts* = (*Type ts'*)
*c-types-agree ctn ts*
**shows** ∃ *c-t'*. *consume ctn cts* = *c-t'* ∧ *c-types-agree c-t' ts'*
**using** *assms*
**proof** (*cases ctn*)
**case** (*TopType x1*)
**have** *1*:*ct-suffix cts* (*to-ct-list ts*)
**using** *assms*
**by** (*simp*, *metis checker-type.distinct*(*5*))

**hence** *ct-suffix cts x1* ∨ *ct-suffix x1 cts*
**using** *TopType 1 assms*(*2*) *ct-suffix-shared*
**by** *simp*
**thus** *?thesis*
**proof** (*rule disjE*)
**assume** *local-assms*:*ct-suffix cts x1*
**hence** *2*:*consume* (*TopType x1*) *cts* = *TopType* (*take* (*length x1* − *length cts*) *x1*)
**by** *simp*
**have** (*take* (*length ts* − *length cts*) *ts*) = *ts*′
**using** *assms 1*
**by** *simp*
**hence** *c-types-agree* (*TopType* (*take* (*length x1* − *length cts*) *x1*)) *ts*′
**using** *2 assms local-assms TopType ct-suffix-take*
**by** (*simp*, *metis length-map take-map to-ct-list-def*)
**thus** *?thesis*
**using** *2 TopType*
**by** *simp*
**next**
**assume** *local-assms*:*ct-suffix x1 cts*
**hence** *3*:*consume* (*TopType x1*) *cts* = *TopType* []
**by** (*simp add*: *ct-suffix-length*)
**thus** *?thesis*
**using** *TopType c-types-agree-top1*
**by** *blast*
**qed**
**qed** *simp-all*

**lemma** *type-update-type*:
**assumes** *type-update* (*Type ts*) (*to-ct-list cons*) *prods* = *ts*′
*ts*′ ≠ *Bot*
**shows** (*ts*′ = *prods* ∧ (∃ *ts-c*. *prods* = (*TopType ts-c*)))
∨ (∃ *ts-a ts-b*. *prods* = *Type ts-a* ∧ *ts* = *ts-b*@*cons* ∧ *ts*′ = *Type* (*ts-b*@*ts-a*))
**using** *assms*
**apply** (*cases prods*)
**apply** *simp-all*
**apply** (*metis* (*full-types*) *produce.simps*(*3*) *produce.simps*(*7*))
**using** *ct-suffix-ts-conv-suffix suffix-take to-ct-list-def*
**apply** *fastforce*
**done**

**lemma** *type-update-empty*: *type-update ts cons* (*Type* []) = *consume ts cons*
**using** *produce-nil*
**by** *simp*

**lemma** *type-update-top-top*:
**assumes** *type-update* (*TopType ts*) (*to-ct-list cons*) (*Type prods*) = (*TopType ts*′)

```
        c-types-agree (TopType ts') t-ag
  shows ct-suffix (to-ct-list prods) ts'
      ∃ t-ag'. t-ag = t-ag'@prods ∧ c-types-agree (TopType ts) (t-ag'@cons)
proof −
  consider (1) ct-suffix (to-ct-list cons) ts
      | (2) ¬ct-suffix (to-ct-list cons) ts ct-suffix ts (to-ct-list cons)
      | (3) ¬ct-suffix (to-ct-list cons) ts ¬ct-suffix ts (to-ct-list cons)
    by blast
  hence ct-suffix (to-ct-list prods) ts' ∧ (∃ t-ag'. t-ag = t-ag'@prods ∧ c-types-agree
(TopType ts) (t-ag'@cons))
  proof (cases)
    case 1
    hence ts' = (take (length ts − length cons) ts) @ to-ct-list prods
      using assms(1) to-ct-list-def
      by simp
    moreover
    then obtain t-ag' where t-ag = t-ag' @ prods
                        ct-suffix (take (length ts − length cons) ts) (to-ct-list t-ag')
      using assms(2) ct-suffix-cons-ct-list1
      unfolding c-types-agree.simps
      by blast
    moreover
    hence ct-suffix ts (to-ct-list (t-ag'@cons))
      using 1 ct-suffix-imp-ct-list-eq ct-suffix-extend-ct-list-eq to-ct-list-def
      by fastforce
    ultimately
    show ?thesis
      using c-types-agree.simps(2) ct-list-eq-ts-conv-eq ct-suffix-def
      by auto
  next
    case 2
    thus ?thesis
      using assms
        by (metis append.assoc c-types-agree.simps(2) checker-type.inject(1) con-
sume.simps(2)
              ct-list-eq-ts-conv-eq ct-suffix-cons-ct-list ct-suffix-def map-append
              produce.simps(1) to-ct-list-def type-update.simps)
  next
    case 3
    thus ?thesis
      using assms
      by simp
  qed
  thus ct-suffix (to-ct-list prods) ts'
      ∃ t-ag'. t-ag = t-ag'@prods ∧ c-types-agree (TopType ts) (t-ag'@cons)
  by simp-all
qed

lemma type-update-select-length0:
```

**assumes** *type-update-select* (*TopType cts*) = *tm*
*length cts* = *0*
*tm* ≠ *Bot*
**shows** *tm* = *TopType* [*TAny*]
**using** *assms*
**by** *simp*

**lemma** *type-update-select-length1*:
**assumes** *type-update-select* (*TopType cts*) = *tm*
*length cts* = *1*
*tm* ≠ *Bot*
**shows** *ct-list-eq cts* [*TSome T-i32*]
*tm* = *TopType* [*TAny*]
**proof** −
**have** *1*:*type-update* (*TopType cts*) [*TSome T-i32*] (*TopType* [*TAny*]) = *tm*
**using** *assms*(*1*,*2*)
**by** *simp*
**hence** *ct-suffix cts* [*TSome T-i32*] ∨ *ct-suffix* [*TSome T-i32*] *cts*
**using** *assms*(*3*)
**by** (*metis consume.simps*(*2*) *produce.simps*(*7*) *type-update.simps*)
**thus** *ct-list-eq cts* [*TSome T-i32*]
**using** *assms*(*2*,*3*) *ct-suffix-imp-ct-list-eq*
**by** (*metis One-nat-def Suc-length-conv ct-list-eq-commute diff-Suc-1 drop-0 list.size*(*3*))
**show** *tm* = *TopType* [*TAny*]
**using** *1 assms*(*3*) *consume-top-leq*
**by** (*metis One-nat-def assms*(*2*) *diff-Suc-1 diff-is-0-eq length-Cons list.size*(*3*) *produce.simps*(*4*,*7*) *type-update.simps*)
**qed**

**lemma** *type-update-select-length2*:
**assumes** *type-update-select* (*TopType cts*) = *tm*
*length cts* = *2*
*tm* ≠ *Bot*
**shows** ∃ *t1 t2*. *cts* = [*t1*, *t2*] ∧ *ct-eq t2* (*TSome T-i32*) ∧ *tm* = *TopType* [*t1*]
**proof** −
**obtain** *x y* **where** *cts-def*:*cts* = [*x*,*y*]
**using** *assms*(*2*) *List.length-Suc-conv*[*of cts Suc 0*]
**by** (*metis length-0-conv length-Suc-conv numeral-2-eq-2*)
**moreover**
**hence** *consume* (*TopType* [*x*,*y*]) [*TSome T-i32*] = *tm*
**using** *assms*(*1*,*2*)
**by** *simp*
**moreover**
**hence** *ct-suffix* [*x*,*y*] [*TSome T-i32*] ∨ *ct-suffix* [*TSome T-i32*] [*x*,*y*]
**using** *assms*(*3*)
**by** (*metis consume.simps*(*2*))
**hence** *ct-suffix* [*TSome T-i32*] ([*x*]@[*y*])

**using** *assms*(*2*) *ct-suffix-length*
**by** *fastforce*
**moreover**
**hence** *ct-eq y* (*TSome T-i32*)
**by** (*metis ct-eq-commute ct-list-eq-def ct-suffix-cons2 list.rel-sel list.sel*(*1*) *list.simps*(*3*) *list.size*(*4*))
**ultimately**
**show** *?thesis*
**by** *auto*
**qed**

**lemma** *type-update-select-length3*:
**assumes** *type-update-select* (*TopType cts*) = (*TopType ctm*)
*length cts* ≥ *3*
**shows** ∃ *cts' ct1 ct2 ct3*. *cts* = *cts'*@[*ct1*, *ct2*, *ct3*] ∧ *ct-eq ct3* (*TSome T-i32*)
**proof** −
**obtain** *cts' cts''* **where** *cts-def*:*cts* = *cts'*@ *cts''* *length cts''* = *3*
**using** *assms*(*2*)
**by** (*metis append-take-drop-id diff-diff-cancel length-drop*)
**then obtain** *ct1 cts''2* **where** *cts''* = *ct1*#*cts''2* *length cts''2* = *Suc* (*Suc 0*)
**using** *List.length-Suc-conv*[*of cts' Suc* (*Suc 0*)]
**by** (*metis length-Suc-conv numeral-3-eq-3*)
**then obtain** *ct2 ct3* **where** *cts''* = [*ct1*,*ct2*,*ct3*]
**using** *List.length-Suc-conv*[*of cts''2 Suc 0*]
**by** (*metis length-0-conv length-Suc-conv*)
**hence** *cts-def2*:*cts* = *cts'*@ [*ct1*,*ct2*,*ct3*]
**using** *cts-def*
**by** *simp*
**obtain** *nat* **where** *length cts* = *Suc* (*Suc* (*Suc nat*))
**using** *assms*(*2*)
**by** (*simp add*: *cts-def*)
**hence** (*type-update* (*TopType cts*) [*TAny*, *TAny*, *TSome T-i32*] (*select-return-top cts* (*cts* ! (*length cts* − *2*)) (*cts* ! (*length cts* − *3*)))) = *TopType ctm*
**using** *assms*
**by** *simp*
**then obtain** *c-mid* **where** *consume* (*TopType cts*) [*TAny*, *TAny*, *TSome T-i32*] = *TopType c-mid*
**by** (*metis consume.simps*(*2*) *produce.simps*(*6*) *type-update.simps*)
**hence** *ct-suffix* [*TAny*, *TAny*, *TSome T-i32*] (*cts'*@ [*ct1*,*ct2*,*ct3*])
**using** *assms*(*2*) *consume-top-geq cts-def2*
**by** (*metis checker-type.distinct*(*3*) *ct-suffix-def length-Cons list.size*(*3*) *numeral-3-eq-3*)
**hence** *ct-eq ct3* (*TSome T-i32*)
**using** *ct-suffix-def ct-list-eq-def*
**by** (*simp*, *metis append-eq-append-conv length-Cons list-all2-Cons list-all2-lengthD*)
**thus** *?thesis*
**using** *cts-def2*
**by** *simp*
**qed**

**lemma** *type-update-select-type-length3*:
**assumes** *type-update-select* (*Type tn*) = (*Type tm*)
**shows** ∃ *t ts'*. *tn* = *ts'*@[*t*, *t*, *T-i32*]
**proof** −
**have** *tn-cond*:(*length tn* ≥ *3* ∧ (*tn*!(*length tn*−*2*)) = (*tn*!(*length tn*−*3*)))
**using** *assms*
**by** (*simp*, *metis checker-type.distinct*(*5*))
**hence** *tm-def*:*consume* (*Type tn*) [*TAny*, *TSome T-i32*] = *Type tm*
**using** *assms*
**by** *simp*
**obtain** *tn' tn''* **where** *tn-split*:*tn* = *tn'*@*tn''*
*length tn''* = *3*
**using** *assms tn-cond*
**by** (*metis append-take-drop-id diff-diff-cancel length-drop*)
**then obtain** *t1 tn''2* **where** *tn''* = *t1*#*tn''2 length tn''2* = *Suc* (*Suc 0*)
**by** (*metis length-Suc-conv numeral-3-eq-3*)
**then obtain** *t2 t3* **where** *tn''-def*:*tn''* = [*t1*,*t2*,*t3*]
**using** *List.length-Suc-conv*[*of tn''2 Suc 0*]
**by** (*metis length-0-conv length-Suc-conv*)
**hence** *tn-def*:*tn* = *tn'*@ [*t1*,*t2*,*t3*]
**using** *tn-split*
**by** *simp*
**hence** *t1-t2-eq*:*t1* = *t2*
**using** *tn-cond*
**by** (*metis* (*no-types*, *lifting*) *Suc-diff-Suc Suc-eq-plus1-left Suc-lessD tn''-def*
*add-diff-cancel-right' diff-is-0-eq length-append neq0-conv*
*not-less-eq-eq nth-Cons-0 nth-Cons-numeral*
*nth-append numeral-2-eq-2 numeral-3-eq-3 numeral-One*
*tn-split*(*2*)
*zero-less-diff*)
**have** *ct-suffix* [*TAny*, *TSome T-i32*] (*to-ct-list* (*tn'* @ [*t1*, *t2*, *t3*]))
**using** *tn-def tm-def*
**by** (*simp*, *metis checker-type.distinct*(*5*))
**hence** *t3* = *T-i32*
**using** *ct-suffix-unfold-one*[*of* [*TAny*] *TSome T-i32 to-ct-list* (*tn'* @ [*t1*, *t2*])
*TSome t3*]
*ct-eq.simps*(*1*)
**unfolding** *to-ct-list-def*
**by** *simp*
**thus** *?thesis*
**using** *t1-t2-eq tn-def*
**by** *simp*
**qed**

**lemma** *select-return-top-exists*:
**assumes** *select-return-top cts c1 c2* = *ctm*
*ctm* ≠ *Bot*
**shows** ∃ *xs*. *ctm* = *TopType xs*

```
  using assms
  by (meson select-return-top.elims)

lemma type-update-select-top-exists:
  assumes type-update-select xs = (TopType tm)
  shows ∃ tn. xs = TopType tn
  using assms
proof (cases xs)
  case (Type x2)
  thus ?thesis
    using assms
   by (simp, metis checker-type.distinct(1) checker-type.distinct(3) consume.simps(1))
qed simp-all

lemma type-update-select-conv-select-return-top:
  assumes ct-suffix [TSome T-i32] cts
          length cts ≥ 3
 shows type-update-select (TopType cts) = (select-return-top cts (cts!(length cts−2))
(cts!(length cts−3)))
proof −
  obtain nat where nat-def:length cts = Suc (Suc (Suc nat))
    using assms(2)
    by (metis add-eq-if diff-Suc-1 le-Suc-ex numeral-3-eq-3 nat.distinct(2))
  have ct-suffix [TAny, TAny, TSome T-i32] cts
    using assms ct-suffix-extend-any1
    by simp
  then obtain cts′ where consume (TopType cts) [TAny, TAny, TSome T-i32] =
TopType cts′
    by simp
  thus ?thesis
    using nat-def select-return-top-exists
    apply (cases select-return-top cts (cts ! Suc nat) (cts ! nat))
      apply simp-all
    apply (metis checker-type.distinct(1) checker-type.distinct(5))
    done
qed

lemma select-return-top-ct-eq:
  assumes select-return-top cts c1 c2 = TopType ctm
          length cts ≥ 3
          c-types-agree (TopType ctm) cm
  shows ∃ c′ cm′. cm = cm′@[c′]
                ∧ ct-suffix (take (length cts − 3) cts) (to-ct-list cm′)
                ∧ ct-eq c1 (TSome c′)
                ∧ ct-eq c2 (TSome c′)
proof (cases c1)
  case TAny
  note outer-TAny = TAny
  show ?thesis
```

```
  proof (cases c2)
    case TAny
    hence take (length cts − 3) cts @ [TAny] = ctm
      using outer-TAny  assms ct-suffix-cons-ct-list
      by simp
    then obtain cm' c where cm = cm' @ [c]
                            ct-suffix (take (length cts − 3) cts) (to-ct-list cm')
      using ct-suffix-cons-ct-list[of take (length cts − 3) cts [TAny]]
          assms(3) c-types-agree.simps(2)[of ctm cm]
      unfolding ct-list-eq-def to-ct-list-def
     by (metis Suc-leI impossible-Cons length-Cons length-map list.exhaust list.size(3)
              list-all2-conv-all-nth zero-less-Suc)
    thus ?thesis
      using TAny outer-TAny ct-eq.simps(2)
      by blast
  next
    case (TSome x2)
    hence take (length cts − 3) cts @ [TSome x2] = ctm
      using outer-TAny assms ct-suffix-cons-ct-list
      by simp
    then obtain cm' where cm = cm' @ [x2]
                          ct-suffix (take (length cts − 3) cts) (to-ct-list cm')
      using ct-suffix-cons-ct-list[of take (length cts − 3) cts [TSome x2]]
          assms(3) c-types-agree.simps(2)[of ctm cm] ct-list-eq-ts-conv-eq
      unfolding ct-list-eq-def to-ct-list-def
      by (metis (no-types, opaque-lifting) list.simps(8,9))
    thus ?thesis
      using TSome outer-TAny
      by simp
  qed
next
  case (TSome x2)
  note outer-TSome = TSome
  show ?thesis
  proof (cases c2)
    case TAny
    hence take (length cts − 3) cts @ [TSome x2] = ctm
      using TSome assms ct-suffix-cons-ct-list
      by simp
    then obtain cm' where cm = cm' @ [x2]
                          ct-suffix (take (length cts − 3) cts) (to-ct-list cm')
      using ct-suffix-cons-ct-list[of take (length cts − 3) cts [TSome x2]]
          assms(3) c-types-agree.simps(2)[of ctm cm] ct-list-eq-ts-conv-eq
      unfolding ct-list-eq-def to-ct-list-def
      by (metis (no-types, opaque-lifting) list.simps(8,9))
    thus ?thesis
      using TSome TAny
      by simp
  next
```

```
    case (TSome x3)
    hence x-eq:x2 = x3
      using outer-TSome assms ct-suffix-cons-ct-list
      by (metis checker-type.distinct(3) select-return-top.simps(3))
    hence take (length cts − 3) cts @ [TSome x2] = ctm
      using TSome outer-TSome assms ct-suffix-cons-ct-list
      by (metis checker-type.inject(1) select-return-top.simps(3))
    then obtain cm' where cm = cm' @ [x2]
                          ct-suffix (take (length cts − 3) cts) (to-ct-list cm')
      using ct-suffix-cons-ct-list[of take (length cts − 3) cts [TSome x2]]
            assms(3) c-types-agree.simps(2)[of ctm cm] ct-list-eq-ts-conv-eq
      unfolding ct-list-eq-def to-ct-list-def
      by (metis (no-types, opaque-lifting) list.simps(8,9))
    thus ?thesis
      using TSome outer-TSome x-eq
      by simp
  qed
qed

end
```

# 9 Executable Type Checker

```
theory Wasm-Checker imports Wasm-Checker-Types begin

fun convert-cond :: t ⇒ t ⇒ sx option ⇒ bool where
  convert-cond t1 t2 sx = ((t1 ≠ t2) ∧ (sx = None) = ((is-float-t t1 ∧ is-float-t
t2)
                                                    ∨ (is-int-t t1 ∧ is-int-t t2 ∧ (t-length
t1 < t-length t2))))

fun same-lab-h :: nat list ⇒ (t list) list ⇒ t list ⇒ (t list) option where
  same-lab-h [] - ts = Some ts
| same-lab-h (i#is) lab-c ts = (if i ≥ length lab-c
                                then None
                                else (if lab-c!i = ts
                                      then same-lab-h is lab-c (lab-c!i)
                                      else None))

fun same-lab :: nat list ⇒ (t list) list ⇒ (t list) option where
  same-lab [] lab-c = None
| same-lab (i#is) lab-c = (if i ≥ length lab-c
                           then None
                           else same-lab-h is lab-c (lab-c!i))

lemma same-lab-h-conv-list-all:
  assumes same-lab-h ils ls ts' = Some ts
  shows list-all (λi. i < length ls ∧ ls!i = ts) ils ∧ ts' = ts
  using assms
```

```
proof(induction ils)
  case (Cons a ils)
  thus ?case
    apply (simp,safe)
      apply (metis not-less option.distinct(1))+
    done
qed simp

lemma same-lab-conv-list-all:
  assumes same-lab ils ls = Some ts
  shows list-all (λi. i < length ls ∧ ls!i = ts) ils
  using assms
proof (induction rule: same-lab.induct)
case (2 i is lab-c)
  thus ?case
    using same-lab-h-conv-list-all
   by (metis (mono-tags, lifting) list-all-simps(1) not-less option.distinct(1) same-lab.simps(2))
qed simp

lemma list-all-conv-same-lab-h:
  assumes list-all (λi. i < length ls ∧ ls!i = ts) ils
  shows same-lab-h ils ls ts = Some ts
  using assms
  by (induction ils, simp-all)

lemma list-all-conv-same-lab:
  assumes list-all (λi. i < length ls ∧ls!i = ts) (is@[i])
  shows same-lab (is@[i]) ls = Some ts
  using assms
proof (induction (is@[i]))
  case (Cons a x)
  thus ?case
    using list-all-conv-same-lab-h[OF Cons(3)]
    by (metis option.distinct(1) same-lab.simps(2) same-lab-h.simps(2))
qed auto

fun b-e-type-checker :: t-context ⇒  b-e list ⇒ tf ⇒ bool
and check :: t-context ⇒ b-e list ⇒ checker-type ⇒ checker-type
and check-single :: t-context ⇒  b-e ⇒ checker-type ⇒ checker-type where
  b-e-type-checker C es (tn -> tm) = c-types-agree (check C es (Type tn)) tm
| check C es ts = (case es of
                     [] ⇒ ts
                   | (e#es) ⇒ (case ts of
                                  Bot ⇒ Bot
                                | - ⇒ check C es (check-single C e ts)))


| check-single C (C v) ts = type-update ts [] (Type [typeof v])
| check-single C (Unop-i t -) ts = (if is-int-t t
```

```
                                then type-update ts [TSome t] (Type [t])
                                else Bot)
| check-single C (Unop-f t -) ts = (if is-float-t t
                                then type-update ts [TSome t] (Type [t])
                                else Bot)
| check-single C (Binop-i t -) ts = (if is-int-t t
                                then type-update ts [TSome t, TSome t] (Type [t])
                                else Bot)
| check-single C (Binop-f t -) ts = (if is-float-t t
                                then type-update ts [TSome t, TSome t] (Type [t])
                                else Bot)
| check-single C (Testop t -) ts = (if is-int-t t
                                then type-update ts [TSome t] (Type [T-i32])
                                else Bot)
| check-single C (Relop-i t -) ts = (if is-int-t t
                                    then type-update ts [TSome t, TSome t] (Type
[T-i32])
                                else Bot)
| check-single C (Relop-f t -) ts =  (if is-float-t t
                                    then type-update ts [TSome t, TSome t] (Type
[T-i32])
                                else Bot)

| check-single C (Cvtop t1 Convert t2 sx) ts = (if (convert-cond t1 t2 sx)
                                        then type-update ts [TSome t2] (Type [t1])
                                          else Bot)

| check-single C (Cvtop t1 Reinterpret t2 sx) ts = (if ((t1 ≠ t2) ∧ t-length t1 =
t-length t2 ∧ sx = None)
                                                then type-update ts [TSome t2] (Type
[t1])
                                                  else Bot)

| check-single C (Unreachable) ts = type-update ts [] (TopType [])
| check-single C (Nop) ts = ts
| check-single C (Drop) ts = type-update ts [TAny] (Type [])
| check-single C (Select) ts = type-update-select ts

| check-single C (Block (tn -> tm) es) ts = (if (b-e-type-checker (C⦇label := ([tm]
@ (label C))⦈) es (tn -> tm))
                                        then type-update ts (to-ct-list tn) (Type tm)
                                         else Bot)

| check-single C (Loop (tn -> tm) es) ts = (if (b-e-type-checker (C⦇label := ([tn] @
(label C))⦈) es (tn -> tm))
                                        then type-update ts (to-ct-list tn) (Type tm)
                                         else Bot)

| check-single C (If (tn -> tm) es1 es2) ts = (if (b-e-type-checker (C⦇label := ([tm]
```

```
@ (label C))|)) es1 (tn -> tm)
                                        ∧ b-e-type-checker (C(|label := ([tm] @
(label C))|)) es2 (tn -> tm))
                                    then type-update ts (to-ct-list (tn@[T-i32]))
(Type tm)
                                    else Bot)

| check-single C (Br i) ts = (if i < length (label C)
                              then type-update ts (to-ct-list ((label C)!i)) (TopType [])
                              else Bot)

| check-single C (Br-if i) ts = (if i < length (label C)
                                 then type-update ts (to-ct-list ((label C)!i @ [T-i32]))
(Type ((label C)!i))
                                 else Bot)

| check-single C (Br-table is i) ts = (case (same-lab (is@[i]) (label C)) of
                                        None ⇒ Bot
                                      | Some tls ⇒ type-update ts (to-ct-list (tls @ [T-i32]))
(TopType []))

| check-single C (Return) ts = (case (return C) of
                                 None ⇒ Bot
                               | Some tls ⇒ type-update ts (to-ct-list tls) (TopType []))

| check-single C (Call i) ts = (if i < length (func-t C)
                                 then (case ((func-t C)!i) of
                                       (tn -> tm) ⇒ type-update ts (to-ct-list tn) (Type
tm))
                                 else Bot)

| check-single C (Call-indirect i) ts = (if (table C) ≠ None ∧ i < length (types-t C)
                                          then (case ((types-t C)!i) of
                                                (tn -> tm) ⇒ type-update ts (to-ct-list
(tn@[T-i32])) (Type tm))
                                          else Bot)

| check-single C (Get-local i) ts = (if i < length (local C)
                                      then type-update ts [] (Type [(local C)!i])
                                      else Bot)

| check-single C (Set-local i) ts = (if i < length (local C)
                                     then type-update ts [TSome ((local C)!i)] (Type [])
                                     else Bot)

| check-single C (Tee-local i) ts = (if i < length (local C)
                                     then type-update ts [TSome ((local C)!i)] (Type [(local
C)!i])
                                     else Bot)
```

| *check-single* $\mathcal{C}$ (*Get-global i*) *ts* = (*if i* < *length* (*global* $\mathcal{C}$)
*then type-update ts* [] (*Type* [*tg-t* ((*global* $\mathcal{C}$)!*i*)])
*else Bot*)

| *check-single* $\mathcal{C}$ (*Set-global i*) *ts* = (*if i* < *length* (*global* $\mathcal{C}$) ∧ *is-mut* (*global* $\mathcal{C}$ ! *i*)
*then type-update ts* [*TSome* (*tg-t* ((*global* $\mathcal{C}$)!*i*))]
(*Type* [])
*else Bot*)

| *check-single* $\mathcal{C}$ (*Load t tp-sx a off*) *ts* = (*if* (*memory* $\mathcal{C}$) ≠ *None* ∧ *load-store-t-bounds a* (*option-projl tp-sx*) *t*
*then type-update ts* [*TSome T-i32*] (*Type* [*t*])
*else Bot*)

| *check-single* $\mathcal{C}$ (*Store t tp a off*) *ts* = (*if* (*memory* $\mathcal{C}$) ≠ *None* ∧ *load-store-t-bounds a tp t*
*then type-update ts* [*TSome T-i32*,*TSome t*]
(*Type* [])
*else Bot*)

| *check-single* $\mathcal{C}$ *Current-memory ts* = (*if* (*memory* $\mathcal{C}$) ≠ *None*
*then type-update ts* [] (*Type* [*T-i32*])
*else Bot*)

| *check-single* $\mathcal{C}$ *Grow-memory ts* = (*if* (*memory* $\mathcal{C}$) ≠ *None*
*then type-update ts* [*TSome T-i32*] (*Type* [*T-i32*])
*else Bot*)

**end**

# 10 Correctness of Type Checker

**theory** *Wasm-Checker-Properties* **imports** *Wasm-Checker Wasm-Properties* **begin**

## 10.1 Soundness

**lemma** *b-e-check-single-type-sound*:
**assumes** *type-update* (*Type x1*) (*to-ct-list t-in*) (*Type t-out*) = *Type x2*
*c-types-agree* (*Type x2*) *tm*
$\mathcal{C}$ ⊢ [*e*] : (*t-in* -> *t-out*)
**shows** ∃ *tn*. *c-types-agree* (*Type x1*) *tn* ∧ $\mathcal{C}$ ⊢ [*e*] : (*tn* -> *tm*)
**using** *assms*(*2*) *b-e-typing.intros*(*35*)[*OF assms*(*3*)] *type-update-type*[*OF assms*(*1*)]
**by** *auto*

**lemma** *b-e-check-single-top-sound*:
**assumes** *type-update* (*TopType x1*) (*to-ct-list t-in*) (*Type t-out*) = *TopType x2*
*c-types-agree* (*TopType x2*) *tm*

$\mathcal{C} \vdash [e] : (t\text{-}in \text{ -> } t\text{-}out)$
**shows** $\exists tn.\ c\text{-}types\text{-}agree\ (TopType\ x1)\ tn \wedge \mathcal{C} \vdash [e] : (tn \text{ -> } tm)$
**proof** −
**obtain** *t-ag* **where** *t-ag-def*:*ct-suffix* (*to-ct-list t-out*) *x2*
*tm* = *t-ag* @ *t-out*
*c-types-agree* (*TopType x1*) (*t-ag* @ *t-in*)
**using** *type-update-top-top*[*OF assms*(*1*,*2*)]
**by** *fastforce*
**hence** $\mathcal{C} \vdash [e] : (t\text{-}ag@t\text{-}in \text{ -> } t\text{-}ag@t\text{-}out)$
**using** *b-e-typing.intros*(*35*)[*OF assms*(*3*)]
**by** *fastforce*
**thus** *?thesis*
**using** *t-ag-def*
**by** *fastforce*
**qed**

**lemma** *b-e-check-single-top-not-bot-sound*:
**assumes** *type-update ts* (*to-ct-list t-in*) (*TopType* []) = *ts′*
*ts* ≠ *Bot*
*ts′* ≠ *Bot*
**shows** ∃ *tn*. *c-types-agree ts tn* ∧ *suffix t-in tn*
**proof** (*cases ts*)
**case** (*TopType x1*)
**then obtain** *t-int* **where** *consume* (*TopType x1*) (*to-ct-list t-in*) = *t-int t-int* ≠ *Bot*
**using** *assms*(*1*,*2*,*3*)
**by** *fastforce*
**thus** *?thesis*
**using** *TopType ct-suffix-ct-list-eq-exists ct-suffix-ts-conv-suffix*
**unfolding** *consume.simps*
**by** (*metis append-Nil c-types-agree.simps*(*2*) *ct-suffix-def*)
**next**
**case** (*Type x2*)
**then obtain** *t-int* **where** *consume* (*Type x2*) (*to-ct-list t-in*) = *t-int t-int* ≠ *Bot*
**using** *assms*(*1*,*2*,*3*)
**by** *fastforce*
**thus** *?thesis*
**using** *c-types-agree-id Type consume-type suffixI ct-suffix-ts-conv-suffix*
**by** *fastforce*
**next**
**case** *Bot*
**thus** *?thesis*
**using** *assms*(*2*)
**by** *simp*
**qed**

**lemma** *b-e-check-single-type-not-bot-sound*:
**assumes** *type-update ts* (*to-ct-list t-in*) (*Type t-out*) = *ts′*
*ts* ≠ *Bot*

```
        ts' ≠ Bot
        c-types-agree ts' tm
        C ⊢ [e] : (t-in -> t-out)
  shows ∃ tn. c-types-agree ts tn ∧ C ⊢ [e] : (tn -> tm)
  using assms b-e-check-single-type-sound
proof (cases ts)
  case (TopType x1)
  then obtain x1' where x-def:TopType x1' = ts'
    using assms
    by (simp, metis (full-types) produce.simps(1) produce.simps(6))
  thus ?thesis
    using assms b-e-check-single-top-sound TopType
    by fastforce
next
  case (Type x2)
  then obtain x2' where x-def:Type x2' = ts'
    using assms
    by (simp, metis (full-types) produce.simps(2) produce.simps(6))
  thus ?thesis
    using assms b-e-check-single-type-sound Type
    by fastforce
next
  case Bot
  thus ?thesis
    using assms(2)
    by simp
qed

lemma b-e-check-single-sound-unop-testop-cvtop:
  assumes check-single C e tn' = tm'
        ((e = (Unop-i t uu) ∨ e = (Testop t uv)) ∧ is-int-t t)
         ∨ (e = (Unop-f t uw) ∧ is-float-t t)
         ∨ (e = (Cvtop t1 Convert t sx) ∧ convert-cond t1 t sx)
         ∨ (e = (Cvtop t1 Reinterpret t sx) ∧ ((t1 ≠ t) ∧ t-length t1 = t-length t
∧ sx = None))
        c-types-agree tm' tm
        tn' ≠ Bot
        tm' ≠ Bot
 shows ∃ tn. c-types-agree tn' tn ∧ C ⊢ [e] : (tn -> tm)
proof −
  have (e = (Cvtop t1 Convert t sx) ⟹ convert-cond t1 t sx)
    using assms(2)
    by simp
  hence temp0:(e = (Cvtop t1 Convert t sx)) ⟹ (type-update tn' [TSome t] (Type
[arity-1-result e]) = tm')
    using assms(1,5) arity-1-result-def
    by (simp del: convert-cond.simps)
  have temp1:(e = (Cvtop t1 Reinterpret t sx)) ⟹ (type-update tn' [TSome t]
(Type [arity-1-result e]) = tm')
```

```
    using assms(1,2,5) arity-1-result-def
    by simp
  have 1:type-update tn' (to-ct-list [t]) (Type [arity-1-result e]) = tm'
    using assms arity-1-result-def
    unfolding to-ct-list-def
    apply (simp del: convert-cond.simps)
   apply (metis (no-types, lifting) temp0 temp1 b-e.simps(978,979,982) check-single.simps(2)
check-single.simps(3) check-single.simps(6) type-update.simps)
    done
  have C ⊢ [e] : ([t] -> [arity-1-result e])
    using assms(2) b-e-typing.intros(2,3,6,9,10)
    unfolding arity-1-result-def
    by fastforce
  thus ?thesis
    using b-e-check-single-type-not-bot-sound[OF 1 assms(4,5,3)]
    by fastforce
qed

lemma b-e-check-single-sound-binop-relop:
  assumes check-single C e tn' = tm'
          ((e = Binop-i t iop ∧ is-int-t t)
            ∨ (e = Binop-f t fop ∧ is-float-t t)
            ∨ (e = Relop-i t irop ∧ is-int-t t)
            ∨ (e = Relop-f t frop ∧ is-float-t t))
          c-types-agree tm' tm
          tn' ≠ Bot
          tm' ≠ Bot
 shows ∃ tn. c-types-agree tn' tn ∧ C ⊢ [e] : (tn -> tm)
proof −
  have type-update tn' (to-ct-list [t,t]) (Type [arity-2-result e]) = tm'
    using assms arity-2-result-def
    unfolding to-ct-list-def
    by auto
  moreover
  have C ⊢ [e] : ([t,t] -> [arity-2-result e])
    using assms(2) b-e-typing.intros(4,5,7,8)
    unfolding arity-2-result-def
    by fastforce
  ultimately
  show ?thesis
    using b-e-check-single-type-not-bot-sound[OF - assms(4,5,3)]
    by fastforce
qed

lemma b-e-type-checker-sound:
  assumes b-e-type-checker C es (tn -> tm)
  shows C ⊢ es : (tn -> tm)
proof −
  fix e tn'
```

**have** *b-e-type-checker* $\mathcal{C}$ *es* (*tn* -> *tm*) $\Longrightarrow$
$\mathcal{C} \vdash$ *es* : (*tn* -> *tm*)
**and** $\bigwedge$*tm' tm.*
*check* $\mathcal{C}$ *es tn'* = *tm'* $\Longrightarrow$
*c-types-agree tm' tm* $\Longrightarrow$
$\exists$ *tn. c-types-agree tn' tn* $\wedge$ $\mathcal{C} \vdash$ *es* : (*tn* -> *tm*)
**and** $\bigwedge$*tm' tm.*
*check-single* $\mathcal{C}$ *e tn'* = *tm'* $\Longrightarrow$
*c-types-agree tm' tm* $\Longrightarrow$
*tn'* $\neq$ *Bot* $\Longrightarrow$
*tm'* $\neq$ *Bot* $\Longrightarrow$
$\exists$ *tn. c-types-agree tn' tn* $\wedge$ $\mathcal{C} \vdash$ [*e*] : (*tn* -> *tm*)
**proof** (*induction rule*: *b-e-type-checker-check-check-single.induct*)
**case** (*1* $\mathcal{C}$ *es tn' tm*)
**thus** *?case*
**by** *simp*
**next**
**case** (*2* $\mathcal{C}$ *es' ts*)
**show** *?case*
**proof** (*cases es'*)
**case** *Nil*
**thus** *?thesis*
**using** *2*(*5*,*6*)
**by** (*simp add*: *b-e-type-empty*)
**next**
**case** (*Cons e es*)
**thus** *?thesis*
**proof** (*cases ts*)
**case** (*TopType x1*)
**have** *check-expand*:*check* $\mathcal{C}$ *es* (*check-single* $\mathcal{C}$ *e ts*) = *tm'*
**using** *2*(*5*,*6*) *TopType Cons*
**by** *simp*
**obtain** *ts'* **where** *ts'-def*:*check-single* $\mathcal{C}$ *e ts* = *ts'*
**by** *blast*
**obtain** *t-int* **where** *t-int-def*:$\mathcal{C} \vdash$ *es* : (*t-int* -> *tm*)
*c-types-agree ts' t-int*
**using** *2*(*2*)[*OF Cons TopType check-expand 2*(*6*)] *ts'-def*
**by** *blast*
**obtain** *t-int'* **where** *c-types-agree ts t-int'* $\mathcal{C} \vdash$ [*e*] : (*t-int'* -> *t-int*)
**using** *2*(*1*)[*OF Cons - ts'-def*] *TopType c-types-agree.simps*(*3*) *t-int-def*(*2*)
**by** *blast*
**thus** *?thesis*
**using** *t-int-def*(*1*) *b-e-type-comp-conc Cons*
**by** *fastforce*
**next**
**case** (*Type x2*)
**have** *check-expand*:*check* $\mathcal{C}$ *es* (*check-single* $\mathcal{C}$ *e ts*) = *tm'*
**using** *2*(*5*,*6*) *Type Cons*
**by** *simp*

```
      obtain ts' where ts'-def:check-single C e ts = ts'
        by blast
      obtain t-int where t-int-def:C ⊢ es : (t-int -> tm)
                                    c-types-agree ts' t-int
        using 2(4)[OF Cons Type check-expand 2(6)] ts'-def
        by blast
      obtain t-int' where c-types-agree ts t-int' C ⊢ [e] : (t-int' -> t-int)
        using 2(3)[OF Cons - ts'-def] Type c-types-agree.simps(3) t-int-def(2)
        by blast
      thus ?thesis
        using t-int-def(1) b-e-type-comp-conc Cons
        by fastforce
    next
      case Bot
      then show ?thesis
        using 2(5,6) Cons
        by auto
    qed
  qed
next
  case (3 C v ts)
  hence type-update ts [] (Type [typeof v]) = tm'
    by simp
  moreover
  have C ⊢ [C v] : ([] -> [typeof v])
    using b-e-typing.intros(1)
    by blast
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 3(3,4,2)]
    by (metis list.simps(8) to-ct-list-def)
next
  case (4 C t uu ts)
  hence is-int-t t
    by (simp, meson)
  thus ?case
    using b-e-check-single-sound-unop-testop-cvtop 4
    by fastforce
next
  case (5 C t uv ts)
  hence is-float-t t
    by (simp, meson)
  thus ?case
    using b-e-check-single-sound-unop-testop-cvtop 5
    by fastforce
next
  case (6 C t uw ts)
  hence is-int-t t
    by (simp, meson)
```

```
  thus ?case
    using b-e-check-single-sound-binop-relop 6
    by fastforce
next
  case (7 C t ux ts)
  hence is-float-t t
    by (simp, meson)
  thus ?case
    using b-e-check-single-sound-binop-relop 7
    by fastforce
next
  case (8 C t uy ts)
  hence is-int-t t
    by (simp, meson)
  thus ?case
    using b-e-check-single-sound-unop-testop-cvtop 8
    by fastforce
next
  case (9 C t uz ts)
  hence is-int-t t
    by (simp, meson)
  thus ?case
    using b-e-check-single-sound-binop-relop 9
    by fastforce
next
  case (10 C t va ts)
  hence is-float-t t
    by (simp, meson)
  thus ?case
    using b-e-check-single-sound-binop-relop 10
    by fastforce
next
  case (11 C t1 t2 sx ts)
  hence convert-cond t1 t2 sx
    by (simp del: convert-cond.simps, meson)
  thus ?case
    using b-e-check-single-sound-unop-testop-cvtop 11
    by fastforce
next
  case (12 C t1 t2 sx ts)
  hence t1 ≠ t2 ∧  t-length t1 = t-length t2 ∧ sx = None
    by (simp, presburger)
  thus ?case
    using b-e-check-single-sound-unop-testop-cvtop 12
    by fastforce
next
  case (13 C ts)
  thus ?case
    using b-e-typing.intros(11) c-types-agree-not-bot-exists
```

```
    by blast
  next
    case (14 C ts)
    thus ?case
      using b-e-typing.intros(12,35)
      by fastforce
  next
    case (15 C ts)
    thus ?case
    proof (cases ts)
      case (TopType x1)
      thus ?thesis
        proof (cases x1 rule: List.rev-cases)
          case Nil
          have C ⊢ [Drop] : (tm@[T-i32] -> tm)
            using b-e-typing.intros(13,35)
            by fastforce
          thus ?thesis
            using c-types-agree-top1 Nil TopType
            by fastforce
        next
          case (snoc ys y)
            hence temp1:(consume (TopType (ys@[y])) [TAny]) = tm'
              using 15 TopType type-update-empty
              by (metis check-single.simps(13))
            hence temp2:c-types-agree (TopType ys) tm
              using consume-top-geq[OF temp1] 15(2,3,4)
                  by (metis Suc-leI add-diff-cancel-right' append-eq-conv-conj con-
sume.simps(2)
                      ct-suffix-def length-Cons length-append list.size(3) trans-le-add2
                       zero-less-Suc)
            obtain t where ct-list-eq [y] (to-ct-list [t])
              using ct-list-eq-exists
              unfolding ct-list-eq-def to-ct-list-def list-all2-map2
              by (metis list-all2-Cons1 list-all2-Nil)
            hence c-types-agree ts (tm@[t])
              using temp2 ct-suffix-extend-ct-list-eq snoc TopType
              by (simp add: to-ct-list-def)
            thus ?thesis
              using b-e-typing.intros(13,35)
              by fastforce
        qed
    next
      case (Type x2)
      thus ?thesis
      proof (cases x2 rule: List.rev-cases)
        case Nil
        hence (consume (Type []) [TAny]) = tm'
          using 15 Type type-update-empty
```

```
      by fastforce
    thus ?thesis
      using 15(4) ct-list-eq-def ct-suffix-def to-ct-list-def
      by simp
  next
    case (snoc ys y)
      hence temp1:(consume (Type (ys@[y])) [TAny]) = tm'
        using 15 Type type-update-empty
        by (metis check-single.simps(13))
      hence temp2:c-types-agree (Type ys) tm
        using 15(2,3,4) ct-suffix-def
      by (simp, metis One-nat-def butlast-conv-take butlast-snoc c-types-agree.simps(1)
                      length-Cons list.size(3))
      obtain t where ct-list-eq [TSome y] (to-ct-list [t])
        using ct-list-eq-exists
        unfolding ct-list-eq-def to-ct-list-def list-all2-map2
        by (metis list-all2-Cons1 list-all2-Nil)
      hence c-types-agree ts (tm@[t])
        using temp2 ct-suffix-extend-ct-list-eq snoc Type
        by (simp add: ct-list-eq-def to-ct-list-def)
      thus ?thesis
        using b-e-typing.intros(13,35)
        by fastforce
  qed
qed simp
next
  case (16 C ts)
  thus ?case
  proof (cases ts)
    case (TopType x1)
    consider
        (1) length x1 = 0
      | (2) length x1 = 1
      | (3) length x1 = 2
      | (4) length x1 ≥ 3
      by linarith
    thus ?thesis
    proof (cases)
      case 1
      hence tm' = TopType [TAny]
        using TopType 16
        by simp
      then obtain t'' tm'' where tm-def:tm = tm''@[t'']
        using 16(2) ct-suffix-def
     by (simp, metis Nil-is-append-conv append-butlast-last-id checker-type.inject(1)
                     ct-prefixI ct-prefix-nil(2) produce.simps(1) produce-nil)
      have C ⊢ [Select] : ([t'',t'',T-i32] -> [t''])
        using b-e-typing.intros(14)
        by blast
```

**thus** *?thesis*
**using** *TopType 16 1 tm-def b-e-typing.intros(35) c-types-agree.simps(2) c-types-agree-top1*
**by** *fastforce*
**next**
**case** *2*
**have** *type-update-select (TopType x1) = tm'*
**using** *16 TopType*
**unfolding** *check-single.simps*
**by** *simp*
**hence** *x1-def:ct-list-eq x1 [TSome T-i32] tm' = TopType [TAny]*
**using** *type-update-select-length1[OF - 2 16(4)]*
**by** *simp-all*
**then obtain** *t'' tm''* **where** *tm-def:tm = tm''@[t'']*
**using** *16(2) ct-suffix-def*
**by** *(metis Nil-is-append-conv append-butlast-last-id c-types-agree.simps(2) ct-prefixI ct-prefix-nil(2) list.simps(8) to-ct-list-def)*
**have** *c-types-agree (TopType x1) ((tm''@[t'',t''])@[T-i32])*
**using** *x1-def(1)*
**by** *(metis c-types-agree-top2 list.simps(8,9) to-ct-list-def)*
**thus** *?thesis*
**using** *TopType b-e-typing.intros(14,35) tm-def*
**by** *auto*
**next**
**case** *3*
**have** *type-update-select (TopType x1) = tm'*
**using** *16 TopType*
**unfolding** *check-single.simps*
**by** *simp*
**then obtain** *ct1 ct2* **where** *x1-def:x1 = [ct1, ct2]*
*ct-eq ct2 (TSome T-i32)*
*tm' = TopType [ct1]*
**using** *type-update-select-length2[OF - 3 16(4)]*
**by** *blast*
**then obtain** *t'' tm''* **where** *tm-def:tm = tm''@[t'']*
*ct-list-eq [ct1] [(TSome t'')]*
**using** *16(2) c-types-agree-imp-ct-list-eq[of [ct1] tm]*
**by** *(metis append-Nil2 append-butlast-last-id append-eq-append-conv-if append-eq-conv-conj ct-list-eq-length diff-Suc-1 length-Cons length-butlast length-map list.simps(8,9) list.size(3) nat.distinct(2) to-ct-list-def)*
**hence** *ct-list-eq x1 (to-ct-list [ t'', T-i32])*
**using** *x1-def(1,2)*
**unfolding** *ct-list-eq-def to-ct-list-def*
**by** *fastforce*
**hence** *c-types-agree (TopType x1) ((tm''@[t''])@[t'',T-i32])*
**using** *c-types-agree-top2*
**by** *blast*

**thus** *?thesis*
**using** *TopType b-e-typing.intros(14,35) tm-def*
**by** *auto*
**next**
**case** *4*
**then obtain** *nat* **where** *nat-def*:*length x1 = Suc (Suc (Suc nat))*
**by** (*metis add-eq-if diff-Suc-1 le-Suc-ex numeral-3-eq-3 nat.distinct(2)*)
**hence** *tm'-def*:*type-update-select (TopType x1) = tm'*
**using** *16 TopType*
**by** *simp*
**then obtain** *tm-int* **where** (*select-return-top x1*
*(x1 ! (length x1 − 2))*
*(x1 ! (length x1 − 3))) = tm-int*
*tm-int ≠ Bot*
**using** *nat-def 16(4)*
**unfolding** *type-update-select.simps*
**by** *fastforce*
**then obtain** *x2* **where** *x2-def*:(*select-return-top x1*
*(x1 ! (length x1 − 2))*
*(x1 ! (length x1 − 3))) = TopType x2*
**using** *select-return-top-exists*
**by** *fastforce*
**have** *ct-suffix x1* [*TAny*, *TAny*, *TSome T-i32*] ∨ *ct-suffix* [*TAny*, *TAny*, *TSome T-i32*] *x1*
**using** *tm'-def nat-def 16(4)*
**by** (*simp*, *metis* (*full-types*) *produce.simps(6)*)
**hence** *tm'-eq*:*tm' = TopType x2*
**using** *tm'-def nat-def 16(4) x2-def*
**by** *force*
**then obtain** *cts' ct1 ct2 ct3* **where** *cts'-def*:*x1 = cts'*@[*ct1*, *ct2*, *ct3*]
*ct-eq ct3 (TSome T-i32)*
**using** *type-update-select-length3 tm'-def 4*
**by** *blast*
**then obtain** *c' cm'* **where** *tm-def*:*tm = cm'*@[*c'*]
*ct-suffix cts' (to-ct-list cm')*
*ct-eq (x1 ! (length x1 − 2)) (TSome c')*
*ct-eq (x1 ! (length x1 − 3)) (TSome c')*
**using** *select-return-top-ct-eq*[*OF x2-def 4*] *tm'-eq 4 16(2)*
**by** *fastforce*
**then obtain** *as bs* **where** *cm'-def*:*cm' = as*@*bs*
*ct-list-eq (to-ct-list bs) cts'*
**using** *ct-list-eq-cons-ct-list1 ct-list-eq-ts-conv-eq*
**by** (*metis ct-suffix-def to-ct-list-append(2)*)
**hence** *ct-eq ct1 (TSome c')*
*ct-eq ct2 (TSome c')*
**using** *cts'-def tm-def*
**apply** *simp-all*
**apply** (*metis append.assoc append-Cons append-Nil length-append-singleton nth-append-length*)

```
    done
  hence c-types-agree ts (cm'@[c',c',T-i32])
    using c-types-agree-top2[of - - as] cm'-def(1) TopType
        ct-list-eq-concat[OF ct-list-eq-commute[OF cm'-def(2)]] cts'-def
    unfolding to-ct-list-def ct-list-eq-def
    by fastforce
  thus ?thesis
    using b-e-typing.intros(14,35) tm-def
    by auto
 qed
next

 case (Type x2)
 hence x2-cond:(length x2 ≥ 3 ∧ (x2!(length x2−2)) = (x2!(length x2−3)))
   using 16
   by (simp, meson)
 hence tm'-def:consume (Type x2) [TAny, TSome T-i32] = tm'
   using 16 Type
   by simp
 obtain ts' ts'' where cts-def:x2 = ts'@ ts'' length ts'' = 3
   using x2-cond
   by (metis append-take-drop-id diff-diff-cancel length-drop)
 then obtain t1 ts''2 where ts'' = t1#ts''2 length ts''2 = Suc (Suc 0)
   using List.length-Suc-conv[of ts' Suc (Suc 0)]
   by (metis length-Suc-conv numeral-3-eq-3)
 then obtain t2 t3 where ts'' = [t1,t2,t3]
   using List.length-Suc-conv[of ts''2 Suc 0]
   by (metis length-0-conv length-Suc-conv)
 hence cts-def2:x2 = ts'@ [t1,t2,t3]
   using cts-def
   by simp
 have ts'-suffix:ct-suffix [TAny, TSome T-i32] (to-ct-list (ts' @ [t1, t2, t3]))
   using tm'-def 16(4)
   by (simp, metis cts-def2)
 hence tm'-def:tm' = Type (ts'@[t1])
   using tm'-def 16(4) cts-def2
   by simp
 obtain as bs where (to-ct-list (ts' @ [t1])) @ (to-ct-list ([t2, t3])) = as@bs
                    ct-list-eq bs [TAny, TSome T-i32]
   using ts'-suffix
   unfolding ct-suffix-def to-ct-list-def
   by fastforce
 hence t3 = T-i32
   unfolding to-ct-list-def ct-list-eq-def
 by (metis (no-types, lifting) Nil-is-map-conv append-eq-append-conv ct-eq.simps(1)
       length-Cons list.sel(1,3) list.simps(9) list-all2-Cons2 list-all2-lengthD)
 moreover
 have t1 = t2
   using x2-cond cts-def2
```

```
    by (simp, metis append.left-neutral append-Cons append-assoc length-append-singleton
                    nth-append-length)
    ultimately
    have c-types-agree (Type x2) ((ts'@[t1,t1])@[T-i32])
      using cts-def2
      by simp
    thus ?thesis
      using b-e-typing.intros(14,35) Type tm'-def 16(2)
      by fastforce
  qed simp
next
  case (17 C tn'' tm'' es ts)
  hence type-update ts (to-ct-list tn'') (Type tm'') = tm'
    by auto
  moreover
  have (b-e-type-checker (C(|label := ([tm'']  @ (label C))|)) es (tn'' -> tm''))
    using 17
    by (simp, meson)
  hence C ⊢ [Block (tn'' -> tm'') es] : (tn'' -> tm'')
    using b-e-typing.intros(15)[OF - 17(1)]
    by blast
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 17(4,5,3)]
    by blast
next
  case (18 C tn'' tm'' es ts)
  hence type-update ts (to-ct-list tn'') (Type tm'') = tm'
    by auto
  moreover
  have (b-e-type-checker (C(|label := ([tn'']  @ (label C))|)) es (tn'' -> tm''))
    using 18
    by (simp, meson)
  hence C ⊢ [Loop (tn'' -> tm'') es] : (tn'' -> tm'')
    using b-e-typing.intros(16)[OF - 18(1)]
    by blast
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 18(4,5,3)]
    by blast
next
  case (19 C tn'' tm'' es1 es2 ts)
  hence type-update ts (to-ct-list (tn''@[T-i32])) (Type tm'') = tm'
    by auto
  moreover
  have (b-e-type-checker (C(|label := ([tm'']  @ (label C))|)) es1 (tn'' -> tm''))
       (b-e-type-checker (C(|label := ([tm'']  @ (label C))|)) es2 (tn'' -> tm''))
    using 19
    by (simp, meson)+
```

```
    hence C ⊢ [If (tn'' -> tm'') es1 es2] : (tn''@[T-i32] -> tm'')
      using b-e-typing.intros(17)[OF - 19(1,2)]
      by blast
    ultimately
    show ?case
      using b-e-check-single-type-not-bot-sound[OF - 19(5,6,4)]
      by blast
  next
    case (20 C i ts)
    hence type-update ts (to-ct-list ((label C)!i)) (TopType []) = tm'
      by auto
    moreover
    have i < length (label C)
      using 20
      by (simp, meson)
    ultimately
    show ?case
      using b-e-check-single-top-not-bot-sound[OF - 20(3,4)]
            b-e-typing.intros(18)
            b-e-typing.intros(35)
      by (metis suffix-def)
  next
    case (21 C i ts)
    hence type-update ts (to-ct-list ((label C)!i @ [T-i32])) (Type ((label C)!i)) =
tm'
      by auto
    moreover
    have i < length (label C)
      using 21
      by (simp, meson)
    hence C ⊢ [Br-if i] : ((label C)!i @ [T-i32] -> (label C)!i)
      using b-e-typing.intros(19)
      by fastforce
    ultimately
    show ?case
      using b-e-check-single-type-not-bot-sound[OF - 21(3,4,2)]
      by fastforce
  next
    case (22 C is i ts)
    then obtain tls where tls-def:(same-lab (is@[i]) (label C)) = Some tls
      by fastforce
    hence type-update ts (to-ct-list (tls @ [T-i32])) (TopType []) = tm'
      using 22
      by simp
    thus ?case
      using b-e-check-single-top-not-bot-sound[OF - 22(3,4)]
            b-e-typing.intros(20)[OF same-lab-conv-list-all[OF tls-def]]
            b-e-typing.intros(35)
      by (metis suffix-def)
```

```
next
  case (23 C ts)
  then obtain ts-r where (return C) = Some ts-r
    by fastforce
  moreover
  hence type-update ts (to-ct-list ts-r) (TopType []) = tm'
    using 23
    by simp
  ultimately
  show ?case
    using b-e-check-single-top-not-bot-sound[OF - 23(3,4)]
          b-e-typing.intros(21,35)
    by (metis suffix-def)
next
  case (24 C i ts)
  obtain tn'' tm'' where func-def:(func-t C)!i = (tn'' -> tm'')
    using tf.exhaust
    by blast
  hence type-update ts (to-ct-list tn'') (Type tm'') = tm'
    using 24
    by auto
  moreover
  have i < length (func-t C)
    using 24
    by (simp, meson)
  hence C ⊢ [Call i] : (tn'' -> tm'')
    using b-e-typing.intros(22) func-def
    by fastforce
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 24(3,4,2)]
    by fastforce
next
  case (25 C i ts)
  obtain tn'' tm'' where type-def:(types-t C)!i = (tn'' -> tm'')
    using tf.exhaust
    by blast
  hence type-update ts (to-ct-list (tn''@[T-i32])) (Type tm'') = tm'
    using 25
    by auto
  moreover
  have (table C) ≠ None ∧ i < length (types-t C)
    using 25
    by (simp, meson)
  hence C ⊢ [Call-indirect i] : (tn''@[T-i32] -> tm'')
    using b-e-typing.intros(23) type-def
    by fastforce
  ultimately
  show ?case
```

```
    using b-e-check-single-type-not-bot-sound[OF - 25(3,4,2)]
    by fastforce
next
  case (26 C i ts)
  hence type-update ts [] (Type [(local C)!i]) = tm'
    by auto
  moreover
  have i < length (local C)
    using 26
    by (simp, meson)
  hence C ⊢ [Get-local i] : ([] -> [(local C)!i])
    using b-e-typing.intros(24)
    by fastforce
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 26(3,4,2)]
    unfolding to-ct-list-def
    by (metis list.map-disc-iff)
next
  case (27 C i ts)
  hence type-update ts (to-ct-list [(local C)!i]) (Type []) = tm'
    unfolding to-ct-list-def
    by auto
  moreover
  have i < length (local C)
    using 27
    by (simp, meson)
  hence C ⊢ [Set-local i] : ([(local C)!i] -> [])
    using b-e-typing.intros(25)
    by fastforce
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 27(3,4,2)]
    by fastforce
next
  case (28 C i ts)
  hence type-update ts (to-ct-list [(local C)!i]) (Type [(local C)!i]) = tm'
    unfolding to-ct-list-def
    by auto
  moreover
  have i < length (local C)
    using 28
    by (simp, meson)
  hence C ⊢ [Tee-local i] : ([(local C)!i] -> [(local C)!i])
    using b-e-typing.intros(26)
    by fastforce
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 28(3,4,2)]
```

```
    by fastforce
  next
    case (29 C i ts)
    hence type-update ts [] (Type [tg-t ((global C)!i)]) = tm'
      by auto
    moreover
    have i < length (global C)
      using 29
      by (simp, meson)
    hence C ⊢ [Get-global i] : ([] -> [tg-t ((global C)!i)])
      using b-e-typing.intros(27)
      by fastforce
    ultimately
    show ?case
      using b-e-check-single-type-not-bot-sound[OF - 29(3,4,2)]
      unfolding to-ct-list-def
      by (metis list.map-disc-iff)
  next
    case (30 C i ts)
    hence type-update ts (to-ct-list [tg-t ((global C)!i)]) (Type []) = tm'
      unfolding to-ct-list-def
      by auto
    moreover
    have i < length (global C) ∧ is-mut (global C ! i)
      using 30
      by (simp, meson)
    then obtain t where (global C ! i) = (|tg-mut = T-mut, tg-t = t|) i < length
(global C)
      unfolding is-mut-def
      by (cases global C ! i, auto)
    hence C ⊢ [Set-global i] : ([tg-t (global C ! i)] -> [])
      using b-e-typing.intros(28)[of i C tg-t (global C ! i)]
      unfolding is-mut-def tg-t-def
      by fastforce
    ultimately
    show ?case
      using b-e-check-single-type-not-bot-sound[OF - 30(3,4,2)]
      by fastforce
  next
    case (31 C t tp-sx a off ts)
    hence type-update ts (to-ct-list [T-i32]) (Type [t]) = tm'
      unfolding to-ct-list-def
      by auto
    moreover
    have (memory C) ≠ None ∧ load-store-t-bounds a (option-projl tp-sx) t
      using 31
      by (simp, meson)
    hence C ⊢ [Load t tp-sx a off] : ([T-i32] -> [t])
      using b-e-typing.intros(29)
```

```
    by fastforce
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 31(3,4,2)]
    by fastforce
next
  case (32 C t tp a off ts)
  hence type-update ts (to-ct-list [T-i32,t]) (Type []) = tm'
    unfolding to-ct-list-def
    by auto
  moreover
  have (memory C) ≠ None ∧ load-store-t-bounds a tp t
    using 32
    by (simp, meson)
  hence C ⊢ [Store t tp a off] : ([T-i32,t] -> [])
    using b-e-typing.intros(30)
    by fastforce
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 32(3,4,2)]
    by fastforce
next
  case (33 C ts)
  hence type-update ts [] (Type [T-i32]) = tm'
    by auto
  moreover
  have memory C ≠ None
    using 33
    by (simp, meson)
  hence C ⊢ [Current-memory] : ([] -> [T-i32])
    using b-e-typing.intros(31)
    by fastforce
  ultimately
  show ?case
    using b-e-check-single-type-not-bot-sound[OF - 33(3,4,2)]
    unfolding to-ct-list-def
    by (metis list.map-disc-iff)
next
  case (34 C ts)
  hence type-update ts (to-ct-list [T-i32]) (Type [T-i32]) = tm'
    unfolding to-ct-list-def
    by auto
  moreover
  have memory C ≠ None
    using 34
    by (simp, meson)
  hence C ⊢ [Grow-memory] : ([T-i32] -> [T-i32])
    using b-e-typing.intros(32)
    by fastforce
```

**ultimately**
**show** *?case*
**using** *b-e-check-single-type-not-bot-sound*[*OF - 34*(*3*,*4*,*2*)]
**by** *fastforce*
**qed**
**thus** *?thesis*
**using** *assms*
**by** *simp*
**qed**

## 10.2 Completeness

**lemma** *check-single-imp*:
**assumes** *check-single* $\mathcal{C}$ *e ctn* = *ctm*
*ctm* ≠ *Bot*
**shows** *check-single* $\mathcal{C}$ *e* = *id*
∨ *check-single* $\mathcal{C}$ *e* = (λ*ctn*. *type-update-select ctn*)
∨ (∃ *cons prods*. (*check-single* $\mathcal{C}$ *e* = (λ*ctn*. *type-update ctn cons prods*)))
**proof** −
**have** *True*
**and** *True*
**and** *check-single* $\mathcal{C}$ *e ctn* = *ctm* ⟹
*ctm* ≠ *Bot* ⟹
*?thesis*
**proof** (*induction rule*: *b-e-type-checker-check-check-single.induct*)
**case** (*1* $\mathcal{C}$ *es tn tm*)
**thus** *?case*
**by** *simp*
**next**
**case** (*2* $\mathcal{C}$ *es ts*)
**thus** *?case*
**by** *simp*
**next**
**case** (*3* $\mathcal{C}$ *v ts*)
**thus** *?case*
**by** *fastforce*
**next**
**case** (*4* $\mathcal{C}$ *t uu ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*5* $\mathcal{C}$ *t uv ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*6* $\mathcal{C}$ *t uw ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**

**case** (*7 C t ux ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*8 C t uy ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*9 C t uz ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*10 C t va ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*11 C t1 t2 sx ts*)
**thus** *?case*
**by** (*simp del*: *convert-cond.simps*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*12 C t1 t2 sx ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*13 C ts*)
**thus** *?case*
**by** *fastforce*
**next**
**case** (*14 C ts*)
**thus** *?case*
**by** *fastforce*
**next**
**case** (*15 C ts*)
**thus** *?case*
**by** *fastforce*
**next**
**case** (*16 C ts*)
**thus** *?case*
**by** *fastforce*
**next**
**case** (*17 C tn tm es ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*18 C tn tm es ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*19 C tn tm es1 es2 ts*)

**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*20 C i ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*21 C i ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*22 C is ts*)
**thus** *?case*
**by** (*simp*, *metis assms*(*2*) *option.case-eq-if type-update.simps*)
**next**
**case** (*23 C ts*)
**thus** *?case*
**by** (*simp*, *metis assms*(*2*) *option.case-eq-if type-update.simps*)
**next**
**case** (*24 C i ts*)
**then show** *?case*
**by** (*simp*, *metis* (*no-types*, *lifting*) *assms*(*2*) *tf.case tf.exhaust type-update.simps*)
**next**
**case** (*25 C i ts*)
**thus** *?case*
**by** (*simp*, *metis* (*no-types*, *lifting*) *assms*(*2*) *tf.case tf.exhaust type-update.simps*)
**next**
**case** (*26 C i ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*27 C i ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*28 C i ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*29 C i ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*30 C i ts*)
**thus** *?case*
**by** (*simp*, *meson assms*(*2*) *type-update.simps*)
**next**
**case** (*31 C t tp-sx a off ts*)
**thus** *?case*

```
    by (simp, meson assms(2) type-update.simps)
  next
    case (32 C t tp a off ts)
    thus ?case
      by (simp, meson assms(2) type-update.simps)
  next
    case (33 C ts)
    thus ?case
      by (simp, meson assms(2) type-update.simps)
  next
    case (34 C ts)
    thus ?case
      by (simp, meson assms(2) type-update.simps)
  qed
  thus ?thesis
    using assms
    by simp
qed

lemma check-equiv-fold:
  check C es ts = foldl (λ ts e. (case ts of Bot ⇒ Bot | - ⇒ check-single C e ts))
ts es
proof (induction es arbitrary: ts)
  case Nil
  thus ?case
    by simp
next
  case (Cons e es)
  obtain ts' where ts'-def:check C (e # es) ts = ts'
    by blast
  show ?case
  proof (cases ts = Bot)
    case True
    thus ?thesis
      using ts'-def
      by (induction es, simp-all)
  next
    case False
    thus ?thesis
      using ts'-def Cons
      by (cases ts, simp-all)
  qed
qed

lemma check-neq-bot-snoc:
  assumes check C (es@[e]) ts ≠ Bot
  shows check C es ts ≠ Bot
  using assms
proof (induction es arbitrary: ts)
```

```
  case Nil
  thus ?case
    by (cases ts, simp-all)
next
  case (Cons a es)
  thus ?case
    by (cases ts, simp-all)
qed

lemma check-unfold-snoc:
  assumes check C es ts ≠ Bot
  shows check C (es@[e]) ts = check-single C e (check C es ts)
proof −
  obtain f where f-def:f = (λ e ts. (case ts of Bot ⇒ Bot | - ⇒ check-single C e
ts))
    by blast
  have f-simp:⋀ts. ts ≠ Bot ⟹ (f e ts = check-single C e ts)
  proof −
    fix ts
    show ts ≠ Bot ⟹ (f e ts = check-single C e ts)
      using f-def
      by (cases ts, simp-all)
  qed
  have check C (es@[e]) ts = foldl (λ ts e. (case ts of Bot ⇒ Bot | - ⇒ check-single
C e ts)) ts (es@[e])
    using check-equiv-fold
    by simp
  also
  have ... = foldr (λ e ts. (case ts of Bot ⇒ Bot | - ⇒ check-single C e ts)) (rev
(es@[e])) ts
    using foldl-conv-foldr
    by fastforce
  also
  have ... = f e (foldr (λ e ts. (case ts of Bot ⇒ Bot | - ⇒ check-single C e ts))
(rev es) ts)
    using f-def
    by simp
  also
  have ... = f e (check C es ts)
    using foldr-conv-foldl[of - (rev es) ts] rev-rev-ident[of es] check-equiv-fold
    by simp
  also
  have ... = check-single C e (check C es ts)
    using assms f-simp
    by simp
  finally
  show ?thesis .
qed
```

**lemma** *check-single-imp-weakening*:
**assumes** *check-single* $\mathcal{C}$ *e* (*Type t1s*) = *ctm*
*ctm* ≠ *Bot*
*c-types-agree ctn t1s*
*c-types-agree ctm t2s*
**shows** ∃ *ctm'*. *check-single* $\mathcal{C}$ *e ctn* = *ctm'* ∧ *c-types-agree ctm' t2s*
**proof** −
**consider** (*1*) *check-single* $\mathcal{C}$ *e* = *id*
| (*2*) *check-single* $\mathcal{C}$ *e* = (λ*ctn*. *type-update-select ctn*)
| (*3*) (∃ *cons prods*. (*check-single* $\mathcal{C}$ *e* = (λ*ctn*. *type-update ctn cons prods*)))
**using** *check-single-imp assms*
**by** *blast*
**thus** *?thesis*
**proof** (*cases*)
**case** *1*
**thus** *?thesis*
**using** *assms*(*1*,*3*,*4*)
**by** *fastforce*
**next**

**case** *2*
**note** *outer-2* = *2*
**hence** *t1s-cond*:(*length t1s* ≥ *3* ∧ (*t1s*!(*length t1s*−*2*)) = (*t1s*!(*length t1s*−*3*)))
**using** *assms*(*1*,*2*)
**by** (*simp*, *meson*)
**hence** *ctm-def*:*ctm* = *consume* (*Type t1s*) [*TAny*, *TSome T-i32*]
**using** *assms*(*1*,*2*) *2*
**by** *simp*
**then obtain** *c-t* **where** *c-t-def*:*ctm* = *Type c-t*
**using** *assms*(*2*)
**by** (*meson consume.simps*(*1*))
**hence** *t2s-eq*:*t2s* = *c-t*
**using** *assms*(*4*)
**by** *simp*
**hence** *t2s-len*:*length t2s* > *0*
**using** *t1s-cond ctm-def c-t-def assms*(*2*)
**by** (*metis Suc-leI Suc-n-not-le-n checker-type.inject*(*2*) *consume.simps*(*1*)
*diff-is-0-eq dual-order.trans length-0-conv length-Cons length-greater-0-conv*
*nat.simps*(*3*) *numeral-3-eq-3 take-eq-Nil*)
**have** *t1s-suffix-full*:*ct-suffix* [*TAny*, *TSome T-i32*] (*to-ct-list t1s*)
**using** *assms*(*2*) *ctm-def ct-suffix-less*
**by** (*metis consume.simps*(*1*))
**hence** *t1s-suffix*:*ct-suffix* [*TSome T-i32*] (*to-ct-list t1s*)
**using** *assms*(*2*) *ctm-def ct-suffix-less*
**by** (*metis append-butlast-last-id last.simps list.distinct*(*1*))
**obtain** *t t1s'* **where** *t1s-suffix2*:*t1s* = *t1s'*@[*t*,*t*,*T-i32*]
**using** *type-update-select-type-length3 assms*(*1*) *c-t-def outer-2*
**by** *fastforce*
**hence** *t2s-def*:*t2s* = *t1s'*@[*t*]

**using** *ctm-def c-t-def t2s-eq t1s-suffix assms*(*2*) *t1s-suffix-full*
**by** *simp*
**show** *?thesis*
**using** *assms*(*1*,*3*,*4*)
**proof** (*cases ctn*)
**case** (*TopType x1*)
**consider**
(*1*) *length x1* = *0*
| (*2*) *length x1* = *1*
| (*3*) *length x1* = *2*
| (*4*) *length x1* ≥ *3*
**by** *linarith*
**thus** *?thesis*
**proof** (*cases*)
**case** *1*
**hence** *check-single* C *e ctn* = *TopType* [*TAny*]
**using** *2 TopType*
**by** *simp*
**thus** *?thesis*
**using** *ct-suffix-singleton to-ct-list-def t2s-len*
**by** *auto*
**next**
**case** *2*
**hence** *ct-suffix* [*TSome T-i32*] *x1*
**using** *assms*(*3*) *TopType ct-suffix-imp-ct-list-eq ct-suffix-shared t1s-suffix*
**by** (*metis One-nat-def append-Nil c-types-agree.simps*(*2*) *ct-list-eq-commute ct-suffix-def*
*diff-self-eq-0 drop-0 length-Cons list.size*(*3*))
**hence** *check-single* C *e ctn* = *TopType* [*TAny*]
**using** *outer-2 TopType 2*
**by** *simp*
**thus** *?thesis*
**using** *t2s-len ct-suffix-singleton*
**by** (*simp add*: *to-ct-list-def*)
**next**
**case** *3*
**have** *ct-list-eq* (*to-ct-list t1s*) (*to-ct-list* (*t1s'* @ [*t*, *t*, *T-i32*]))
**using** *t1s-suffix2*
**by** (*simp add*: *ct-list-eq-ts-conv-eq*)
**hence** *temp1*:*to-ct-list t1s* = (*to-ct-list* (*t1s'* @ [*t*])) @ (*to-ct-list* [*t*, *T-i32*])
**using** *t1s-suffix2 to-ct-list-def*
**by** *simp*
**hence** *ct-suffix* (*to-ct-list* [*t*, *T-i32*]) (*to-ct-list t1s*)
**using** *ct-suffix-def*[*of* (*to-ct-list* [*t*, *T-i32*]) (*to-ct-list t1s*)]
**by** (*simp add*: *ct-suffix-cons-it*)
**hence** *ct-suffix* (*to-ct-list* [*t*, *T-i32*]) *x1*
**using** *assms*(*3*) *TopType 3*
**by** (*simp*, *metis temp1 append-Nil ct-suffix-cons2 ct-suffix-def length-Cons length-map*

*list.size(3) numeral-2-eq-2 to-ct-list-def*)
**hence** *temp3*:*ct-list-eq* (*to-ct-list* [*t*, *T-i32*]) *x1*
**using** *3 ct-suffix-imp-ct-list-eq*
**unfolding** *to-ct-list-def*
**by** (*metis Suc-leI ct-list-eq-commute diff-is-0-eq drop-0 length-Cons length-map lessI*
*list.size(3) numeral-2-eq-2*)
**hence** *temp4*:*ct-suffix* [*TSome T-i32*] *x1*
**using** *ct-suffix-less*[*of* [*TSome t*] [*TSome T-i32*] *x1*]
*ct-suffix-extend-ct-list-eq*[*of* [] []] *ct-suffix-nil*
**unfolding** *to-ct-list-def*
**by** *fastforce*
**hence** *ct-suffix* (*take 1 x1*) (*to-ct-list* [*t*])
**using** *temp3 ct-suffix-nil ct-list-eq-commute ct-suffix-extend-ct-list-eq*[*of* [] [] (*take 1 x1*) (*to-ct-list* [*t*])]
**unfolding** *to-ct-list-def*
**by** (*simp*, *metis butlast.simps*(*2*) *butlast-conv-take ct-list-eq-take diff-Suc-1 length-Cons*
*list.distinct*(*1*) *list.size*(*3*))
**thus** *?thesis*
**using** *TopType 2 3 ct-suffix-nil temp3 temp4 t2s-def to-ct-list-def*
**apply** (*simp*, *safe*)
**apply** (*metis append.assoc ct-suffix-def*)
**done**
**next**
**case** *4*
**then obtain** *nat* **where** *nat-def*:*length x1* = *Suc* (*Suc* (*Suc nat*))
**by** (*metis add-eq-if diff-Suc-1 le-Suc-ex numeral-3-eq-3 nat.distinct*(*2*))
**obtain** *x1'* *x* *x'* *x''* **where** *x1-split*:*x1* = *x1'*@[*x*,*x'*,*x''*]
**proof** −
**assume** *local-assms*:(⋀*x1'* *x* *x'* *x''*. *x1* = *x1'* @ [*x*, *x'*, *x''*] ⟹ *thesis*)
**obtain** *x1'* *x1''* **where** *tn-split*:*x1* = *x1'*@*x1''*
*length x1''* = *3*
**using** *4*
**by** (*metis append-take-drop-id diff-diff-cancel length-drop*)
**then obtain** *x x1''2* **where** *x1''* = *x*#*x1''2* *length x1''2* = *Suc* (*Suc 0*)
**by** (*metis length-Suc-conv numeral-3-eq-3*)
**then obtain** *x'* *x''* **where** *tn''-def*:*x1''*= [*x*,*x'*,*x''*]
**using** *List.length-Suc-conv*[*of x1''2 Suc 0*]
**by** (*metis length-0-conv length-Suc-conv*)
**thus** *?thesis*
**using** *tn-split local-assms*
**by** *simp*
**qed**
**hence** *a*:*ct-suffix* (*x1'*@[*x*,*x'*,*x''*]) (*to-ct-list* (*t1s'* @ [*t*, *t*, *T-i32*]))
**using** *t1s-suffix2 assms*(*3*) *TopType*
**by** *simp*
**hence** *b*:*ct-suffix* (*x1'*@[*x*,*x'*]) (*to-ct-list* (*t1s'* @ [*t*, *t*])) ∧ (*ct-eq x''* (*TSome T-i32*))

```
        using to-ct-list-def ct-suffix-unfold-one[of (x1'@[x,x']) x'' to-ct-list (t1s' @
[t, t])]
        by fastforce
      hence c:ct-suffix (x1'@[x]) (to-ct-list (t1s' @ [t])) ∧ (ct-eq x' (TSome t))
        using to-ct-list-def ct-suffix-unfold-one[of (x1'@[x]) x' to-ct-list (t1s' @
[t])]
        by fastforce
      hence d:ct-suffix x1' (to-ct-list t1s') ∧ (ct-eq x (TSome t))
        using to-ct-list-def ct-suffix-unfold-one[of (x1') x to-ct-list (t1s')]
        by fastforce
      have (take (length x1 − 3) x1) = x1'
        using x1-split
        by simp
      have x'-ind:(x1!(length x1−2)) = x'
        using x1-split List.nth-append-length[of x1' @ [x]]
        by simp
      have x-ind:(x1!(length x1−3)) = x
        using x1-split
        by simp
      have ct-suffix [TSome T-i32] x1
        using b x1-split ct-suffix-def ct-list-eq-def ct-suffixI[of x1 x1' @ [x, x']]
        by simp
       hence check-single C e (TopType x1) = (select-return-top x1 (x1!(length
x1−2)) (x1!(length x1−3)))
        using type-update-select-conv-select-return-top[OF - 4]
        unfolding 2
        by blast
      moreover
      have ... = (TopType (x1'@[x])) ∨ ... = (TopType (x1'@[x']))
        apply (cases x; cases x')
        using x1-split 4 nat-def 2 x-ind x'-ind c d
        by simp-all
      moreover
      have ct-suffix (x1'@[x]) (to-ct-list t2s)
        by (simp add: c t2s-def)
      moreover
      have ct-suffix (x1'@[x']) (to-ct-list t2s)
        using ct-suffix-unfold-one[symmetric, of x' (TSome t) x1' (to-ct-list t1s')]
c d
              t2s-def
        unfolding to-ct-list-def
        by fastforce
      ultimately
      show ?thesis
        using TopType
        by auto
    qed
  qed simp-all
 next
```

**case** *3*
**then obtain** *cons prods* **where** *c-s-def*:*check-single* $\mathcal{C}$ *e* = (λ*ctn*. *type-update ctn cons prods*)
**by** *blast*
**hence** *ctm-def*:*ctm* = *type-update* (*Type t1s*) *cons prods*
**using** *assms*(*1*)
**by** *fastforce*
**hence** *cons-suffix*:*ct-suffix cons* (*to-ct-list t1s*)
**using** *assms*
**by** (*simp*, *metis* (*full-types*) *produce.simps*(*6*))
**hence** *t-int-def*:*consume* (*Type t1s*) *cons* = (*Type* (*take* (*length t1s* − *length cons*) *t1s*))
**using** *ctm-def*
**by** *simp*
**hence** *ctm-def2*:*ctm* = *produce* (*Type* (*take* (*length t1s* − *length cons*) *t1s*)) *prods*
**using** *ctm-def*
**by** *simp*
**show** *?thesis*
**proof** (*cases ctn*)
**case** (*TopType x1*)
**hence** *ct-suffix x1* (*to-ct-list t1s*)
**using** *assms*(*3*)
**by** *simp*
**thus** *?thesis*
**using** *assms*(*2*) *ctm-def2*
**proof** (*cases prods*)
**case** (*TopType x1*)
**thus** *?thesis*
**using** *consume-c-types-agree*[*OF t-int-def assms*(*3*)] *ctm-def2 assms*(*4*) *c-s-def*
**by** (*metis c-types-agree.elims*(*2*) *produce.simps*(*3*,*4*) *type-update.simps*)
**next**
**case** (*Type x2*)
**hence** *ctm-def3*:*ctm* = *Type* ((*take* (*length t1s* − *length cons*) *t1s*)@ *x2*)
**using** *ctm-def2*
**by** *simp*
**have** *ct-suffix x1 cons* ∨ *ct-suffix cons x1*
**using** *ct-suffix-shared assms*(*3*) *TopType cons-suffix*
**by** *auto*
**thus** *?thesis*
**proof** (*rule disjE*)
**assume** *ct-suffix x1 cons*
**hence** *consume* (*TopType x1*) *cons* = *TopType* []
**by** (*simp add*: *ct-suffix-length*)
**hence** *check-single* $\mathcal{C}$ *e ctn* = *TopType* (*to-ct-list x2*)
**using** *c-s-def TopType Type*
**by** *simp*
**thus** *?thesis*

```
          using TopType ctm-def3 assms(4) c-types-agree-top2 ct-list-eq-refl
          by auto
        next
         assume ct-suffix cons x1
        hence 4:consume (TopType x1) cons = TopType (take (length x1 − length
cons ) x1)
          by (simp add: ct-suffix-length)
         hence 3:check-single C e ctn = TopType ((take (length x1 − length cons
) x1) @ to-ct-list x2)
          using c-s-def TopType Type
          by simp
        have ((take (length t1s − length cons ) t1s) @  x2) = t2s
          using assms(4) ctm-def3
          by simp
         have c-types-agree (TopType (take (length x1 − length cons ) x1)) (take
(length t1s − length cons) t1s)
          using consume-c-types-agree[OF t-int-def assms(3)] 4 TopType
          by simp
          hence c-types-agree (TopType (take (length x1 − length cons ) x1 @
to-ct-list x2)) (take (length t1s − length cons) t1s @ x2)
          unfolding c-types-agree.simps to-ct-list-def
          by (simp add: ct-suffix-cons2 ct-suffix-cons-it ct-suffix-extend-ct-list-eq)
        thus ?thesis
          using ctm-def3 assms 3
          by simp
       qed
     qed simp
   next
     case (Type x2)
     thus ?thesis
       using assms
       by simp
   next
     case Bot
     thus ?thesis
       using assms
       by simp
   qed
 qed
qed

lemma b-e-type-checker-compose:
 assumes b-e-type-checker C es (t1s -> t2s)
         b-e-type-checker C [e] (t2s -> t3s)
 shows b-e-type-checker C (es @ [e]) (t1s -> t3s)
proof −
 have c-types-agree (check-single C e (Type t2s)) t3s
   using assms(2)
   by simp
```

```
  then obtain ctm where ctm-def:check-single C e (Type t2s) = ctm
                        c-types-agree ctm t3s
                        ctm ≠ Bot
    by fastforce
  have c-types-agree (check C es (Type t1s)) t2s
    using assms(1)
    by simp
  then obtain ctn where ctn-def:check C es (Type t1s) = ctn
                        c-types-agree ctn t2s
                        ctn ≠ Bot
    by fastforce
  thus ?thesis
    using check-single-imp-weakening[OF ctm-def(1,3) ctn-def(2) ctm-def(2)]
          check-unfold-snoc[of C es (Type t1s) e]
    by simp
qed

lemma b-e-check-single-type-type:
  assumes check-single C e xs = (Type tm)
  shows ∃ tn. xs = (Type tn)
proof −
  consider (1) check-single C e = id
         | (2) check-single C e = (λctn. type-update-select ctn)
         | (3) (∃ cons prods. (check-single C e = (λctn. type-update ctn cons prods)))
    using check-single-imp assms
    by blast
  thus ?thesis
  proof (cases)
    case 1
    thus ?thesis
      using assms
      by simp
  next
    case 2
    note outer-2 = 2
    thus ?thesis
      using assms
    proof (cases xs)
      case (TopType x1)
      consider
          (1) length x1 = 0
        | (2) length x1 = Suc 0
        | (3) length x1 = Suc (Suc 0)
        | (4) length x1 ≥ 3
        by linarith
      thus ?thesis
      proof cases
        case 1
        thus ?thesis
```

```
      using assms 2 TopType
      by simp
    next
     case 2
     thus ?thesis
      using assms outer-2 TopType produce-type-type
      by fastforce
    next
     case 3
     thus ?thesis
      using assms 2 TopType
      by (simp, metis checker-type.distinct(1) checker-type.distinct(5))
    next
     case 4
     then obtain nat where nat-def:length x1 = Suc (Suc (Suc nat))
      by (metis add-eq-if diff-Suc-1 le-Suc-ex numeral-3-eq-3 nat.distinct(2))
     thus ?thesis
      using assms 2 TopType
     proof −
      {
       assume a1: produce (if ct-suffix [TAny, TAny, TSome T-i32] x1 then
TopType (take (length x1 − length [TAny, TAny, TSome T-i32]) x1) else if ct-suffix
x1 [TAny, TAny, TSome T-i32] then TopType [] else Bot) (select-return-top x1 (x1
! Suc nat) (x1 ! nat)) = Type tm
       obtain tts :: checker-type ⇒ t list where
        f2: ∀ c. (∀ ca ts. produce c ca ≠ Type ts) ∨ c = Type (tts c)
        using produce-type-type by moura
       then have f3: ⋀ts. ¬ ct-suffix [TAny, TAny, TSome T-i32] x1 ∨ Type
tm ≠ Type ts
        using a1 by fastforce
       then have ⋀ts. ¬ ct-suffix x1 [TAny, TAny, TSome T-i32] ∨ Type tm
≠ Type ts
        using f2 a1 by fastforce
       then have False
        using f3 a1 by fastforce
      }
      thus ?thesis
       using assms 2 TopType nat-def
       by simp
     qed
    qed
   qed simp-all
  next
   case 3
   then obtain cons prods where check-def:check-single C e = (λctn. type-update
ctn cons prods)
    by blast
   hence produce (consume xs cons) prods = (Type tm)
    using assms(1)
```

```
    by simp
  thus ?thesis
    using assms check-def consume-type-type produce-type-type
    by blast
 qed
qed

lemma b-e-check-single-weaken-type:
 assumes check-single C e (Type tn) = (Type tm)
 shows check-single C e (Type (ts@tn)) = Type (ts@tm)
proof −
 consider (1) check-single C e = id
      | (2) check-single C e = (λctn. type-update-select ctn)
      | (3) (∃ cons prods. (check-single C e = (λctn. type-update ctn cons prods)))
   using check-single-imp assms
   by blast
 thus ?thesis
 proof (cases)
   case 1
   thus ?thesis
     using assms(1)
     by simp
 next
   case 2
   hence cond:(length tn ≥ 3 ∧ (tn!(length tn−2)) = (tn!(length tn−3)))
     using assms
     by (simp, metis checker-type.distinct(5))
   hence consume (Type tn) [TAny, TSome T-i32] = (Type tm)
     using assms 2
     by simp
   hence consume (Type (ts@tn)) [TAny, TSome T-i32] = (Type (ts@tm))
     using consume-weaken-type
     by blast
   moreover
    have (length (ts@tn) ≥ 3 ∧ ((ts@tn)!(length (ts@tn)−2)) = ((ts@tn)!(length
(ts@tn)−3)))
     using cond
      by (simp, metis add.commute add-leE nth-append-length-plus numeral-Bit1
numeral-One
          one-add-one ordered-cancel-comm-monoid-diff-class.diff-add-assoc2)
   ultimately
   show ?thesis
     using 2
     by simp
 next
   case 3
  then obtain cons prods where check-def:check-single C e = (λctn. type-update
ctn cons prods)
     by blast
```

```
    hence produce (consume (Type tn) cons) prods = (Type tm)
      using assms(1)
      by simp
    then obtain t-int where t-int-def:consume (Type tn) cons = (Type t-int)
      by (metis consume.simps(1) produce.simps(6))
    thus ?thesis
      using assms(1) check-def
            consume-weaken-type[OF t-int-def, of ts]
            produce-weaken-type[of t-int prods tm ts]
      by simp
  qed
qed

lemma b-e-check-single-weaken-top:
  assumes check-single C e (Type tn) = TopType tm
  shows check-single C e (Type (ts@tn)) = TopType tm
proof −
  consider (1) check-single C e = id
        | (2) check-single C e = (λctn. type-update-select ctn)
        | (3) (∃ cons prods. (check-single C e = (λctn. type-update ctn cons prods)))
    using check-single-imp assms
    by blast
  thus ?thesis
  proof (cases)
    case 1
    thus ?thesis
      using assms
      by simp
  next
    case 2
    thus ?thesis
      using assms
    by (simp, metis checker-type.distinct(1) checker-type.distinct(3) consume.simps(1))
  next
    case 3
   then obtain cons prods where check-def:check-single C e = (λctn. type-update
ctn cons prods)
      by blast
    hence produce (consume (Type tn) cons) prods = (TopType tm)
      using assms(1)
      by simp
    moreover
    then obtain t-int where t-int-def:consume (Type tn) cons = (Type t-int)
      by (metis checker-type.distinct(3) consume.simps(1) produce.simps(6))
    ultimately
    show ?thesis
      using check-def consume-weaken-type
      by (cases prods, auto)
  qed
```

**qed**

**lemma** *b-e-check-weaken-type*:
**assumes** *check* $\mathcal{C}$ *es* (*Type tn*) = (*Type tm*)
**shows** *check* $\mathcal{C}$ *es* (*Type* (*ts*@*tn*)) = (*Type* (*ts*@*tm*))
**using** *assms*
**proof** (*induction es arbitrary*: *tn tm rule*: *List.rev-induct*)
**case** *Nil*
**thus** *?case*
**by** *simp*
**next**
**case** (*snoc e es*)
**hence** *check-single* $\mathcal{C}$ *e* (*check* $\mathcal{C}$ *es* (*Type tn*)) = *Type tm*
**using** *check-unfold-snoc*[*OF check-neq-bot-snoc*]
**by** (*metis checker-type.distinct*(*5*))
**thus** *?case*
**using** *b-e-check-single-weaken-type b-e-check-single-type-type snoc*
**by** (*metis check-unfold-snoc checker-type.distinct*(*5*))
**qed**

**lemma** *check-bot*: *check* $\mathcal{C}$ *es Bot* = *Bot*
**by** (*simp add*: *list.case-eq-if*)

**lemma** *b-e-check-weaken-top*:
**assumes** *check* $\mathcal{C}$ *es* (*Type tn*) = (*TopType tm*)
**shows** *check* $\mathcal{C}$ *es* (*Type* (*ts*@*tn*)) = (*TopType tm*)
**using** *assms*
**proof** (*induction es arbitrary*: *tn tm*)
**case** *Nil*
**thus** *?case*
**by** *simp*
**next**
**case** (*Cons e es*)
**show** *?case*
**proof** (*cases* (*check-single* $\mathcal{C}$ *e* (*Type tn*)))
**case** (*TopType x1*)
**hence** *check-single* $\mathcal{C}$ *e* (*Type* (*ts*@*tn*)) = *TopType x1*
**using** *b-e-check-single-weaken-top*
**by** *blast*
**thus** *?thesis*
**using** *TopType Cons*
**by** *simp*
**next**
**case** (*Type x2*)
**hence** *check-single* $\mathcal{C}$ *e* (*Type* (*ts*@*tn*)) = *Type* (*ts*@*x2*)
**using** *b-e-check-single-weaken-type*
**by** *blast*
**thus** *?thesis*
**using** *Cons Type*

```
    by fastforce
  next
    case Bot
    thus ?thesis
      using check-bot Cons
      by simp
  qed

qed

lemma b-e-type-checker-weaken:
  assumes b-e-type-checker C es (t1s -> t2s)
  shows b-e-type-checker C es (ts@t1s -> ts@t2s)
proof −
  have c-types-agree (check C es (Type t1s)) t2s
    using assms(1)
    by simp
  then obtain ctn where ctn-def:check C es (Type t1s) = ctn
                        c-types-agree ctn t2s
                        ctn ≠ Bot
    by fastforce
  show ?thesis
  proof (cases ctn)
    case (TopType x1)
    thus ?thesis
      using ctn-def(1,2) b-e-check-weaken-top[of C es t1s x1 ts]
        by (metis append-assoc b-e-type-checker.simps c-types-agree-imp-ct-list-eq
c-types-agree-top2)
  next
    case (Type x2)
    thus ?thesis
      using ctn-def(1,2) b-e-check-weaken-type[of C es t1s x2 ts]
      by simp
  next
    case Bot
    thus ?thesis
      using ctn-def(3)
      by simp
  qed
qed

lemma b-e-type-checker-complete:
  assumes C ⊢ es : (tn -> tm)
  shows b-e-type-checker C es (tn -> tm)
  using assms
proof (induction es (tn -> tm) arbitrary: tn tm rule: b-e-typing.induct)
  case (select C t)
  have ct-list-eq [TAny, TSome T-i32] [TSome t, TSome T-i32]
    by (simp add: to-ct-list-def ct-list-eq-def)
```

```
  thus ?case
    using ct-suffix-extend-ct-list-eq[OF ct-suffix-nil[of [TSome t]]] to-ct-list-def
    by auto
next
  case (br-table C ts is i t1s t2s)
  show ?case
    using list-all-conv-same-lab[OF br-table]
    by (auto simp add: to-ct-list-def ct-suffix-nil ct-suffix-cons-it)
next
  case (set-global i C t)
  thus ?case
    using to-ct-list-def ct-suffix-refl is-mut-def tg-t-def
    by auto
next
  case (composition C es t1s t2s e t3s)
  thus ?case
    using b-e-type-checker-compose
    by simp
next
  case (weakening C es t1s t2s ts)
  thus ?case
    using b-e-type-checker-weaken
    by simp
qed (auto simp add: to-ct-list-def ct-suffix-refl ct-suffix-nil ct-suffix-cons-it
                    ct-suffix-singleton-any)

theorem b-e-typing-equiv-b-e-type-checker:
  shows (C ⊢ es : (tn -> tm)) = (b-e-type-checker C es (tn -> tm))
  using b-e-type-checker-sound b-e-type-checker-complete
  by blast

end
```

# 11 WebAssembly Interpreter

```
theory Wasm-Interpreter imports Wasm begin

datatype res-crash =
  CError
| CExhaustion

datatype res =
  RCrash res-crash
| RTrap
| RValue v list

datatype res-step =
  RSCrash res-crash
| RSBreak nat v list
```

| *RSReturn v list*
| *RSNormal e list*

**abbreviation** *crash-error* **where** *crash-error* ≡ *RSCrash CError*

**type-synonym** *depth* = *nat*
**type-synonym** *fuel* = *nat*

**type-synonym** *config-tuple* = *s* × *v list* × *e list*

**type-synonym** *config-one-tuple* = *s* × *v list* × *v list* × *e*

**type-synonym** *res-tuple* = *s* × *v list* × *res-step*

**fun** *split-vals* :: *b-e list* ⇒ *v list* × *b-e list* **where**
*split-vals* ((*C v*)#*es*) = (*let* (*vs′*, *es′*) = *split-vals es in* (*v*#*vs′*, *es′*))
| *split-vals es* = ([], *es*)

**fun** *split-vals-e* :: *e list* ⇒ *v list* × *e list* **where**
*split-vals-e* (($ *C v*)#*es*) = (*let* (*vs′*, *es′*) = *split-vals-e es in* (*v*#*vs′*, *es′*))
| *split-vals-e es* = ([], *es*)

**fun** *split-n* :: *v list* ⇒ *nat* ⇒ *v list* × *v list* **where**
*split-n* [] *n* = ([], [])
| *split-n es 0* = ([], *es*)
| *split-n* (*e*#*es*) (*Suc n*) = (*let* (*es′*, *es′′*) = *split-n es n in* (*e*#*es′*, *es′′*))

**lemma** *split-n-conv-take-drop*: *split-n es n* = (*take n es*, *drop n es*)
**by** (*induction es n rule*: *split-n.induct*, *simp-all*)

**lemma** *split-n-length*:
**assumes** *split-n es n* = (*es1*, *es2*) *length es* ≥ *n*
**shows** *length es1* = *n*
**using** *assms*
**unfolding** *split-n-conv-take-drop*
**by** *fastforce*

**lemma** *split-n-conv-app*:
**assumes** *split-n es n* = (*es1*, *es2*)
**shows** *es* = *es1*@*es2*
**using** *assms*
**unfolding** *split-n-conv-take-drop*
**by** *auto*

**lemma** *app-conv-split-n*:
**assumes** *es* = *es1*@*es2*
**shows** *split-n es* (*length es1*) = (*es1*, *es2*)
**using** *assms*
**unfolding** *split-n-conv-take-drop*

**by** *auto*

**lemma** *split-vals-const-list*: *split-vals* (*map EConst vs*) = (*vs*, [])
**by** (*induction vs*, *simp-all*)

**lemma** *split-vals-e-const-list*: *split-vals-e* ($$∗ *vs*) = (*vs*, [])
**by** (*induction vs*, *simp-all*)

**lemma** *split-vals-e-conv-app*:
**assumes** *split-vals-e xs* = (*as*, *bs*)
**shows** *xs* = ($$∗ *as*)@*bs*
**using** *assms*
**proof** (*induction xs arbitrary*: *as rule*: *split-vals-e.induct*)
**case** (*1 v es*)
**obtain** *as′ bs′* **where** *split-vals-e es* = (*as′*, *bs′*)
**by** (*meson surj-pair*)
**thus** *?case*
**using** *1*
**by** *fastforce*
**qed** *simp-all*

**abbreviation** *expect* :: *′a option* ⇒ (*′a* ⇒ *′b*) ⇒ *′b* ⇒ *′b* **where**
*expect a f b* ≡ (*case a of*
*Some a′* ⇒ *f a′*
| *None* ⇒ *b*)

**abbreviation** *vs-to-es* :: *v list* ⇒ *e list*
**where** *vs-to-es v* ≡ $$∗ (*rev v*)

**definition** *e-is-trap* :: *e* ⇒ *bool* **where**
*e-is-trap e* = (*case e of Trap* ⇒ *True* | - ⇒ *False*)

**definition** *es-is-trap* :: *e list* ⇒ *bool* **where**
*es-is-trap es* = (*case es of* [*e*] ⇒ *e-is-trap e* | - ⇒ *False*)

**lemma**[*simp*]: *e-is-trap e* = (*e* = *Trap*)
**using** *e-is-trap-def*
**by** (*cases e*) *auto*

**lemma**[*simp*]: *es-is-trap es* = (*es* = [*Trap*])
**proof** (*cases es*)
**case** *Nil*
**thus** *?thesis*
**using** *es-is-trap-def*
**by** *auto*
**next**
**case** *outer-Cons*:(*Cons a list*)
**thus** *?thesis*
**proof** (*cases list*)

```
    case Nil
    thus ?thesis
      using outer-Cons es-is-trap-def
      by auto
  next
    case (Cons a' list')
    thus ?thesis
      using es-is-trap-def outer-Cons
      by auto
  qed
qed

axiomatization
  mem-grow-impl:: mem ⇒ nat ⇒ mem option where
  mem-grow-impl-correct:(mem-grow-impl m n = Some m') ⟹ (mem-grow m n =
m')


axiomatization
  host-apply-impl:: s ⇒ tf ⇒ host ⇒ v list ⇒ (s × v list) option where
  host-apply-impl-correct:(host-apply-impl s tf h vs = Some m') ⟹ (∃ hs. host-apply
s tf h vs hs = Some m')

function (sequential)
    run-step :: depth ⇒ nat ⇒ config-tuple ⇒ res-tuple
and run-one-step :: depth ⇒ nat ⇒ config-one-tuple ⇒ res-tuple where
  run-step d i (s,vs,es) = (let (ves, es') = split-vals-e es in
                            case es' of
                              [] ⇒ (s,vs, crash-error)
                            | e#es'' ⇒
                              if e-is-trap e
                                then
                                  if (es'' ≠ [] ∨ ves ≠ [])
                                    then
                                      (s, vs, RSNormal [Trap])
                                    else
                                      (s, vs, crash-error)
                                else
                                  (let (s',vs',r) = run-one-step d i (s,vs,(rev ves),e) in
                                   case r of
                                     RSNormal res ⇒ (s', vs', RSNormal (res@es''))
                                   | - ⇒ (s', vs', r)))
| run-one-step d i (s, vs, ves, e) =
    (case e of
   — B-E
     — UNOPS
       $(Unop-i T-i32 iop) ⇒
        (case ves of
           (ConstInt32 c)#ves' ⇒
```

```
            (s, vs, RSNormal (vs-to-es ((ConstInt32 (app-unop-i iop c))#ves')))
          | - ⇒ (s, vs, crash-error))
      | $(Unop-i T-i64 iop) ⇒
          (case ves of
            (ConstInt64 c)#ves' ⇒
              (s, vs, RSNormal (vs-to-es ((ConstInt64 (app-unop-i iop c))#ves')))
          | - ⇒ (s, vs, crash-error))
      | $(Unop-i - iop) ⇒ (s, vs, crash-error)
      | $(Unop-f T-f32 fop) ⇒
          (case ves of
            (ConstFloat32 c)#ves' ⇒
              (s, vs, RSNormal (vs-to-es ((ConstFloat32 (app-unop-f fop c))#ves')))
          | - ⇒ (s, vs, crash-error))
      | $(Unop-f T-f64 fop) ⇒
          (case ves of
            (ConstFloat64 c)#ves' ⇒
              (s, vs, RSNormal (vs-to-es ((ConstFloat64 (app-unop-f fop c))#ves')))
          | - ⇒ (s, vs, crash-error))
      | $(Unop-f - fop) ⇒ (s, vs, crash-error)
      — BINOPS
      | $(Binop-i T-i32 iop) ⇒
          (case ves of
            (ConstInt32 c2)#(ConstInt32 c1)#ves' ⇒
                  expect (app-binop-i iop c1 c2) (λc. (s, vs, RSNormal (vs-to-es
((ConstInt32 c)#ves')))) (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
          | - ⇒ (s, vs, crash-error))
      | $(Binop-i T-i64 iop) ⇒
          (case ves of
            (ConstInt64 c2)#(ConstInt64 c1)#ves' ⇒
                  expect (app-binop-i iop c1 c2) (λc. (s, vs, RSNormal (vs-to-es
((ConstInt64 c)#ves')))) (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
          | - ⇒ (s, vs, crash-error))
      | $(Binop-i - iop) ⇒ (s, vs, crash-error)
      | $(Binop-f T-f32 fop) ⇒
          (case ves of
            (ConstFloat32 c2)#(ConstFloat32 c1)#ves' ⇒
                  expect (app-binop-f fop c1 c2) (λc. (s, vs, RSNormal (vs-to-es
((ConstFloat32 c)#ves')))) (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
          | - ⇒ (s, vs, crash-error))
      | $(Binop-f T-f64 fop) ⇒
        (case ves of
          (ConstFloat64 c2)#(ConstFloat64 c1)#ves' ⇒
                expect (app-binop-f fop c1 c2) (λc. (s, vs, RSNormal (vs-to-es
((ConstFloat64 c)#ves')))) (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
        | - ⇒ (s, vs, crash-error))
      | $(Binop-f - fop) ⇒ (s, vs, crash-error)
      — TESTOPS
      | $(Testop T-i32 testop) ⇒
          (case ves of
```

```
          (ConstInt32 c)#ves' ⇒
          (s, vs, RSNormal (vs-to-es ((ConstInt32 (wasm-bool (app-testop-i testop
c)))#ves')))
        | - ⇒ (s, vs, crash-error))
    | $(Testop T-i64 testop) ⇒
        (case ves of
          (ConstInt64 c)#ves' ⇒
          (s, vs, RSNormal (vs-to-es ((ConstInt32 (wasm-bool (app-testop-i testop
c)))#ves')))
        | - ⇒ (s, vs, crash-error))
    | $(Testop - testop) ⇒ (s, vs, crash-error)
    — RELOPS
    | $(Relop-i T-i32 iop) ⇒
        (case ves of
          (ConstInt32 c2)#(ConstInt32 c1)#ves' ⇒
            (s, vs, RSNormal (vs-to-es ((ConstInt32 (wasm-bool (app-relop-i iop
c1 c2)))#ves')))
        | - ⇒ (s, vs, crash-error))
    | $(Relop-i T-i64 iop) ⇒
        (case ves of
          (ConstInt64 c2)#(ConstInt64 c1)#ves' ⇒
            (s, vs, RSNormal (vs-to-es ((ConstInt32 (wasm-bool (app-relop-i iop
c1 c2)))#ves')))
        | - ⇒ (s, vs, crash-error))
    | $(Relop-i - iop) ⇒ (s, vs, crash-error)
    | $(Relop-f T-f32 fop) ⇒
        (case ves of
          (ConstFloat32 c2)#(ConstFloat32 c1)#ves' ⇒
            (s, vs, RSNormal (vs-to-es ((ConstInt32 (wasm-bool (app-relop-f fop
c1 c2)))#ves')))
        | - ⇒ (s, vs, crash-error))
    | $(Relop-f T-f64 fop) ⇒
        (case ves of
          (ConstFloat64 c2)#(ConstFloat64 c1)#ves' ⇒
            (s, vs, RSNormal (vs-to-es ((ConstInt32 (wasm-bool (app-relop-f fop
c1 c2)))#ves')))
        | - ⇒ (s, vs, crash-error))
    | $(Relop-f - fop) ⇒ (s, vs, crash-error)
    — CONVERT
    | $(Cvtop t2 Convert t1 sx) ⇒
        (case ves of
          v#ves' ⇒
            (if (types-agree t1 v)
              then
                expect (cvt t2 sx v) (λv'. (s, vs, RSNormal (vs-to-es (v'#ves'))))
(s, vs, RSNormal ((vs-to-es ves')@[Trap]))
              else
                (s, vs, crash-error))
        | - ⇒ (s, vs, crash-error))
```

```
    | $(Cvtop t2 Reinterpret t1 sx) ⇒
        (case ves of
          v#ves' ⇒
            (if (types-agree t1 v ∧ sx = None)
              then
                (s, vs, RSNormal (vs-to-es ((wasm-deserialise (bits v) t2)#ves')))
              else
                (s, vs, crash-error))
        | - ⇒ (s, vs, crash-error))
    — UNREACHABLE
    | $Unreachable ⇒
        (s, vs, RSNormal ((vs-to-es ves)@[Trap]))
    — NOP
    | $Nop ⇒
        (s, vs, RSNormal (vs-to-es ves))
    — DROP
    | $Drop ⇒
        (case ves of
          v#ves' ⇒
            (s, vs, RSNormal (vs-to-es ves'))
        | - ⇒ (s, vs, crash-error))
    — SELECT
    | $Select ⇒
        (case ves of
          (ConstInt32 c)#v2#v1#ves' ⇒
            (if int-eq c 0 then (s, vs, RSNormal (vs-to-es (v2#ves'))) else (s, vs,
RSNormal (vs-to-es (v1#ves'))))
        | - ⇒ (s, vs, crash-error))
    — BLOCK
    | $(Block (t1s -> t2s) es) ⇒
        (if length ves ≥ length t1s
          then
            let (ves', ves'') = split-n ves (length t1s) in
              (s, vs, RSNormal ((vs-to-es ves'') @ [Label (length t2s) [] ((vs-to-es
ves')@($∗ es))]))
          else
            (s, vs, crash-error))
    — LOOP
    | $(Loop (t1s -> t2s) es) ⇒
        (if length ves ≥ length t1s
          then
            let (ves', ves'') = split-n ves (length t1s) in
            (s, vs, RSNormal ((vs-to-es ves'') @ [Label (length t1s) [$(Loop (t1s ->
t2s) es)] ((vs-to-es ves')@($∗ es))]))
          else
            (s, vs, crash-error))
    — IF
    | $(If tf es1 es2) ⇒
        (case ves of
```

```
      (ConstInt32 c)#ves' ⇒
        if int-eq c 0
          then
            (s, vs, RSNormal ((vs-to-es ves')@[$(Block tf es2)]))
          else
            (s, vs, RSNormal ((vs-to-es ves')@[$(Block tf es1)]))
    | - ⇒ (s, vs, crash-error))
— BR
| $Br j ⇒
    (s, vs, RSBreak j ves)
— BR-IF
| $Br-if j ⇒
    (case ves of
      (ConstInt32 c)#ves' ⇒
        if int-eq c 0
          then
            (s, vs, RSNormal (vs-to-es ves'))
          else
            (s, vs, RSNormal ((vs-to-es ves') @ [$Br j]))
    | - ⇒ (s, vs, crash-error))
— BR-TABLE
| $Br-table js j ⇒
    (case ves of
      (ConstInt32 c)#ves' ⇒
      let k = nat-of-int c in
        if k < length js
          then
            (s, vs, RSNormal ((vs-to-es ves') @ [$Br (js!k)]))
          else
            (s, vs, RSNormal ((vs-to-es ves') @ [$Br j]))
    | - ⇒ (s, vs, crash-error))
— CALL
| $Call j ⇒
    (s, vs, RSNormal ((vs-to-es ves) @ [Callcl (sfunc s i j)]))
— CALL-INDIRECT
| $Call-indirect j ⇒
    (case ves of
      (ConstInt32 c)#ves' ⇒
       (case (stab s i (nat-of-int c)) of
          Some cl ⇒
            if (stypes s i j = cl-type cl)
              then
                (s, vs, RSNormal ((vs-to-es ves') @ [Callcl cl]))
              else
                (s, vs, RSNormal ((vs-to-es ves')@[Trap]))
        | - ⇒ (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
    | - ⇒ (s, vs, crash-error))
— RETURN
| $Return ⇒
```

```
    (s, vs, RSReturn ves)
  — GET-LOCAL
  | $Get-local j ⇒
    (if j < length vs
      then (s, vs, RSNormal (vs-to-es ((vs!j)#ves)))
      else (s, vs, crash-error))
  — SET-LOCAL
  | $Set-local j ⇒
    (case ves of
      v#ves' ⇒
        if j < length vs
          then (s, vs[j := v], RSNormal (vs-to-es ves'))
          else (s, vs, crash-error)
    | - ⇒ (s, vs, crash-error))
  — TEE-LOCAL
  | $Tee-local j ⇒
    (case ves of
      v#ves' ⇒
        (s, vs, RSNormal ((vs-to-es (v#ves)) @ [$(Set-local j)]))
    | - ⇒ (s, vs, crash-error))
  — GET-GLOBAL
  | $Get-global j ⇒
    (s, vs, RSNormal (vs-to-es ((sglob-val s i j)#ves)))
  — SET-GLOBAL
  | $Set-global j ⇒
    (case ves of
      v#ves' ⇒ ((supdate-glob s i j v), vs, RSNormal (vs-to-es ves'))
    | - ⇒ (s, vs, crash-error))
  — LOAD
  | $(Load t None a off) ⇒
    (case ves of
      (ConstInt32 k)#ves' ⇒
        expect (smem-ind s i)
          (λj.
            expect (load ((mem s)!j) (nat-of-int k) off (t-length t))
            (λbs. (s, vs, RSNormal (vs-to-es ((wasm-deserialise bs t)#ves'))))
              (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
          (s, vs, crash-error)
    | - ⇒ (s, vs, crash-error))
  — LOAD PACKED
  | $(Load t (Some (tp, sx)) a off) ⇒
    (case ves of
      (ConstInt32 k)#ves' ⇒
        expect (smem-ind s i)
          (λj.
            expect (load-packed sx ((mem s)!j) (nat-of-int k) off (tp-length tp)
(t-length t))
            (λbs. (s, vs, RSNormal (vs-to-es ((wasm-deserialise bs t)#ves'))))
              (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
```

```
                (s, vs, crash-error)
          | - ⇒ (s, vs, crash-error))
      — STORE
      | $(Store t None a off) ⇒
          (case ves of
            v#(ConstInt32 k)#ves' ⇒
              (if (types-agree t v)
                then
                  expect (smem-ind s i)
                    (λj.
                      expect (store ((mem s)!j) (nat-of-int k) off (bits v) (t-length t))
                          (λmem'. (s⦇mem:= ((mem s)[j := mem'])⦈, vs, RSNormal
(vs-to-es ves')))
                        (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
                    (s, vs, crash-error)
                else
                  (s, vs, crash-error))
          | - ⇒ (s, vs, crash-error))
      — STORE-PACKED
      | $(Store t (Some tp) a off) ⇒
          (case ves of
                v#(ConstInt32 k)#ves' ⇒
                  (if (types-agree t v)
                    then
                      expect (smem-ind s i)
                        (λj.
                          expect (store-packed ((mem s)!j) (nat-of-int k) off (bits v)
(tp-length tp))
                            (λmem'. (s⦇mem:= ((mem s)[j := mem'])⦈, vs, RSNormal
(vs-to-es ves')))
                              (s, vs, RSNormal ((vs-to-es ves')@[Trap])))
                        (s, vs, crash-error)
                    else
                      (s, vs, crash-error))
              | - ⇒ (s, vs, crash-error))
      — CURRENT-MEMORY
      | $Current-memory ⇒
          expect (smem-ind s i)
              (λj. (s, vs, RSNormal (vs-to-es ((ConstInt32 (int-of-nat (mem-size
((s.mem s)!j))))#ves))))
            (s, vs, crash-error)
      — GROW-MEMORY
      | $Grow-memory ⇒
          (case ves of
            (ConstInt32 c)#ves' ⇒
              expect (smem-ind s i)
                (λj.
                  let l = (mem-size ((s.mem s)!j)) in
                  (expect (mem-grow-impl ((mem s)!j) (nat-of-int c))
```

```
                        (λmem'. (s⦇mem:= ((mem s)[j := mem'])⦈, vs, RSNormal
(vs-to-es ((ConstInt32 (int-of-nat l))#ves'))))
                  (s, vs, RSNormal (vs-to-es ((ConstInt32 int32-minus-one)#ves'))))
                  (s, vs, crash-error)
          | - ⇒ (s, vs, crash-error))
      — VAL - should not be executed
      | $C v ⇒ (s, vs, crash-error)
    — E
      — CALLCL
      | Callcl cl ⇒
          (case cl of
            Func-native i' (t1s -> t2s) ts es ⇒
              let n = length t1s in
              let m = length t2s in
              if length ves ≥ n
                then
                  let (ves', ves'') = split-n ves n in
                  let zs = n-zeros ts in
                    (s, vs, RSNormal ((vs-to-es ves'') @ ([Local m i' ((rev ves')@zs)
[$(Block ([] -> t2s) es)]])))
                else
                  (s, vs, crash-error)
          | Func-host (t1s -> t2s) f ⇒
              let n = length t1s in
              let m = length t2s in
              if length ves ≥ n
                then
                  let (ves', ves'') = split-n ves n in
                  case host-apply-impl s (t1s -> t2s) f (rev ves') of
                    Some (s',rves) ⇒
                      if list-all2 types-agree t2s rves
                        then
                          (s', vs, RSNormal ((vs-to-es ves'') @ ($$* rves)))
                        else
                          (s', vs, crash-error)
                  | None ⇒ (s, vs, RSNormal ((vs-to-es ves'')@[Trap]))
                else
                  (s, vs, crash-error))
      — LABEL
      | Label ln les es ⇒
          if es-is-trap es
            then
              (s, vs, RSNormal ((vs-to-es ves)@[Trap]))
            else
              (if (const-list es)
                 then
                   (s, vs, RSNormal ((vs-to-es ves)@es))
                 else
                   let (s', vs', res) = run-step d i (s, vs, es) in
```

```
                (case res of
                   RSBreak 0 bvs ⇒
                     if (length bvs ≥ ln)
                      then (s', vs', RSNormal ((vs-to-es ((take ln bvs)@ves))@les))
                       else (s', vs', crash-error)
                 | RSBreak (Suc n) bvs ⇒
                     (s', vs', RSBreak n bvs)
                 | RSReturn rvs ⇒
                     (s', vs', RSReturn rvs)
                 | RSNormal es' ⇒
                     (s', vs', RSNormal ((vs-to-es ves)@[Label ln les es']))
                 | - ⇒ (s', vs', crash-error)))
    — LOCAL
    | Local ln j vls es ⇒
        if es-is-trap es
         then
          (s, vs, RSNormal ((vs-to-es ves)@[Trap]))
         else
          (if (const-list es)
             then
              if (length es = ln)
               then (s, vs, RSNormal ((vs-to-es ves)@es))
               else (s, vs, crash-error)
             else
              case d of
                0 ⇒ (s, vs, crash-error)
              | Suc d' ⇒
                  let (s', vls', res) = run-step d' j (s, vls, es) in
                  (case res of
                     RSReturn rvs ⇒
                       if (length rvs ≥ ln)
                        then (s', vs, RSNormal (vs-to-es ((take ln rvs)@ves)))
                        else (s', vs, crash-error)
                   | RSNormal es' ⇒
                       (s', vs, RSNormal ((vs-to-es ves)@[Local ln j vls' es']))
                   | - ⇒ (s', vs, RSCrash CExhaustion)))
    — TRAP - should not be executed
    | Trap ⇒ (s, vs, crash-error))
  by pat-completeness auto
termination
proof −
  {
    fix xs::e list and as b bs
    assume local-assms:(as, b#bs) = split-vals-e xs
    have 2*(size b) < 2*(size-list size xs) + 1
      using local-assms[symmetric] split-vals-e-conv-app
            size-list-estimation'[of b xs size b size]
      unfolding size-list-def
      by fastforce
```

```
  }
  thus ?thesis
    by (relation measure (case-sum
                          (λp. 2 * (size-list size (snd (snd (snd (snd p))))) + 1)
                          (λp. 2 * size (snd (snd (snd (snd (snd p)))))))) auto
qed

fun run-v :: fuel ⇒ depth ⇒ nat ⇒ config-tuple ⇒ (s × res) where
  run-v (Suc n) d i (s,vs,es) = (if (es-is-trap es)
                                 then (s, RTrap)
                                 else if (const-list es)
                                       then (s, RValue (fst (split-vals-e es)))
                                      else (let (s',vs',res) = (run-step d i (s,vs,es)) in
                                            case res of
                                              RSNormal es' ⇒ run-v n d i (s',vs',es')
                                            | RSCrash error ⇒ (s, RCrash error)
                                            | - ⇒ (s, RCrash CError)))
| run-v 0 d i (s,vs,es) = (s, RCrash CExhaustion)

end
```

# 12 Soundness of Interpreter

```
theory Wasm-Interpreter-Properties imports Wasm-Interpreter Wasm-Properties
begin

lemma is-const-list-vs-to-es-list: const-list ($$* vs)
  using is-const-list
  by auto

lemma not-const-vs-to-es-list:
  assumes ~(is-const e)
  shows vs1 @ [e] @ vs2 ≠ $$* vs
proof −
  fix vs
  {
    assume vs1 @ [e] @ vs2 = $$* vs
    hence (∀ y∈set (vs1 @ [e] @ vs2). ∃ x. y = $C x)
      by simp
    hence False
      using assms
      unfolding is-const-def
      by fastforce
  }
  thus vs1 @ [e] @ vs2 ≠ $$* vs
    by fastforce
qed

lemma neq-label-nested:[Label n les es] ≠ es
```

**proof** −
**have** *size-list size* [*Label n les es*] > *size-list size es*
**by** *simp*
**thus** *?thesis*
**by** *fastforce*
**qed**

**lemma** *neq-local-nested*:[*Local n i lvs es*] ≠ *es*
**proof** −
**have** *size-list size* [*Local n i lvs es*] > *size-list size es*
**by** *simp*
**thus** *?thesis*
**by** *fastforce*
**qed**

**lemma** *trap-not-value*:[*Trap*] ≠ $$∗*es*
**by** *fastforce*

**thm** *Lfilled.simps*[*of - - -* [*e*], *simplified*]

**lemma** *lfilled-single*:
**assumes** *Lfilled k lholed es* [*e*]
⋀ *a b c. e* ≠ *Label a b c*
**shows** (*es* = [*e*] ∧ *lholed* = *LBase* [] []) ∨ *es* = []
**using** *assms*
**proof** (*cases rule*: *Lfilled.cases*)
**case** (*L0 vs es′*)
**thus** *?thesis*
**by** (*metis Nil-is-append-conv append-self-conv2 butlast-append butlast-snoc*)
**next**
**case** (*LN vs n es′ l es″ k lfilledk*)
**assume** (⋀*a b c. e* ≠ *Label a b c*)
**thus** *?thesis*
**using** *LN*(*2*)
**unfolding** *Cons-eq-append-conv*
**by** *fastforce*
**qed**

**lemma** *lfilled-eq*:
**assumes** *Lfilled j lholed es LI*
*Lfilled j lholed es′ LI*
**shows** *es* = *es′*
**using** *assms*
**proof** (*induction arbitrary*: *es′ rule*: *Lfilled.induct*)
**case** (*L0 vs lholed es′ es*)
**thus** *?case*
**using** *Lfilled.simps*[*of 0*, *simplified*]
**by** *auto*
**next**

**case** (*LN vs lholed n les′ l les″ k les lfilledk*)
**thus** *?case*
**using** *Lfilled.simps*[*of* (*k*+*1*) *LRec vs n les′ l les″ es′* (*vs* @ [*Label n les′ lfilledk*] @ *les″*), *simplified*]
**by** *auto*
**qed**

**lemma** *lfilled-size*:
**assumes** *Lfilled j lholed es LI*
**shows** *size-list size LI* ≥ *size-list size es*
**using** *assms*
**by** (*induction rule*: *Lfilled.induct*) *auto*

**thm** *Lfilled.simps*[*of* - - *es es*, *simplified*]

**lemma** *reduce-simple-not-eq*:
**assumes** (|*es*|) ⇝ (|*es′*|)
**shows** *es* ≠ *es′*
**using** *assms*
**proof** (*induction es′ rule*: *reduce-simple.induct*)
**case** (*label-const vs n es*)
**thus** *?case*
**using** *neq-label-nested*
**by** *auto*
**next**
**case** (*br vs n i lholed LI es*)
**have** *size-list size* [*Label n es LI*] > *size-list size* (*vs* @ *es*)
**using** *lfilled-size*[*OF br*(*3*)]
**by** *simp*
**thus** *?case*
**by** *fastforce*
**next**
**case** (*local-const es n i vs*)
**thus** *?case*
**using** *neq-local-nested*
**by** *auto*
**next**
**case** (*return vs n j lholed es i vls*)
**hence** *size-list size* [*Local n i vls es*] > *size-list size vs*
**using** *lfilled-size*[*OF return*(*3*)]
**by** *simp*
**thus** *?case*
**by** *auto*
**qed** *auto*

**lemma** *reduce-not-eq*:
**assumes** (|*s*;*vs*;*es*|) ⇝-*i* (|*s′*;*vs′*;*es′*|)
**shows** *es* ≠ *es′*
**using** *assms*

**proof** (*induction es′ rule*: *reduce.induct*)
**case** (*basic e e′ s vs i*)
**thus** *?case*
**using** *reduce-simple-not-eq*
**by** *simp*
**next**
**case** (*callcl-host-Some cl t1s t2s f ves vcs n m s hs s′ vcs′ vs i*)
**thus** *?case*
**by** (*cases vcs′ rule*:*rev-cases*) *auto*
**next**
**case** (*label s vs es i s′ vs′ es′ k lholed les les′*)
**thus** *?case*
**using** *lfilled-eq*
**by** *fastforce*
**qed** *auto*

**lemma** *reduce-simple-not-value*:
**assumes** (|*es*|) ⇝ (|*es′*|)
**shows** *es* ≠ $$∗ *vs*
**using** *assms*
**proof** (*induction rule*: *reduce-simple.induct*)
**case** (*block vs n t1s t2s m es*)
**have** ¬(*is-const* ($*Block* (*t1s* -> *t2s*) *es*))
**unfolding** *is-const-def*
**by** *simp*
**thus** *?case*
**using** *not-const-vs-to-es-list*
**by** (*metis append.right-neutral*)
**next**
**case** (*loop vs n t1s t2s m es*)
**have** ¬(*is-const* ($*Loop* (*t1s* -> *t2s*) *es*))
**unfolding** *is-const-def*
**by** *simp*
**thus** *?case*
**using** *not-const-vs-to-es-list*
**by** (*metis append.right-neutral*)
**next**
**case** (*trap lholed es*)
**show** *?case*
**using** *trap*(*2*)
**proof** (*cases rule*: *Lfilled.cases*)
**case** *L0*
**have** ¬(*is-const Trap*)
**unfolding** *is-const-def*
**by** *simp*
**thus** *?thesis*
**using** *L0 not-const-vs-to-es-list*
**by** *fastforce*
**qed** *auto*

**qed** *auto*

**lemma** *reduce-not-value*:
**assumes** $(|s;vs;es|) \rightsquigarrow\text{-}i\ (|s';vs';es'|)$
**shows** $es \neq \$\$*\ ves$
**using** *assms*
**proof** (*induction es' arbitrary*: *ves rule*: *reduce.induct*)
**case** (*basic e e' s vs i*)
**thus** *?case*
**using** *reduce-simple-not-value*
**by** *fastforce*
**next**
**case** (*callcl-native cl i' j ts es s t1s t2s ves vcs n k m zs vs i*)
**have** ¬(*is-const* (*Callcl cl*))
**unfolding** *is-const-def*
**by** *simp*
**thus** *?case*
**using** *not-const-vs-to-es-list*
**by** (*metis append.right-neutral*)
**next**
**case** (*callcl-host-Some cl t1s t2s f ves vcs n m s i s' vcs' vs*)
**have** ¬(*is-const* (*Callcl cl*))
**unfolding** *is-const-def*
**by** *simp*
**thus** *?case*
**using** *not-const-vs-to-es-list*
**by** (*metis append.right-neutral*)
**next**
**case** (*callcl-host-None cl t1s t2s f ves vcs n m s vs i*)
**have** ¬(*is-const* (*Callcl cl*))
**unfolding** *is-const-def*
**by** *simp*
**thus** *?case*
**using** *not-const-vs-to-es-list*
**by** (*metis append.right-neutral*)
**next**
**case** (*label s vs es i s' vs' es' k lholed les les'*)
**show** *?case*
**using** *label*(*2*,*4*)
**proof** (*induction rule*: *Lfilled.induct*)
**case** (*L0 lvs lholed les' les*)
**{**
**assume** *lvs* @ *les* @ *les'* = $\$\$*\ ves$
**hence** (∀ *y*∈*set* (*lvs* @ *les* @ *les'*). ∃ *x*. *y* = $\$C\ x$)
**by** *simp*
**hence** (∀ *y*∈*set les*. ∃ *x*. *y* = $\$C\ x$)
**by** *simp*
**hence** ∃ *vs1*. *les* = $\$\$*\ vs1$
**unfolding** *ex-map-conv***.**

```
    }
    thus ?case
      using L0(3)
      by fastforce
  next
    case (LN lvs lholed ln les' l les'' k les lfilledk)
    have ¬(is-const (Label ln les' lfilledk))
      unfolding is-const-def
      by simp
    thus ?case
      using not-const-vs-to-es-list
      by fastforce
  qed
qed auto

lemma reduce-simple-not-nil:
  assumes (|es|) ⇝ (|es'|)
  shows es ≠ []
  using assms
proof (induction rule: reduce-simple.induct)
  case (trap es lholed)
  thus ?case
    using Lfilled.simps[of 0 lholed [Trap]]
    by auto
qed auto

lemma reduce-not-nil:
  assumes (|s;vs;es|) ⇝-i (|s';vs';es'|)
  shows es ≠ []
  using assms
proof (induction rule: reduce.induct)
  case (basic e e' s vs i)
  thus ?case
    using reduce-simple-not-nil
    by simp
next
  case (label s vs es i s' vs' es' k lholed les les')
  show ?case
    using lfilled-size[OF label(2)] label(4)
    by (metis One-nat-def add-is-0 le-0-eq list.exhaust list.size(2) list.size-gen(1)
zero-neq-one)
qed auto

lemma reduce-simple-not-trap:
  assumes (|es|) ⇝ (|es'|)
  shows es ≠ [Trap]
  using assms
  by (induction rule: reduce-simple.induct) auto
```

**lemma** *reduce-not-trap*:
  **assumes** $(|s;vs;es|) \rightsquigarrow\text{-}i\ (|s';vs';es'|)$
  **shows** $es \neq [Trap]$
  **using** *assms*
**proof** (*induction rule*: *reduce.induct*)
  **case** (*basic e e' s vs i*)
  **thus** *?case*
    **using** *reduce-simple-not-trap*
    **by** *simp*
**next**
  **case** (*label s vs es i s' vs' es' k lholed les les'*)
  **{**
    **assume** $les = [Trap]$
    **hence** *Lfilled k lholed es* [*Trap*]
      **using** *label*(*2*)
      **by** *simp*
    **hence** *False*
      **using** *lfilled-single reduce-not-nil*[*OF label*(*1*)] *label*(*4*)
      **by** *fastforce*
  **}**
  **thus** *?case*
    **by** *auto*
**qed** *auto*

**lemma** *reduce-simple-call*: $\neg(|[\$Call\ j]|) \rightsquigarrow (|es'|)$
  **using** *reduce-simple.simps*[*of* [$*Call j*], *simplified*] *lfilled-single*
  **by** *fastforce*

**lemma** *reduce-call*:
  **assumes** $(|s;vs;[\$Call\ j]|) \rightsquigarrow\text{-}\ i\ (|s';vs';es'|)$
  **shows** $s = s'$
        $vs = vs'$
        $es' = [Callcl\ (sfunc\ s\ i\ j)]$
  **using** *assms*
**proof** (*induction* [$*Call j*]:: *e list i s' vs' es' rule*: *reduce.induct*)
  **case** (*label s vs es i s' vs' es' k lholed les'*)
  **have** $es = [\$Call\ j]$
       $lholed = LBase\ []\ []$
    **using** *reduce-not-nil*[*OF label*(*1*)] *lfilled-single*[*OF label*(*5*)]
    **by** *auto*
  **thus** $s = s'$
       $vs = vs'$
       $les' = [Callcl\ (sfunc\ s\ i\ j)]$
    **using** *label*(*2*,*3*,*4*,*6*) *Lfilled.simps*[*of k LBase [] [] [Callcl* (*sfunc s i j*)] *les'*]
    **by** *auto*
**qed** (*auto simp add*: *reduce-simple-call*)

**lemma** *run-one-step-basic-unreachable-result*:
  **assumes** *run-one-step d i* (*s*,*vs*,*ves*,$*Unreachable*) = (*s'*, *vs'*, *res*)

```
  shows ∃r. res = RSNormal r
  using assms
  by auto

lemma run-one-step-basic-nop-result:
  assumes run-one-step d i (s,vs,ves,$Nop) = (s', vs', res)
  shows ∃r. res = RSNormal r
  using assms
  by auto

lemma run-one-step-basic-drop-result:
  assumes run-one-step d i (s,vs,ves,$Drop) = (s', vs', res)
  shows (∃r. res = RSNormal r) ∨ (∃e. res = RSCrash e)
  using assms
  by (cases ves) auto

lemma run-one-step-basic-select-result:
  assumes run-one-step d i (s,vs,ves,$Select) = (s', vs', res)
  shows (∃r. res = RSNormal r) ∨ (∃e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  thus ?thesis
    using assms
  proof (cases a; cases list)
    fix x1a aa listaa
    assume a = ConstInt32 x1a and list = aa#listaa
    thus ?thesis
      using assms Cons
      by (cases listaa; cases int-eq x1a 0) auto
  qed auto
qed auto

lemma run-one-step-basic-block-result:
  assumes run-one-step d i (s,vs,ves,$(Block x51 x52)) = (s', vs', res)
  shows (∃r. res = RSNormal r) ∨ (∃e. res = RSCrash e)
  using assms
proof −
  obtain t1s t2s where x51 = (t1s -> t2s)
    using tf.exhaust
    by blast
  moreover obtain ves' ves'' where split-n ves (length t1s) = (ves', ves'')
    by (metis surj-pair)
  ultimately
    show ?thesis
    using assms
    by (cases length t1s ≤ length ves) auto
qed
```

**lemma** *run-one-step-basic-loop-result*:
**assumes** *run-one-step d i* (*s*,*vs*,*ves*,$(*Loop x61 x62*)) = (*s'*, *vs'*, *res*)
**shows** (∃ *r*. *res* = *RSNormal r*) ∨ (∃ *e*. *res* = *RSCrash e*)
**using** *assms*
**proof** −
**obtain** *t1s t2s* **where** *x61* = (*t1s* -> *t2s*)
**using** *tf.exhaust*
**by** *blast*
**moreover obtain** *ves' ves''* **where** *split-n ves* (*length t1s*) = (*ves'*, *ves''*)
**by** (*metis surj-pair*)
**ultimately**
**show** *?thesis*
**using** *assms*
**by** (*cases length t1s* ≤ *length ves*) *auto*
**qed**

**lemma** *run-one-step-basic-if-result*:
**assumes** *run-one-step d i* (*s*,*vs*,*ves*,$(*If x71 x72 x73*)) = (*s'*, *vs'*, *res*)
**shows** (∃ *r*. *res* = *RSNormal r*) ∨ (∃ *e*. *res* = *RSCrash e*)
**using** *assms*
**proof** (*cases ves*)
**case** (*Cons a list*)
**thus** *?thesis*
**using** *assms*
**proof** (*cases a*)
**fix** *x1a*
**assume** *a* = *ConstInt32 x1a*
**thus** *?thesis*
**using** *assms Cons*
**by** (*cases int-eq x1a 0*) *auto*
**qed** *auto*
**qed** *auto*

**lemma** *run-one-step-basic-br-result*:
**assumes** *run-one-step d i* (*s*,*vs*,*ves*,$*Br x8*) = (*s'*, *vs'*, *res*)
**shows** ∃ *r vrs*. *res* = *RSBreak r vrs*
**using** *assms*
**by** (*cases ves*) *auto*

**lemma** *run-one-step-basic-br-if-result*:
**assumes** *run-one-step d i* (*s*,*vs*,*ves*,$*Br-if x9*) = (*s'*, *vs'*, *res*)
**shows** (∃ *r*. *res* = *RSNormal r*) ∨ (∃ *e*. *res* = *RSCrash e*)
**using** *assms*
**proof** (*cases ves*)
**case** (*Cons a list*)
**thus** *?thesis*
**using** *assms*
**proof** (*cases a*)
**case** (*ConstInt32 x1*)

```
    thus ?thesis
      using assms Cons
      by (cases int-eq x1 0) auto
  qed auto
qed auto

lemma run-one-step-basic-br-table-result:
  assumes run-one-step d i (s,vs,ves,$Br-table js j) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  thus ?thesis
    using assms
  proof (cases a)
    case (ConstInt32 x1)
    thus ?thesis
      using assms Cons
      by (cases nat-of-int x1 < length js) auto
  qed auto
qed auto

lemma run-one-step-basic-return-result:
  assumes run-one-step d i (s,vs,ves,$Return) = (s', vs', res)
  shows ∃ vrs. res = RSReturn vrs
  using assms
  by (cases ves) auto

lemma run-one-step-basic-call-result:
  assumes run-one-step d i (s,vs,ves,$Call x12) = (s', vs', res)
  shows ∃ r. res = RSNormal r
  using assms
  by (cases ves) auto

lemma run-one-step-basic-call-indirect-result:
  assumes run-one-step d i (s,vs,ves,$Call-indirect x13) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  thus ?thesis
    using assms
  proof (cases a)
    case (ConstInt32 x1)
    thus ?thesis
      using Cons assms
    proof (cases stab s i (nat-of-int x1))
      case (Some cl)
      thus ?thesis
```

```
      using Cons assms ConstInt32
      by (cases cl; cases stypes s i x13 = cl-type cl) auto
    qed auto
  qed auto
qed auto

lemma run-one-step-basic-get-local-result:
  assumes run-one-step d i (s,vs,ves,$Get-local x14) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
  by (cases x14 < length vs) auto

lemma run-one-step-basic-set-local-result:
  assumes run-one-step d i (s,vs,ves,$Set-local x15) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
  by (cases ves; cases x15 < length vs) auto

lemma run-one-step-basic-tee-local-result:
  assumes run-one-step d i (s,vs,ves,$Tee-local x16) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
  by (cases ves) auto

lemma run-one-step-basic-get-global-result:
  assumes run-one-step d i (s,vs,ves,$Get-global x17) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
  by auto

lemma run-one-step-basic-set-global-result:
  assumes run-one-step d i (s,vs,ves,$Set-global x18) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
  by (cases ves) auto

lemma run-one-step-basic-load-result:
  assumes run-one-step d i (s,vs,ves,$Load x191 x192 x193 x194) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
proof (cases x192)
  case None
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms None
    proof (cases smem-ind s i; cases a)
      fix aa x1
```

```
    assume smem-ind s i = Some aa and a = ConstInt32 x1
    thus ?thesis
      using assms None Cons
      by (cases load (s.mem s ! aa) (nat-of-int x1) x194 (t-length x191)) auto
  qed auto
 qed auto
next
 case (Some a)
 thus ?thesis
  using assms
 proof (cases ves)
  case (Cons a' list)
  thus ?thesis
   using assms Some
  proof (cases smem-ind s i; cases a; cases a')
   fix aa x y x1
   assume smem-ind s i = Some aa and a = (x, y) and a' = ConstInt32 x1
   thus ?thesis
    using assms Some Cons
     by (cases load-packed y (s.mem s ! aa) (nat-of-int x1) x194 (tp-length x)
(t-length x191)) auto
  qed auto
 qed auto
qed

lemma run-one-step-basic-store-result:
 assumes run-one-step d i (s,vs,ves,$Store x201 x202 x203 x204) = (s', vs', res)
 shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
proof (cases x202)
 case None
 thus ?thesis
  using assms
 proof (cases ves)
  case (Cons a list)
  note outer-Cons = Cons
  thus ?thesis
   using assms None
  proof (cases list)
   case (Cons a' list')
   thus ?thesis
    using assms None outer-Cons
   proof (cases a'; cases types-agree x201 a; cases smem-ind s i)
    fix k aa
     assume a' = ConstInt32 k and types-agree x201 a and smem-ind s i =
Some aa
    thus ?thesis
     using assms None outer-Cons Cons
     by (cases store (s.mem s ! aa) (nat-of-int k) x204 (bits a) (t-length x201))
auto
```

```
      qed auto
    qed auto
  qed auto
next
  case (Some a'')
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    note outer-Cons = Cons
    thus ?thesis
      using assms Some
    proof (cases list)
      case (Cons a' list')
      thus ?thesis
        using assms Some outer-Cons
      proof (cases a'; cases types-agree x201 a; cases smem-ind s i)
        fix k aa
         assume a' = ConstInt32 k and types-agree x201 a and smem-ind s i =
Some aa
        thus ?thesis
          using assms Some outer-Cons Cons
         by (cases store-packed (s.mem s ! aa) (nat-of-int k) x204 (bits a) (tp-length
a'')) auto
      qed auto
    qed auto
  qed auto
qed

lemma run-one-step-basic-current-memory-result:
  assumes run-one-step d i (s,vs,ves,$Current-memory) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
  by (cases smem-ind s i) auto

lemma run-one-step-basic-grow-memory-result:
  assumes run-one-step d i (s,vs,ves,$Grow-memory) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  thus ?thesis
    using assms
  proof (cases a; cases smem-ind s i)
    fix c a'
    assume a = ConstInt32 c and smem-ind s i = Some a'
    thus ?thesis
      using assms Cons
      by (cases mem-grow-impl (s.mem s ! a') (nat-of-int c)) auto
```

```
  qed auto
qed auto

lemma run-one-step-basic-const-result:
  assumes run-one-step d i (s,vs,ves,$EConst x23) = (s', vs', res)
  shows ∃ e. res = RSCrash e
  using assms
  by auto

lemma run-one-step-basic-unop-i-result:
  assumes run-one-step d i (s,vs,ves,$Unop-i x241 x242) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  thus ?thesis
    using assms
    by (cases x241; cases a) auto
qed (cases x241; auto)

lemma run-one-step-basic-unop-f-result:
  assumes run-one-step d i (s,vs,ves,$Unop-f x251 x252) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  thus ?thesis
    using assms
    by (cases x251; cases a) auto
qed (cases x251; auto)

lemma run-one-step-basic-binop-i-result:
  assumes run-one-step d i (s,vs,ves,$Binop-i x261 x262) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  note outer-Cons = Cons
  thus ?thesis
    using assms
  proof (cases list)
    case (Cons a' list')
    thus ?thesis
      using assms outer-Cons
    proof (cases x261; cases a; cases a')
      fix x1 x2
      assume x261 = T-i32 a = ConstInt32 x1 and a' = ConstInt32 x2
      thus ?thesis
        using assms outer-Cons Cons
```

```
      by (cases app-binop-i x262 x2 x1) auto
    next
      fix x1 x2
      assume x261 = T-i64 a = ConstInt64 x1 and a' = ConstInt64 x2
      thus ?thesis
        using assms outer-Cons Cons
        by (cases app-binop-i x262 x2 x1) auto
    qed auto
  qed (cases x261; cases a; auto)
qed (cases x261; auto)

lemma run-one-step-basic-binop-f-result:
  assumes run-one-step d i (s,vs,ves,$Binop-f x271 x272) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  note outer-Cons = Cons
  thus ?thesis
    using assms
  proof (cases list)
    case (Cons a' list')
    thus ?thesis
      using assms outer-Cons
    proof (cases x271; cases a; cases a')
      fix x1 x2
      assume x271 = T-f32 a = ConstFloat32 x1 and a' = ConstFloat32 x2
      thus ?thesis
        using assms outer-Cons Cons
        by (cases app-binop-f x272 x2 x1) auto
    next
      fix x1 x2
      assume x271 = T-f64 a = ConstFloat64 x1 and a' = ConstFloat64 x2
      thus ?thesis
        using assms outer-Cons Cons
        by (cases app-binop-f x272 x2 x1) auto
    qed auto
  qed (cases x271; cases a; auto)
qed (cases x271; auto)

lemma run-one-step-basic-testop-result:
  assumes run-one-step d i (s,vs,ves,$Testop x281 x282) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves)
  case (Cons a list)
  thus ?thesis
    using assms
    by (cases x281; cases a) auto
```

**qed** (*cases x281*; *auto*)

**lemma** *run-one-step-basic-relop-i-result*:
**assumes** *run-one-step d i* (*s*,*vs*,*ves*,*$Relop-i x291 x292*) = (*s'*, *vs'*, *res*)
**shows** (∃ *r*. *res* = *RSNormal r*) ∨ (∃ *e*. *res* = *RSCrash e*)
**using** *assms*
**proof** (*cases ves*)
**case** (*Cons a list*)
**note** *outer-Cons* = *Cons*
**thus** *?thesis*
**using** *assms*
**proof** (*cases list*)
**case** (*Cons a' list'*)
**thus** *?thesis*
**using** *assms outer-Cons*
**proof** (*cases x291*; *cases a*; *cases a'*)
**fix** *x1 x2*
**assume** *x291* = *T-i32 a* = *ConstInt32 x1* **and** *a'* = *ConstInt32 x2*
**thus** *?thesis*
**using** *assms outer-Cons Cons*
**by** (*cases app-relop-i x292 x2 x1*) *auto*
**next**
**fix** *x1 x2*
**assume** *x291* = *T-i64 a* = *ConstInt64 x1* **and** *a'* = *ConstInt64 x2*
**thus** *?thesis*
**using** *assms outer-Cons Cons*
**by** (*cases app-relop-i x292 x2 x1*) *auto*
**qed** *auto*
**qed** (*cases x291*; *cases a*; *auto*)
**qed** (*cases x291*; *auto*)

**lemma** *run-one-step-basic-relop-f-result*:
**assumes** *run-one-step d i* (*s*,*vs*,*ves*,*$Relop-f x301 x302*) = (*s'*, *vs'*, *res*)
**shows** (∃ *r*. *res* = *RSNormal r*) ∨ (∃ *e*. *res* = *RSCrash e*)
**using** *assms*
**proof** (*cases ves*)
**case** (*Cons a list*)
**note** *outer-Cons* = *Cons*
**thus** *?thesis*
**using** *assms*
**proof** (*cases list*)
**case** (*Cons a' list'*)
**thus** *?thesis*
**using** *assms outer-Cons*
**proof** (*cases x301*; *cases a*; *cases a'*)
**fix** *x1 x2*
**assume** *x301* = *T-f32 a* = *ConstFloat32 x1* **and** *a'* = *ConstFloat32 x2*
**thus** *?thesis*
**using** *assms outer-Cons Cons*

```
      by (cases app-relop-f x302 x2 x1) auto
    next
      fix x1 x2
      assume x301 = T-f64 a = ConstFloat64 x1 and a' = ConstFloat64 x2
      thus ?thesis
        using assms outer-Cons Cons
        by (cases app-relop-f x302 x2 x1) auto
    qed auto
  qed (cases x301; cases a; auto)
qed (cases x301; auto)

lemma run-one-step-basic-cvtop-result:
  assumes run-one-step d i (s,vs,ves,$Cvtop t2 x312 t1 sx) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases ves; cases x312)
  fix a ves'
  assume ves = a#ves' and x312 = Convert
  thus ?thesis
    using assms
    by (cases cvt t2 sx a; cases types-agree t1 a) auto
next
  fix a ves'
  assume ves = a#ves' and x312 = Reinterpret
  thus ?thesis
    using assms
    by (cases sx; cases types-agree t1 a) auto
qed auto

lemma run-one-step-trap-result:
  assumes run-one-step d i (s,vs,ves,Trap) = (s', vs', res)
  shows ∃ e. res = RSCrash e
  using assms
  by auto

lemma run-one-step-callcl-result:
  assumes run-one-step d i (s,vs,ves,Callcl cl) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
proof −
  obtain t1s t2s where cl-type-is:cl-type cl = (t1s -> t2s)
    using tf.exhaust
    by blast
  obtain ves' ves'' where split-n-is:split-n ves (length t1s) = (ves', ves'')
    by fastforce
  show ?thesis
  proof (cases cl)
    case (Func-native x11 x12 x13 x14)
    thus ?thesis
      using assms cl-type-is split-n-is
```

```
      unfolding cl-type-def
      by (cases length t1s ≤ length ves) auto
  next
    case (Func-host x21 x22)
    show ?thesis
    proof (cases host-apply-impl s (t1s -> t2s) x22 (rev ves'))
      case None
      thus ?thesis
        using assms cl-type-is split-n-is Func-host
        unfolding cl-type-def
        by (cases length t1s ≤ length ves)  auto
    next
      case (Some a)
      thus ?thesis
      proof (cases a)
        case (Pair s' vcs')
        thus ?thesis
          using assms cl-type-is split-n-is Func-host Some
          unfolding cl-type-def
          by (cases length t1s ≤ length ves; cases list-all2 types-agree t2s vcs')  auto
      qed
    qed
  qed
qed

lemma run-one-step-label-result:
  assumes run-one-step d i (s,vs,ves,Label x41 x42 x43) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ r rvs. res = RSBreak r rvs) ∨ (∃ rvs. res =
RSReturn rvs) ∨ (∃ e. res = RSCrash e)
  using assms
  by (cases res) auto

lemma run-one-step-local-result:
  assumes run-one-step d i (s,vs,ves,Local x51 x52 x53 x54) = (s', vs', res)
  shows (∃ r. res = RSNormal r) ∨ (∃ e. res = RSCrash e)
  using assms
proof (cases x54 = [Trap])
  case False
  note outer-False = False
  thus ?thesis
  proof (cases const-list x54)
    case True
    thus ?thesis
      using assms outer-False
      by (cases length x54 = x51) auto
  next
    case False
    thus ?thesis
      using assms outer-False
```

```
    proof (cases d)
      case (Suc d')
      obtain s' vs' res where rs-def:run-step d' x52 (s, x53, x54) = (s', vs', res)
      by (metis surj-pair)
      thus ?thesis
        using assms outer-False False Suc
      proof (cases res)
        case (RSReturn x3)
        thus ?thesis
          using assms outer-False False rs-def Suc
          by (cases x51 ≤ length x3) auto
      qed auto
    qed auto
  qed
qed auto

lemma run-one-step-break:
  assumes run-one-step d i (s,vs,ves,e) = (s', vs', RSBreak n res)
  shows (e = $Br n) ∨ (∃ n les es. e = Label n les es)
proof (cases e)
  case (Basic x1)
  thus ?thesis
  proof (cases x1)
    case Unreachable
    thus ?thesis
      using run-one-step-basic-unreachable-result assms Basic
      by fastforce
  next
    case Nop
    thus ?thesis
      using assms Basic
      by fastforce
  next
    case Drop
    thus ?thesis
      using run-one-step-basic-drop-result assms Basic
      by fastforce
  next
    case Select
    thus ?thesis
      using run-one-step-basic-select-result assms Basic
      by fastforce
  next
    case (Block x51 x52)
    thus ?thesis
      using run-one-step-basic-block-result assms Basic
      by fastforce
  next
    case (Loop x61 x62)
```

**thus** *?thesis*
**using** *run-one-step-basic-loop-result assms Basic*
**by** *fastforce*
**next**
**case** (*If x71 x72 x73*)
**thus** *?thesis*
**using** *run-one-step-basic-if-result assms Basic*
**by** *fastforce*
**next**
**case** (*Br x8*)
**thus** *?thesis*
**using** *run-one-step-basic-br-result assms Basic*
**by** *fastforce*
**next**
**case** (*Br-if x9*)
**thus** *?thesis*
**using** *run-one-step-basic-br-if-result assms Basic*
**by** *fastforce*
**next**
**case** (*Br-table x10*)
**thus** *?thesis*
**using** *run-one-step-basic-br-table-result assms Basic*
**by** *fastforce*
**next**
**case** *Return*
**thus** *?thesis*
**using** *run-one-step-basic-return-result assms Basic*
**by** *fastforce*
**next**
**case** (*Call x12*)
**thus** *?thesis*
**using** *run-one-step-basic-call-result assms Basic*
**by** *fastforce*
**next**
**case** (*Call-indirect x13*)
**thus** *?thesis*
**using** *run-one-step-basic-call-indirect-result assms Basic*
**by** *fastforce*
**next**
**case** (*Get-local x14*)
**thus** *?thesis*
**using** *run-one-step-basic-get-local-result assms Basic*
**by** *fastforce*
**next**
**case** (*Set-local x15*)
**thus** *?thesis*
**using** *run-one-step-basic-set-local-result assms Basic*
**by** *fastforce*
**next**

**case** (*Tee-local x16*)
**thus** *?thesis*
**using** *run-one-step-basic-tee-local-result assms Basic*
**by** *fastforce*
**next**
**case** (*Get-global x17*)
**thus** *?thesis*
**using** *assms Basic*
**by** *fastforce*
**next**
**case** (*Set-global x18*)
**thus** *?thesis*
**using** *run-one-step-basic-set-global-result assms Basic*
**by** *fastforce*
**next**
**case** (*Load x191 x192 x193 x194*)
**thus** *?thesis*
**using** *run-one-step-basic-load-result assms Basic*
**by** *fastforce*
**next**
**case** (*Store x201 x202 x203 x204*)
**thus** *?thesis*
**using** *run-one-step-basic-store-result assms Basic*
**by** *fastforce*
**next**
**case** *Current-memory*
**thus** *?thesis*
**using** *run-one-step-basic-current-memory-result assms Basic*
**by** *fastforce*
**next**
**case** *Grow-memory*
**thus** *?thesis*
**using** *run-one-step-basic-grow-memory-result assms Basic*
**by** *fastforce*
**next**
**case** (*EConst x23*)
**thus** *?thesis*
**using** *assms Basic*
**by** *fastforce*
**next**
**case** (*Unop-i x241 x242*)
**thus** *?thesis*
**using** *run-one-step-basic-unop-i-result assms Basic*
**by** *fastforce*
**next**
**case** (*Unop-f x251 x252*)
**thus** *?thesis*
**using** *run-one-step-basic-unop-f-result assms Basic*
**by** *fastforce*

```
  next
    case (Binop-i x261 x262)
    thus ?thesis
      using run-one-step-basic-binop-i-result assms Basic
      by fastforce
  next
    case (Binop-f x271 x272)
    thus ?thesis
      using run-one-step-basic-binop-f-result assms Basic
      by fastforce
  next
    case (Testop x281 x282)
    thus ?thesis
      using run-one-step-basic-testop-result assms Basic
      by fastforce
  next
    case (Relop-i x291 x292)
    thus ?thesis
      using run-one-step-basic-relop-i-result assms Basic
      by fastforce
  next
    case (Relop-f x301 x302)
    thus ?thesis
      using run-one-step-basic-relop-f-result assms Basic
      by fastforce
  next
    case (Cvtop x311 x312 x313 x314)
    thus ?thesis
      using run-one-step-basic-cvtop-result assms Basic
      by fastforce
  qed
next
  case Trap
  thus ?thesis
    using assms
    by auto
next
  case (Callcl x3)
  thus ?thesis
    using assms run-one-step-callcl-result
    by fastforce
next
  case (Label x41 x42 x43)
  thus ?thesis
    by auto
next
  case (Local x51 x52 x53 x54)
  thus ?thesis
    using assms run-one-step-local-result
```

```
    by fastforce
qed

lemma run-one-step-return:
  assumes run-one-step d i (s,vs,ves,e) = (s', vs', RSReturn res)
  shows (e = $Return) ∨ (∃ n les es. e = Label n les es)
proof (cases e)
  case (Basic x1)
  thus ?thesis
  proof (cases x1)
    case Unreachable
    thus ?thesis
      using run-one-step-basic-unreachable-result assms Basic
      by fastforce
  next
    case Nop
    thus ?thesis
      using assms Basic
      by fastforce
  next
    case Drop
    thus ?thesis
      using run-one-step-basic-drop-result assms Basic
      by fastforce
  next
    case Select
    thus ?thesis
      using run-one-step-basic-select-result assms Basic
      by fastforce
  next
    case (Block x51 x52)
    thus ?thesis
      using run-one-step-basic-block-result assms Basic
      by fastforce
  next
    case (Loop x61 x62)
    thus ?thesis
      using run-one-step-basic-loop-result assms Basic
      by fastforce
  next
    case (If x71 x72 x73)
    thus ?thesis
      using run-one-step-basic-if-result assms Basic
      by fastforce
  next
    case (Br x8)
    thus ?thesis
      using run-one-step-basic-br-result assms Basic
      by fastforce
```

**next**
**case** (*Br-if x9*)
**thus** *?thesis*
**using** *run-one-step-basic-br-if-result assms Basic*
**by** *fastforce*
**next**
**case** (*Br-table x10*)
**thus** *?thesis*
**using** *run-one-step-basic-br-table-result assms Basic*
**by** *fastforce*
**next**
**case** *Return*
**thus** *?thesis*
**using** *run-one-step-basic-return-result assms Basic*
**by** *fastforce*
**next**
**case** (*Call x12*)
**thus** *?thesis*
**using** *run-one-step-basic-call-result assms Basic*
**by** *fastforce*
**next**
**case** (*Call-indirect x13*)
**thus** *?thesis*
**using** *run-one-step-basic-call-indirect-result assms Basic*
**by** *fastforce*
**next**
**case** (*Get-local x14*)
**thus** *?thesis*
**using** *run-one-step-basic-get-local-result assms Basic*
**by** *fastforce*
**next**
**case** (*Set-local x15*)
**thus** *?thesis*
**using** *run-one-step-basic-set-local-result assms Basic*
**by** *fastforce*
**next**
**case** (*Tee-local x16*)
**thus** *?thesis*
**using** *run-one-step-basic-tee-local-result assms Basic*
**by** *fastforce*
**next**
**case** (*Get-global x17*)
**thus** *?thesis*
**using** *assms Basic*
**by** *fastforce*
**next**
**case** (*Set-global x18*)
**thus** *?thesis*
**using** *run-one-step-basic-set-global-result assms Basic*

**by** *fastforce*
**next**
**case** (*Load x191 x192 x193 x194*)
**thus** *?thesis*
**using** *run-one-step-basic-load-result assms Basic*
**by** *fastforce*
**next**
**case** (*Store x201 x202 x203 x204*)
**thus** *?thesis*
**using** *run-one-step-basic-store-result assms Basic*
**by** *fastforce*
**next**
**case** *Current-memory*
**thus** *?thesis*
**using** *run-one-step-basic-current-memory-result assms Basic*
**by** *fastforce*
**next**
**case** *Grow-memory*
**thus** *?thesis*
**using** *run-one-step-basic-grow-memory-result assms Basic*
**by** *fastforce*
**next**
**case** (*EConst x23*)
**thus** *?thesis*
**using** *assms Basic*
**by** *fastforce*
**next**
**case** (*Unop-i x241 x242*)
**thus** *?thesis*
**using** *run-one-step-basic-unop-i-result assms Basic*
**by** *fastforce*
**next**
**case** (*Unop-f x251 x252*)
**thus** *?thesis*
**using** *run-one-step-basic-unop-f-result assms Basic*
**by** *fastforce*
**next**
**case** (*Binop-i x261 x262*)
**thus** *?thesis*
**using** *run-one-step-basic-binop-i-result assms Basic*
**by** *fastforce*
**next**
**case** (*Binop-f x271 x272*)
**thus** *?thesis*
**using** *run-one-step-basic-binop-f-result assms Basic*
**by** *fastforce*
**next**
**case** (*Testop x281 x282*)
**thus** *?thesis*

```
    using run-one-step-basic-testop-result assms Basic
    by fastforce
  next
    case (Relop-i x291 x292)
    thus ?thesis
    using run-one-step-basic-relop-i-result assms Basic
    by fastforce
  next
    case (Relop-f x301 x302)
    thus ?thesis
    using run-one-step-basic-relop-f-result assms Basic
    by fastforce
  next
    case (Cvtop x311 x312 x313 x314)
    thus ?thesis
    using run-one-step-basic-cvtop-result assms Basic
    by fastforce
  qed
next
  case Trap
  thus ?thesis
    using assms
    by auto
next
  case (Callcl x3)
  thus ?thesis
    using assms run-one-step-callcl-result
    by fastforce
next
  case (Label x41 x42 x43)
  thus ?thesis
    by auto
next
  case (Local x51 x52 x53 x54)
  thus ?thesis
    using assms run-one-step-local-result
    by fastforce
qed

lemma run-step-break-imp-not-trap-const-list:
  assumes run-step d i (s, vs, es) = (s', vs', RSBreak n res)
  shows es ≠ [Trap] ¬const-list es
proof −
  {
    assume es = [Trap]
    hence False
    using assms
    by simp
  }
```

```
  thus es ≠ [Trap]
    by blast
  {
    assume const-list es
    then obtain vs where split-vals-e es = (vs, [])
      using split-vals-e-const-list e-type-const-conv-vs
      by fastforce
    hence False
      using assms
      by simp
  }
  thus ¬const-list es
    by blast
qed

lemma run-step-return-imp-not-trap-const-list:
  assumes run-step d i (s, vs, es) = (s', vs', RSReturn res)
  shows es ≠ [Trap] ¬const-list es
proof −
  {
    assume es = [Trap]
    hence False
      using assms
      by simp
  }
  thus es ≠ [Trap]
    by blast
  {
    assume const-list es
    then obtain vs where split-vals-e es = (vs, [])
      using split-vals-e-const-list e-type-const-conv-vs
      by fastforce
    hence False
      using assms
      by simp
  }
  thus ¬const-list es
    by blast
qed

lemma run-one-step-label-break-imp-break:
  assumes run-one-step d i (s, vs, ves, Label ln les es) = (s', vs', RSBreak n res)
  shows run-step d i (s, vs, es) = (s', vs', RSBreak (Suc n) res)
  using assms
proof (cases es = [Trap]; cases const-list es)
  assume local-assms:es ≠ [Trap] ¬const-list es
  obtain s'' vs'' res'' where rs-def:run-step d i (s, vs, es) = (s'', vs'', res'')
    by (metis surj-pair)
  thus ?thesis
```

**using** *assms local-assms*
**proof** (*cases res''*)
**case** (*RSBreak x21 x22*)
**thus** *?thesis*
**using** *assms local-assms rs-def*
**by** (*cases x21*; *cases ln* ≤ *length x22*) *auto*
**qed** *auto*
**qed** *auto*

**lemma** *run-one-step-label-return-imp-return*:
**assumes** *run-one-step d i* (*s*, *vs*, *ves*, *Label n les es*) = (*s'*, *vs'*, *RSReturn res*)
**shows** *run-step d i* (*s*, *vs*, *es*) = (*s'*, *vs'*, *RSReturn res*)
**using** *assms*
**proof** (*cases es* = [*Trap*]; *cases const-list es*)
**assume** *local-assms*:*es* ≠ [*Trap*] ¬*const-list es*
**obtain** *s'' vs'' res''* **where** *rs-def*:*run-step d i* (*s*, *vs*, *es*) = (*s''*, *vs''*, *res''*)
**by** (*metis surj-pair*)
**thus** *?thesis*
**using** *assms local-assms*
**proof** (*cases res''*)
**case** (*RSBreak x21 x22*)
**thus** *?thesis*
**using** *assms local-assms rs-def*
**by** (*cases x21*; *cases n* ≤ *length x22*) *auto*
**qed** *auto*
**qed** *auto*
**thm** *run-step-run-one-step.induct*

**definition** *run-step-break-imp-lfilled-prop* **where**
*run-step-break-imp-lfilled-prop s' vs' n res* =
(λ*d i* (*s*,*vs*,*es*). (*run-step d i* (*s*,*vs*,*es*) = (*s'*, *vs'*, *RSBreak n res*)) ⟶
*s* = *s'* ∧ *vs* = *vs'* ∧
(∃ *n' lfilled es-c*. *n'* ≥ *n* ∧ *Lfilled-exact* (*n'*−*n*) *lfilled* ((*vs-to-es res*) @ [$*Br n'*] @ *es-c*) *es*))

**definition** *run-one-step-break-imp-lfilled-prop* **where**
*run-one-step-break-imp-lfilled-prop s' vs' n res* =
(λ*d i* (*s*,*vs*,*ves*,*e*). *run-one-step d i* (*s*,*vs*,*ves*,*e*) = (*s'*, *vs'*, *RSBreak n res*) ⟶
*s* = *s'* ∧ *vs* = *vs'* ∧ ((*res* = *ves* ∧ *e* = $*Br n*) ∨ (∃ *n' lfilled es-c es les' ln*. *n'* > *n* ∧ *Lfilled-exact* (*n'*−(*n*+1)) *lfilled* ((*vs-to-es res*) @ [$*Br n'*] @ *es-c*) *es* ∧ *e* = *Label ln les' es*)))

**lemma** *run-step-break-imp-lfilled*:
**assumes** *run-step d i* (*s*,*vs*,*es*) = (*s'*, *vs'*, *RSBreak n res*)
**shows** *s* = *s'* ∧
*vs* = *vs'* ∧
(∃ *n' lfilled es-c*. *n'* ≥ *n* ∧
*Lfilled-exact* (*n'*−*n*) *lfilled* ((*vs-to-es res*) @ [$*Br n'*] @ *es-c*)

*es*)
**proof** −
**fix** *ves e*
**have** (*run-step-break-imp-lfilled-prop s′ vs′ n res*) *d i* (*s*,*vs*,*es*)
**and** (*run-one-step-break-imp-lfilled-prop s′ vs′ n res*) *d i* (*s*,*vs*,*ves*,*e*)
**proof** (*induction d i* (*s*,*vs*,*es*) **and** *d i* (*s*,*vs*,*ves*,*e*) *arbitrary*: *n es* **and** *n ves e rule*: *run-step-run-one-step.induct*)
**case** (*1 d i es*)
**{**
**assume** *local-assms*:*run-step d i* (*s*,*vs*,*es*) = (*s′*, *vs′*, *RSBreak n res*)
**obtain** *ves es′* **where** *split-vals-es*:*split-vals-e es* = (*ves*, *es′*)
**by** (*metis surj-pair*)
**then obtain** *a as* **where** *es′-def*:*es′* = *a*#*as*
**using** *local-assms*
**by** (*cases es′*) *auto*
**hence** *a-def*:*a* ≠ *Trap*
**using** *local-assms split-vals-es*
**by** (*cases a* = *Trap*; *cases* (*as* ≠ [] ∨ *ves* ≠ [])) *simp-all*
**obtain** *s′′ vs′′ res′′* **where** *run-one-step d i* (*s*,*vs*,(*rev ves*),*a*) = (*s′′*, *vs′′*, *res′′*)
**by** (*metis surj-pair*)
**hence** *ros-def*:*run-one-step d i* (*s*,*vs*,(*rev ves*),*a*) = (*s′*, *vs′*, *RSBreak n res*)
**using** *local-assms split-vals-es es′-def a-def*
**by** (*cases res′′*) (*auto simp del*: *run-one-step.simps*)
**hence** *run-one-step-break-imp-lfilled-prop s′ vs′ n res d i* (*s*, *vs*, *rev ves*, *a*)
**using** *1 split-vals-es a-def es′-def*
**by** *fastforce*
**then obtain** *n′ lfilled es-c les les′ ln* **where**
*s* = *s′ vs* = *vs′*
((*res* = (*rev ves*) ∧ *a* = $*Br n*) ∨
*n′* > *n* ∧ (*Lfilled-exact* (*n′*−(*n*+*1*)) *lfilled* ((*vs-to-es res*) @ [$*Br n′*] @ *es-c*) *les* ∧ *a* = *Label ln les′ les*))
**using** *ros-def*
**unfolding** *run-one-step-break-imp-lfilled-prop-def*
**by** *fastforce*
**then consider**
(*1*) *s* = *s′ vs* = *vs′ res* = (*rev ves*) *a* = $*Br n*
| (*2*) *s* = *s′ vs* = *vs′ n′* > *n Lfilled-exact* (*n′*−(*n*+*1*)) *lfilled* ((*vs-to-es res*) @ [$*Br n′*] @ *es-c*) *les a* = *Label ln les′ les*
**by** *blast*
**hence** *s* = *s′* ∧ *vs* = *vs′* ∧
(∃ *n′ lfilled es-c*. *n′* ≥ *n* ∧ *Lfilled-exact* (*n′*−*n*) *lfilled* ((*vs-to-es res*) @ [$*Br n′*] @ *es-c*) *es*)
**proof** *cases*
**case** *1*
**thus** *?thesis*
**using** *es′-def split-vals-e-conv-app*[*OF split-vals-es*] *Lfilled-exact.intros*(*1*) *is-const-list*[*of* - *ves*]
**by** *fastforce*
**next**

```
      case 2
    have test:const-list ($$* ves)
      using is-const-list
      by auto
    have (Suc (n' - Suc n)) = n' - n
      using 2(3)
      by simp
    thus ?thesis
     using 2(1,2,3,5) Lfilled-exact.intros(2)[OF test - 2(4), of - ln les' as] es'-def
split-vals-e-conv-app[OF split-vals-es]
      by (metis Suc-eq-plus1 append-Cons append-Nil less-imp-le-nat)
    qed
  }
  thus ?case
    unfolding run-step-break-imp-lfilled-prop-def
    by fastforce
  next
    case (2 d i ves e)
    {
    assume local-assms:run-one-step d i (s,vs,ves,e) = (s', vs', RSBreak n res)
    consider (a) e = $Br n | (b) (∃ n les es. e = Label n les es)
      using run-one-step-break[OF local-assms]
      by blast
    hence s = s' ∧ vs = vs' ∧ ((res = ves ∧ e = $Br n) ∨ (∃ n' lfilled es-c es les'
ln. n' > n ∧ Lfilled-exact (n'−(n+1)) lfilled ((vs-to-es res) @ [$Br n'] @ es-c) es
∧ e = Label ln les' es))
    proof cases
      case a
      thus ?thesis
        using local-assms
        by simp
    next
      case b
      then obtain ln les es where e-def:e = Label ln les es
        by blast
      hence run-one-step d i (s, vs, ves,  Label ln les es) = (s', vs', RSBreak n res)
        using local-assms by simp
      hence rs-def:run-step d i (s, vs, es) = (s', vs', RSBreak (Suc n) res)
        using run-one-step-label-break-imp-break
        by fastforce
      hence run-step-break-imp-lfilled-prop s' vs' (Suc n) res d i (s, vs, es)
        using 2(1)[OF e-def - run-step-break-imp-not-trap-const-list(2)]
        by fastforce
      thus ?thesis
        using e-def rs-def
        unfolding run-step-break-imp-lfilled-prop-def
        by fastforce
    qed
  }
```

**thus** *?case*
**unfolding** *run-one-step-break-imp-lfilled-prop-def*
**by** *fastforce*
**qed**
**thus** *?thesis*
**using** *assms*
**unfolding** *run-step-break-imp-lfilled-prop-def*
**by** *fastforce*
**qed**

**lemma** *run-step-return-imp-lfilled*:
**assumes** *run-step d i* (*s*,*vs*,*es*) = (*s'*, *vs'*, *RSReturn res*)
**shows** *s* = *s'* ∧ *vs* = *vs'* ∧ (∃ *n lfilled es-c*. *Lfilled-exact n lfilled* ((*vs-to-es res*) @ [$*Return*] @ *es-c*) *es*)
**proof** −
**fix** *ves e*
**have** (*run-step d i* (*s*,*vs*,*es*) = (*s'*, *vs'*, *RSReturn res*)) ⟹
*s* = *s'* ∧ *vs* = *vs'* ∧ (∃ *n lfilled es-c*. *Lfilled-exact n lfilled* ((*vs-to-es res*) @ [$*Return*] @ *es-c*) *es*)
**and** (*run-one-step d i* (*s*,*vs*,*ves*,*e*) = (*s'*, *vs'*, *RSReturn res*)) ⟹
*s* = *s'* ∧ *vs* = *vs'* ∧
((*res* = *ves* ∧ *e* = $*Return*) ∨
(∃ *n lfilled ves es-c es n' les'*. *Lfilled-exact n lfilled* ((*vs-to-es res*) @ [$*Return*] @ *es-c*) *es* ∧
*e* = *Label n' les' es*))
**proof** (*induction d i* (*s*,*vs*,*es*) **and** *d i* (*s*,*vs*,*ves*,*e*) *arbitrary*: *s vs es s' vs' res* **and** *s vs ves e s' vs' res rule*: *run-step-run-one-step.induct*)
**case** (*1 d i s vs es*)
**obtain** *ves es'* **where** *split-vals-es*:*split-vals-e es* = (*ves*, *es'*)
**by** (*metis surj-pair*)
**then obtain** *a as* **where** *es'-def*:*es'* = *a*#*as*
**using** *1*(*2*)
**by** (*cases es'*) *auto*
**hence** *a-def*:¬ *e-is-trap a*
**using** *1*(*2*) *split-vals-es*
**by** (*cases a* = *Trap*; *cases* (*as* ≠ [] ∨ *ves* ≠ [])) *simp-all*
**obtain** *s''* *vs''* *res''* **where** *run-one-step d i* (*s*,*vs*,(*rev ves*),*a*) = (*s''*, *vs''*, *res''*)
**by** (*metis surj-pair*)
**hence** *ros-def*:*run-one-step d i* (*s*,*vs*,(*rev ves*),*a*) = (*s'*, *vs'*, *RSReturn res*)
**using** *1*(*2*) *split-vals-es es'-def a-def*
**by** (*cases res''*) (*auto simp del*: *run-one-step.simps*)
**obtain** *n lfilled les-c les n' les'* **where**
*s* = *s'* *vs* = *vs'*
(*res* = *rev ves* ∧ *a* = $*Return*) ∨ (*Lfilled-exact n lfilled* ((*vs-to-es res*) @ [$*Return*] @ *les-c*) *les* ∧ *a* = *Label n' les' les*)
**using** *1*(*1*)[*OF split-vals-es*[*symmetric*] - *es'-def a-def ros-def*]
**by** *fastforce*
**then consider**
(*1*) *s* = *s'* *vs* = *vs'* *res* = *rev ves* *a* = $*Return*

```
  | (2) s = s' vs = vs' (Lfilled-exact n lfilled ((vs-to-es res) @ [$Return] @ les-c)
les) (a = Label n' les' les)
    by blast
  thus ?case
  proof cases
    case 1
    thus ?thesis
      using es'-def split-vals-e-conv-app[OF split-vals-es] Lfilled-exact.intros(1)
is-const-list[of - ves]
      by fastforce
  next
    case 2
    have const-list ($$* ves)
      using is-const-list
      by fastforce
    thus ?thesis
      using 2 Lfilled-exact.intros(2) es'-def split-vals-e-conv-app[OF split-vals-es]
        by fastforce
  qed
 next
  case (2 d i s vs ves e s' vs')
  consider (a) e = $Return | (b) (∃ n les es. e = Label n les es)
    using run-one-step-return[OF 2(3)]
    by blast
  thus ?case
  proof cases
    case a
    thus ?thesis
      using 2(3)
      by simp
  next
    case b
    then obtain n les es where e-def:e = Label n les es
      by blast
    hence run-one-step d i (s, vs, ves,  Label n les es) = (s', vs', RSReturn res)
      using 2(3) by simp
    hence run-step d i (s, vs, es) = (s', vs', RSReturn res)
      using run-one-step-label-return-imp-return
      by fastforce
    thus ?thesis
     using 2(3) 2(1)[OF e-def - run-step-return-imp-not-trap-const-list(2)] e-def
      by fastforce
  qed
 qed
 thus ?thesis
  using assms
  by blast
qed
```

```
lemma run-step-basic-unop-testop-sound:
  assumes (run-one-step d i (s,vs,ves,$b-e) = (s', vs', RSNormal es'))
          b-e = Unop-i t iop ∨ b-e = Unop-f t fop ∨ b-e = Testop t testop
  shows (|s;vs;(vs-to-es ves)@[$b-e]|) ↪- i (|s';vs';es'|)
proof −
  consider (1) b-e = Unop-i t iop | (2) b-e = Unop-f t fop | (3) b-e = Testop t
testop
    using assms(2)
    by blast
  note b-e-cases = this
  show ?thesis
    using assms(1)
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms(1)
    proof (cases a; cases t)
      case (ConstInt32 x1)
      case T-i32
      thus ?thesis
        using assms(1) Cons ConstInt32
          is-const-list-vs-to-es-list[of rev list]
           progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(1)]]
           progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(13)]]
        by (cases rule: b-e-cases) auto
    next
      case (ConstInt64 x2)
      case T-i64
      thus ?thesis
        using assms(1) Cons ConstInt64
          is-const-list-vs-to-es-list[of rev list]
           progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(2)]]
           progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(14)]]
        by (cases rule: b-e-cases) auto
    next
      case (ConstFloat32 x3)
      case T-f32
      thus ?thesis
        using assms(1) Cons ConstFloat32
          is-const-list-vs-to-es-list[of rev list]
           progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(3)]]
        by (cases rule: b-e-cases) auto
    next
      case (ConstFloat64 x4)
      case T-f64
      thus ?thesis
        using assms(1) Cons ConstFloat64
          is-const-list-vs-to-es-list[of rev list]
           progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(4)]]
```

```
      by (cases rule: b-e-cases) auto
    qed (cases rule: b-e-cases; auto)+
  qed (cases rule: b-e-cases; cases t; auto)
qed

lemma run-step-basic-binop-relop-sound:
  assumes (run-one-step d i (s,vs,ves,$b-e) = (s', vs', RSNormal es'))
          b-e = Binop-i t iop ∨ b-e = Binop-f t fop ∨ b-e = Relop-i t irop ∨ b-e =
Relop-f t frop
  shows (|s;vs;(vs-to-es ves)@[$b-e]|) ↪- i (|s';vs';es'|)
proof −
  consider
    (1) b-e = Binop-i t iop
  | (2) b-e = Binop-f t fop
  | (3) b-e = Relop-i t irop
  | (4) b-e = Relop-f t frop
    using assms(2)
    by blast
  note b-e-cases = this
  show ?thesis
    using assms(1)
  proof (cases ves)
    case outer-Cons:(Cons v1 list)
    thus ?thesis
      using assms(1)
    proof (cases list)
      case (Cons v2 list')
      thus ?thesis
        using assms(1) outer-Cons
      proof (cases v1; cases v2; cases t)
        fix c1 c2
        assume v1 = ConstInt32 c1 and v2 = ConstInt32 c2 and t = T-i32
        thus ?thesis
          using assms(1) Cons outer-Cons
            is-const-list-vs-to-es-list[of rev list']
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(5)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(6)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(15)]]
          by (cases rule: b-e-cases; cases app-binop-i iop c2 c1) auto
      next
        fix c1 c2
        assume v1 = ConstInt64 c1 and v2 = ConstInt64 c2 and t = T-i64
        thus ?thesis
          using assms(1) Cons outer-Cons
            is-const-list-vs-to-es-list[of rev list']
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(7)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(8)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(16)]]
          by (cases rule: b-e-cases; cases app-binop-i iop c2 c1) auto
```

```
      next
        fix c1 c2
        assume v1 = ConstFloat32 c1 and v2 = ConstFloat32 c2 and t = T-f32
        thus ?thesis
          using assms(1) Cons outer-Cons
            is-const-list-vs-to-es-list[of rev list']
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(9)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(10)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(17)]]
          by (cases rule: b-e-cases; cases app-binop-f fop c2 c1) auto
      next
        fix c1 c2
        assume v1 = ConstFloat64 c1 and v2 = ConstFloat64 c2 and t = T-f64
        thus ?thesis
          using assms(1) Cons outer-Cons
            is-const-list-vs-to-es-list[of rev list']
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(11)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(12)]]
             progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(18)]]
          by (cases rule: b-e-cases; cases app-binop-f fop c2 c1) auto
      qed (cases rule: b-e-cases; auto)+
    qed (cases rule: b-e-cases; cases t; cases v1; auto)
  qed (cases rule: b-e-cases; cases t; auto)
qed

lemma run-step-basic-sound:
  assumes (run-one-step d i (s,vs,ves,$b-e) = (s', vs', RSNormal es'))
  shows (|s;vs;(vs-to-es ves)@[$b-e]|) ↪- i (|s';vs';es'|)
proof −
  show ?thesis
  proof (cases b-e)
    case Unreachable
    thus ?thesis
      using is-const-list-vs-to-es-list[of rev ves]
            progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(22)]]
            assms
      by fastforce
  next
    case Nop
    thus ?thesis
      using is-const-list-vs-to-es-list[of rev ves]
            progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(23)]]
            assms
      by fastforce
  next
    case Drop
    thus ?thesis
      using assms
    proof (cases ves)
```

```
    case (Cons a list)
    hence vs-to-es ves = vs-to-es list @ [$C a]
      by fastforce
    thus ?thesis
      using is-const-list-vs-to-es-list[of rev list]
            progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(24)]]
            Drop assms Cons
      by auto
  qed auto
next
  case Select
  thus ?thesis
    using assms
  proof (cases ves)
    case outer-outer-cons:(Cons a list)
    thus ?thesis
      using Select assms
    proof (cases a; cases list)
      case (ConstInt32 x1a)
      case outer-cons:(Cons a' list')
      thus ?thesis
        using assms outer-outer-cons ConstInt32 Select
      proof (cases list')
        case (Cons a'' list'')
        hence vs-to-es ves = vs-to-es list'' @ [$C a'', $C a', $C ConstInt32 x1a]
          using outer-outer-cons outer-cons ConstInt32
          by fastforce
        thus ?thesis
          using is-const-list-vs-to-es-list[of rev list'']
                progress-L0-left[OF reduce.intros(1)]
                reduce-simple.intros(25,26)
                assms outer-outer-cons outer-cons Cons ConstInt32 Select
          by (cases int-eq x1a 0) auto
      qed auto
    qed auto
  qed auto
next
  case (Block x51 x52)
  thus ?thesis
  proof (cases x51)
    case (Tf t1s t2s)
    thus ?thesis
      using Block assms
    proof (cases length t1s ≤ length ves; cases split-n ves (length t1s))
      case True
      case (Pair ves' ves'')
      hence vs-to-es ves = vs-to-es ves'' @ vs-to-es ves'
        using split-n-conv-app
        by fastforce
```

```
      moreover
       have s = s' vs = vs' es' = vs-to-es ves'' @ [Label (length t2s) [] (vs-to-es
ves' @ ($* x52))]
        using Block assms Tf True Pair
        by auto
      moreover
     have (|s;vs;(vs-to-es ves'')@(vs-to-es ves')@[$Block x51 x52]|) ↝-i (|s;vs;(vs-to-es
ves'')@[Label (length t2s) [] (vs-to-es ves' @ ($* x52))]|)
      using Tf reduce-simple.intros(27) split-n-length[OF Pair True] progress-L0-left[OF
reduce.intros(1)]
            is-const-list-vs-to-es-list[of rev ves'] is-const-list-vs-to-es-list[of rev ves'']
        by fastforce
      ultimately
      show ?thesis
        using Block
        by auto
    qed auto
  qed
 next
  case (Loop x61 x62)
  thus ?thesis
  proof (cases x61)
    case (Tf t1s t2s)
    thus ?thesis
      using Loop assms
    proof (cases length t1s ≤ length ves; cases split-n ves (length t1s))
      case True
      case (Pair ves' ves'')
      hence vs-to-es ves = vs-to-es ves'' @ vs-to-es ves'
        using split-n-conv-app
        by fastforce
      moreover
       have s = s' vs = vs' es' = vs-to-es ves'' @ [Label (length t1s) [$Loop x61
x62] (vs-to-es ves' @ ($* x62))]
        using Loop assms Tf True Pair
        by auto
      moreover
     have (|s;vs;(vs-to-es ves'')@(vs-to-es ves')@[$Loop x61 x62]|) ↝-i (|s;vs;(vs-to-es
ves'')@[Label (length t1s) [$Loop x61 x62] (vs-to-es ves' @ ($* x62))]|)
      using Tf reduce-simple.intros(28) split-n-length[OF Pair True] progress-L0-left[OF
reduce.intros(1)]
            is-const-list-vs-to-es-list[of rev ves'] is-const-list-vs-to-es-list[of rev ves'']
        by fastforce
      ultimately
      show ?thesis
        using Loop
        by auto
    qed auto
  qed
```

```
next
  case (If x71 x72 x73)
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms If
    proof (cases a)
      case (ConstInt32 x1)
    hence vs-to-es ves = vs-to-es list @ [$C ConstInt32 x1]
      unfolding Cons
      by simp
    thus ?thesis
      using progress-L0-left[OF reduce.intros(1)]
            is-const-list-vs-to-es-list[of rev list]
            reduce-simple.intros(29,30)
            assms Cons If ConstInt32
      by (cases int-eq x1 0) auto
    qed auto
  qed auto
next
  case (Br x8)
  thus ?thesis
    using assms
    by auto
next
  case (Br-if x9)
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms Br-if
    proof (cases a)
      case (ConstInt32 x1)
    hence vs-to-es ves = vs-to-es list @ [$C ConstInt32 x1]
      unfolding Cons
      by simp
    thus ?thesis
      using progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(34)]]
            progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(35)]]
            is-const-list-vs-to-es-list[of rev list]
            assms Cons Br-if ConstInt32
      by (cases int-eq x1 0) auto
    qed auto
  qed auto
next
  case (Br-table x10)
```

```
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms Br-table
    proof (cases a)
      case (ConstInt32 x1)
      thus ?thesis
        using progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(36)]]
              progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(37)]]
              is-const-list-vs-to-es-list[of rev list]
              assms Br-table Cons
        by (cases (nat-of-int x1) < length x10) auto
    qed auto
  qed auto
next
  case Return
  thus ?thesis
    using assms
    by simp
next
  case (Call x12)
  thus ?thesis
    using assms progress-L0-left[OF reduce.intros(2)]
          is-const-list-vs-to-es-list[of rev ves]
    by auto
next
  case (Call-indirect x13)
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms Call-indirect
    proof (cases a)
      case (ConstInt32 c)
      thus ?thesis
      proof (cases stab s i (nat-of-int c))
        case None
        thus ?thesis
          using assms Call-indirect Cons ConstInt32
                progress-L0-left[OF reduce.intros(4)]
                is-const-list-vs-to-es-list[of rev list]
          by auto
      next
        case (Some cl)
        thus ?thesis
        proof (cases stypes s i x13 = cl-type cl)
```

```
          case True
          hence (|s;vs;(vs-to-es list) @ [$C ConstInt32 c, $Call-indirect x13]|) ↝-
i (|s;vs;(vs-to-es list) @ [Callcl cl]|)
        using progress-L0-left[OF reduce.intros(3)] True Some is-const-list-vs-to-es-list[of
rev list]
          by fastforce
          thus ?thesis
          using assms Call-indirect Cons ConstInt32 Some True
          by auto
        next
          case False
          hence (|s;vs;(vs-to-es list)@[$C ConstInt32 c, $Call-indirect x13]|) ↝- i
(|s;vs;(vs-to-es list)@[Trap]|)
        using progress-L0-left[OF reduce.intros(4)] False Some is-const-list-vs-to-es-list[of
rev list]
          by fastforce
          thus ?thesis
          using assms Call-indirect Cons ConstInt32 Some False
          by auto
        qed
      qed
    qed auto
  qed auto
 next
  case (Get-local j)
  thus ?thesis
    using assms
  proof (cases j < length vs)
    case True
    then obtain vs1 v vs2 where vs = vs1@[v]@vs2 length vs1 = j
      using id-take-nth-drop
      by fastforce
    thus ?thesis
      using assms Get-local True
            progress-L0-left[OF reduce.intros(8)]
            is-const-list-vs-to-es-list[of rev ves]
      by auto
  qed auto
 next
  case (Set-local j)
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms Set-local
    proof (cases j < length vs)
      case True
      obtain vs1 v vs2 where vs-def:vs = vs1@[v]@vs2 length vs1 = j
```

```
      using id-take-nth-drop True
      by fastforce
    thus ?thesis
      using assms Set-local True Cons
          progress-L0-left[OF reduce.intros(9)]
          is-const-list-vs-to-es-list[of rev list]
      by auto
  qed auto
 qed auto
next
 case (Tee-local x16)
 thus ?thesis
  using assms
 proof (cases ves)
  case (Cons a list)
  thus ?thesis
   using assms Tee-local
       progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(41)]]
                   is-const-list-vs-to-es-list[of rev list]
   by (auto simp add: is-const-def)
 qed auto
next
 case (Get-global x17)
 thus ?thesis
  using assms
      progress-L0-left[OF reduce.intros(10)]
      is-const-list-vs-to-es-list[of rev ves]
  by (auto simp add: is-const-def)
next
 case (Set-global x18)
 thus ?thesis
  using assms
 proof (cases ves)
  case (Cons a list)
  thus ?thesis
   using assms Set-global
       progress-L0-left[OF reduce.intros(11)]
       is-const-list-vs-to-es-list[of rev list]
   by (auto simp add: is-const-def)
 qed auto
next
 case (Load x191 x192 x193 x194)
 thus ?thesis
  using assms
 proof (cases x192; cases ves)
  case None
  case (Cons a list)
  thus ?thesis
   using Load assms None
```

```
      proof (cases a; cases smem-ind s i)
        case (ConstInt32 x1)
        case (Some a)
        thus ?thesis
          using Load assms None Cons ConstInt32
              progress-L0-left[OF reduce.intros(12)]
              progress-L0-left[OF reduce.intros(13)]
              is-const-list-vs-to-es-list[of rev list]
          by (cases load (s.mem s ! a) (nat-of-int x1) x194 (t-length x191) )
            (auto simp add: is-const-def)
      qed auto
    next
      case outer-some:(Some tp-sx)
      case (Cons a list)
      thus ?thesis
        using Load assms outer-some
        proof (cases a; cases smem-ind s i; cases tp-sx)
          case (ConstInt32 x1)
          case (Pair tp sx)
          case (Some a)
          thus ?thesis
            using Load assms outer-some Cons ConstInt32 Pair
                progress-L0-left[OF reduce.intros(14)]
                progress-L0-left[OF reduce.intros(15)]
                is-const-list-vs-to-es-list[of rev list]
           by (cases load-packed sx (s.mem s ! a) (nat-of-int x1) x194 (tp-length tp)
(t-length x191))
              (auto simp add: is-const-def)
        qed auto
    qed auto
  next
    case (Store t tp a off)
    thus ?thesis
      using assms
    proof (cases ves)
      case outer-Cons:(Cons a list)
      thus ?thesis
        using Store assms
      proof (cases list)
        case (Cons a' list')
        thus ?thesis
          using Store outer-Cons assms
        proof (cases a')
          case (ConstInt32 x1)
          thus ?thesis
            using Store outer-Cons Cons assms
          proof (cases (types-agree t a); cases smem-ind s i)
            case True
            case outer-Some:(Some j)
```

```
          show ?thesis
          proof (cases tp)
            case None
            thus ?thesis
              using Store outer-Cons Cons assms True outer-Some ConstInt32
                    progress-L0-left[OF reduce.intros(16)]
                    progress-L0-left[OF reduce.intros(17)]
                    is-const-list-vs-to-es-list[of rev list']
              by (cases store (s.mem s ! j) (nat-of-int x1) off (bits a) (t-length t))
                 auto
          next
            case (Some the-tp)
            thus ?thesis
              using Store outer-Cons Cons assms True outer-Some ConstInt32
                    progress-L0-left[OF reduce.intros(18)]
                    progress-L0-left[OF reduce.intros(19)]
                    is-const-list-vs-to-es-list[of rev list']
                by (cases store-packed (s.mem s ! j) (nat-of-int x1) off (bits a)
(tp-length the-tp))
                   auto
          qed
        qed (cases tp; auto)+
      qed (cases tp; auto)+
    qed (cases tp; auto)
  qed (cases tp; auto)
next
  case Current-memory
  thus ?thesis
    using assms
  proof (cases smem-ind s i)
    case (Some a)
    thus ?thesis
      using assms Current-memory
            progress-L0-left[OF reduce.intros(20)]
            is-const-list-vs-to-es-list[of rev ves]
      by (auto simp add: is-const-def)
  qed auto
next
  case Grow-memory
  thus ?thesis
    using assms
  proof (cases ves)
    case (Cons a list)
    thus ?thesis
      using assms Grow-memory
    proof (cases a; cases smem-ind s i)
      case (ConstInt32 x1)
      case (Some j)
      thus ?thesis
```

```
        using assms Grow-memory Cons ConstInt32
                        progress-L0-left[OF reduce.intros(21)]
                        progress-L0-left[OF reduce.intros(22)]
            is-const-list-vs-to-es-list[of rev list]
        by (cases mem-grow-impl (s.mem s ! j) (nat-of-int x1)) (auto simp add:
mem-grow-impl-correct is-const-def)
      qed auto
    qed auto
  next
    case (EConst x23)
    thus ?thesis
      using assms
      by auto
  next
    case (Unop-i x241 x242)
    thus ?thesis
      using run-step-basic-unop-testop-sound[OF assms]
      by fastforce
  next
    case (Unop-f x251 x252)
    thus ?thesis
      using run-step-basic-unop-testop-sound[OF assms]
      by fastforce
  next
    case (Binop-i x261 x262)
    thus ?thesis
      using run-step-basic-binop-relop-sound[OF assms]
      by fastforce
  next
    case (Binop-f x271 x272)
    thus ?thesis
      using run-step-basic-binop-relop-sound[OF assms]
      by fastforce
  next
    case (Testop x281 x282)
    thus ?thesis
      using run-step-basic-unop-testop-sound[OF assms]
      by fastforce
  next
    case (Relop-i x291 x292)
    thus ?thesis
      using run-step-basic-binop-relop-sound[OF assms]
      by fastforce
  next
    case (Relop-f x301 x302)
    thus ?thesis
      using run-step-basic-binop-relop-sound[OF assms]
      by fastforce
  next
```

```
    case (Cvtop t2 cvtop t1 sx)
    thus ?thesis
      using assms
    proof (cases ves)
      case (Cons a list)
      thus ?thesis
        using assms Cvtop
      proof (cases cvtop; cases types-agree t1 a)
        case Convert
        case True
        thus ?thesis
          using Convert assms Cvtop Cons
                progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(19)]]
                progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(20)]]
                is-const-list-vs-to-es-list[of rev list]
          by (cases (cvt t2 sx a)) auto
      next
        case Reinterpret
        case True
        thus ?thesis
          using Reinterpret assms Cvtop Cons
                progress-L0-left[OF reduce.intros(1)[OF reduce-simple.intros(21)]]
                is-const-list-vs-to-es-list[of rev list]
          by (cases sx) auto
      qed auto
    qed (cases cvtop; auto)
  qed
qed

theorem run-step-sound:
  assumes run-step d i (s,vs,es) = (s', vs', RSNormal es')
  shows (|s;vs;es|) ↝- i (|s';vs';es'|)
  using assms
proof −
  fix ves e
  have (run-step d i (s,vs,es) = (s', vs', RSNormal es')) ⟹
         (λi (s, vs, es). (|s;vs;es|) ↝- i (|s';vs';es'|)) i (s, vs, es)
  and  (run-one-step d i (s,vs,ves,e) = (s', vs', RSNormal es')) ⟹
         (λi (s, vs, ves, e). (|s;vs;(vs-to-es ves)@[e]|) ↝- i (|s';vs';es'|)) i (s, vs, ves,
e)
   proof (induction d i - and d i - arbitrary: s' vs' es' and s' vs' es' rule:
run-step-run-one-step.induct)
    case (1 d i s vs es)
    obtain ves ses where ves-def:split-vals-e es = (ves, ses)
      by (metis surj-pair)
    thus ?case
    proof (cases ses)
      case Nil
      thus ?thesis
```

```
      using 1(2) ves-def
      by simp
    next
     case (Cons a list)
     thus ?thesis
     proof (cases a = Trap)
      case True
      have c-ves:const-list ($$* ves)
       using is-const-list[of - ves]
       by simp
      have es' = [Trap] ∧ (list ≠ [] ∨ ves ≠ [])
       using Cons 1(2) ves-def True
       by (cases (list ≠ [] ∨ ves ≠ [])) auto
      thus ?thesis
      using Cons 1(2) ves-def split-vals-e-conv-app[OF ves-def] True progress-L0-trap[OF
c-ves]
       by auto
     next
      case False
      obtain os ovs oes where ros-def:run-one-step d i (s, vs, (rev ves), a) = (os,
ovs, oes)
       by (metis surj-pair)
      moreover
      then obtain roes where oes = RSNormal roes
       using 1(2) ves-def Cons False
       by (cases oes) auto
      moreover
      hence os = s' ovs = vs' and es'-def:es' = roes @ list
       using 1(2) ves-def Cons ros-def False
       by (cases roes = [Trap], auto simp del: run-one-step.simps)+
      ultimately
      have ros-red:(|s;vs;($$* ves) @ [a]|) ↝- i (|s';vs';roes|)
       using 1(1)[OF ves-def[symmetric] - Cons] ros-def False
       by (simp del: run-one-step.simps)
      have (|s;vs;($$* ves)@[a]@list|) ↝- i (|s';vs';roes@list|)
       using progress-L0[OF ros-red, of [] list]
       unfolding const-list-def
       by simp
      thus ?thesis
       using es'-def Cons split-vals-e-conv-app[OF ves-def]
       by simp
     qed
    qed
   next
    case (2 d i s vs ves e)
    show ?case
    proof (cases e)
     case (Basic x1)
     thus ?thesis
```

**using** *run-step-basic-sound 2(3)*
**by** *simp*
**next**
**case** *Trap*
**thus** *?thesis*
**using** *2(3)*
**by** *simp*
**next**
**case** (*Callcl cl*)
**obtain** *t1s t2s* **where** *cl-type cl* = (*t1s* -> *t2s*)
**using** *tf.exhaust*[*of* - *thesis*]
**by** *fastforce*
**moreover**
**obtain** *n* **where** *length t1s* = *n*
**by** *blast*
**moreover**
**obtain** *m* **where** *length t2s* = *m*
**by** *blast*
**moreover**
**note** *local-defs* = *calculation*
**show** *?thesis*
**proof** (*cases length ves* ≥ *n*)
**case** *outer-True*:*True*
**obtain** *ves' ves''* **where** *true-defs*:*split-n ves n* = (*ves'*, *ves''*)
**by** (*metis surj-pair*)
**have** *ves'-length*:*length* (*rev ves'*) = *n*
**using** *split-n-length*[*OF true-defs outer-True*] *inj-basic-econst length-rev map-injective*
**by** *blast*
**show** *?thesis*
**proof** (*cases cl*)
**case** (*Func-native i' tf fts fes*)
**hence** *s'* = *s vs'* = *vs es'* = (*vs-to-es ves''* @ [*Local* (*length t2s*) *i'* (*rev ves'* @ (*n-zeros fts*)) [$*Block* ([] -> *t2s*) *fes*]])
**using** *2(3) Callcl local-defs outer-True true-defs*
**unfolding** *cl-type-def*
**by** *auto*
**moreover**
**have** (|*s*;*vs*;(*vs-to-es ves'*)@[*Callcl cl*]|) ⇝-*i* (|*s*;*vs*;([*Local* (*length t2s*) *i'* (*rev ves'* @ (*n-zeros fts*)) [$*Block* ([] -> *t2s*) *fes*]])|)
**using** *reduce.intros*(*5*) *local-defs*(*1*,*2*) *Func-native ves'-length*
**unfolding** *cl-type-def*
**by** *fastforce*
**ultimately**
**show** *?thesis*
**using** *Callcl progress-L0-left is-const-list*[*of* - (*rev ves''*)]
**unfolding** *split-n-conv-app*[*OF true-defs*(*1*)]
**by** *auto*
**next**

```
      case (Func-host x21 x22)
      thus ?thesis
      proof (cases host-apply-impl s (t1s -> t2s) x22 (rev ves'))
        case None
        hence s = s'
            vs = vs'
            es' = vs-to-es ves'' @ [Trap]
          using 2(3) Callcl local-defs outer-True true-defs Func-host
          unfolding cl-type-def
          by auto
        thus ?thesis
          using is-const-list[of - (rev ves'')]
              reduce.intros(7)[OF - - ves'-length local-defs(2)]
              split-n-conv-app[OF true-defs]
              progress-L0-left Callcl Func-host local-defs(1)
          unfolding cl-type-def
          by fastforce
      next
        case (Some a)
        show ?thesis
        proof (cases a)
        case (Pair rs rves)
          thus ?thesis
            using 2(3) Callcl local-defs outer-True true-defs Func-host Some
            unfolding cl-type-def
          proof (cases list-all2 types-agree t2s rves)
            case True
            hence rs = s'
                vs = vs'
                es' = vs-to-es ves'' @ ($$* rves)
              using 2(3) Callcl local-defs outer-True true-defs Func-host Pair
Some
              unfolding cl-type-def
              by auto
            thus ?thesis
           using progress-L0-left reduce.intros(6)[OF - - ves'-length local-defs(2)]
Pair
                  Callcl Func-host local-defs(1) True is-const-list[of - (rev ves'')]
                split-n-conv-app[OF true-defs] host-apply-impl-correct[OF Some]
              unfolding cl-type-def
              by fastforce
          qed auto
        qed
      qed
    qed
  next
    case False
    thus ?thesis
      using 2(3) Callcl local-defs
```

```
        unfolding cl-type-def
        by (cases cl) auto
    qed
  next
    case (Label ln les es)
    thus ?thesis
    proof (cases es-is-trap es)
      case True
      thus ?thesis
        using 2(3) is-const-list-vs-to-es-list
              Label progress-L0[OF reduce.intros(1)[OF reduce-simple.intros(32)]]
          by fastforce
    next
      case False
      note outer-outer-false = False
      show ?thesis
      proof (cases (const-list es))
        case True
        thus ?thesis
       using 2(3) outer-outer-false Label reduce.intros(1)[OF reduce-simple.intros(31)]
             progress-L0[OF - is-const-list-vs-to-es-list[of rev ves], where ?es-c=[]]
          by fastforce
      next
        case False
        obtain s'' vs'' es'' where run-step-is:run-step d i (s, vs, es) = (s'', vs'',
es'')
          by (metis surj-pair)
        show ?thesis
        proof (cases es'')
          case RSCrash
          thus ?thesis
            using outer-outer-false False run-step-is Label 2(3)
              by auto
        next
          case (RSBreak bn bvs)
          thus ?thesis
          proof (cases bn)
            case 0
            have run-step-is-break0:run-step d i (s, vs, es) = (s'', vs'', RSBreak 0
bvs)
              using run-step-is RSBreak 0
              by simp
             hence es'-def:es' = ((vs-to-es ((take ln bvs)@ves))@les) ∧ s' = s'' ∧
vs' = vs'' ∧ ln ≤ length bvs
              using outer-outer-false False run-step-is Label 2(3) RSBreak
              by (cases ln ≤ length bvs) auto
            then obtain n lfilled es-c where local-eqs:s=s' vs=vs' ln ≤ length bvs
Lfilled-exact n lfilled ((vs-to-es bvs) @ [$Br n] @ es-c) es
            using run-step-break-imp-lfilled[OF run-step-is-break0] RSBreak es'-def
```

**by** *fastforce*
**then obtain** *lfilled'* **where** *lfilled-int*:*Lfilled n lfilled'* ((*vs-to-es bvs*) @ [$*Br n*]) *es*
**using** *lfilled-collapse2*[*OF Lfilled-exact-imp-Lfilled*]
**by** *fastforce*
**obtain** *lfilled''* **where** *Lfilled n lfilled''* ((*drop* (*length bvs* − *ln*) (*vs-to-es bvs*)) @ [$*Br n*]) *es*
**using** *lfilled-collapse1*[*OF lfilled-int*] *is-const-list-vs-to-es-list*[*of rev bvs*] *local-eqs*(*3*)
**by** *fastforce*
**hence** (|[*Label ln les es*]|) ⇝ (|(*drop* (*length bvs* − *ln*) (*vs-to-es bvs*))@*les*|)
**using** *reduce-simple.intros*(*33*) *local-eqs*(*3*) *is-const-list-vs-to-es-list*
**unfolding** *drop-map*
**by** *fastforce*
**hence** *1*:(|*s*;*vs*;[*Label ln les es*]|) ⇝-*i* (|*s'*;*vs'*;(*drop* (*length bvs* − *ln*) (*vs-to-es bvs*))@*les*|)
**using** *reduce.intros*(*1*) *local-eqs*(*1*,*2*)
**by** *fastforce*
**have** (|*s*;*vs*;(*vs-to-es ves*)@[*e*]|) ⇝-*i* (|*s'*;*vs'*;(*vs-to-es ves*)@(*drop* (*length bvs* − *ln*) (*vs-to-es bvs*))@*les*|)
**using** *progress-L0*[*OF 1 is-const-list-vs-to-es-list*[*of rev ves*], *of* []] *Label*
**by** *fastforce*
**thus** *?thesis*
**using** *es'-def*
**unfolding** *drop-map rev-take*[*symmetric*]
**by** *auto*
**next**
**case** (*Suc nat*)
**thus** *?thesis*
**using** *outer-outer-false False run-step-is Label 2*(*3*) *RSBreak*
**by** *auto*
**qed**
**next**
**case** (*RSReturn x3*)
**thus** *?thesis*
**using** *outer-outer-false False run-step-is Label 2*(*3*)
**by** *auto*
**next**
**case** (*RSNormal x4*)
**hence** *es'* = (*vs-to-es ves*)@[*Label ln les x4*] *s'* = *s''* *vs'* = *vs''*
**using** *outer-outer-false False run-step-is Label 2*(*3*) *run-step-is*
**by** *auto*
**moreover**
**have** *Lfilled 1* (*LRec* (*vs-to-es ves*) *ln les* (*LBase* [] []) []) *es* ((*vs-to-es ves*)@[*Label ln les es*])
**using** *Lfilled.intros*(*1*)[*of* [] - [] *es*]
*Lfilled.intros*(*2*)
*is-const-list-vs-to-es-list*[*of rev ves*]

```
            unfolding const-list-def
            by fastforce
          moreover
           have Lfilled 1 (LRec (vs-to-es ves) ln les (LBase [] []) []) x4 ((vs-to-es
ves)@[Label ln les x4])
            using Lfilled.intros(1)[of [] - [] x4]
                  Lfilled.intros(2)
                  is-const-list-vs-to-es-list[of rev ves]
            unfolding const-list-def
            by fastforce
          moreover
          have inner-reduce:⟪s;vs;es⟫ ↝-i ⟪s'';vs'';x4⟫
            using 2(1)[OF Label outer-outer-false False] run-step-is RSNormal
            by auto
          ultimately
          show ?thesis
            using Label 2(3) outer-outer-false False run-step-is
                  reduce.intros(23)[OF inner-reduce]
            by fastforce
        qed
       qed
     qed
   next
     case (Local ln j vls es)
     thus ?thesis
     proof (cases es-is-trap es)
       case True
       thus ?thesis
         using 2(3) is-const-list-vs-to-es-list
               Local progress-L0[OF reduce.intros(1)[OF reduce-simple.intros(39)]]
         by fastforce
     next
       case False
       note outer-outer-false = False
       show ?thesis
       proof (cases (const-list es))
         case True
         note outer-true = True
         thus ?thesis
         proof (cases length es = ln)
           case True
           thus ?thesis
            using 2(3) Local outer-true outer-outer-false is-const-list-vs-to-es-list[of
rev ves]
                  reduce.intros(1)[OF reduce-simple.intros(38)[OF outer-true True]]
                  progress-L0[where ?es-c=[]]
                  by fastforce
         next
           case False
```

```
          thus ?thesis
           using 2(3) Local outer-outer-false outer-true is-const-list-vs-to-es-list[of
rev ves]
            by auto
         qed
       next
         case False
         show ?thesis
         proof (cases d)
           case 0
           thus ?thesis
            using 2(3) Local outer-outer-false False is-const-list-vs-to-es-list[of rev
ves]
            by auto
         next
           case (Suc d')
          obtain s'' vls' les' where run-step-is:run-step d' j (s, vls, es) = (s'', vls',
les')
           by (metis surj-pair)
           show ?thesis
           proof (cases les')
             case RSCrash
             thus ?thesis
               using outer-outer-false False run-step-is Local 2(3) Suc
                 by auto
           next
             case (RSBreak x21 x22)
             thus ?thesis
               using outer-outer-false False run-step-is Local 2(3) Suc
                 by auto
           next
             case (RSReturn x3)
            hence es'-def:es' = (vs-to-es ((take ln x3)@ves)) ∧ s' = s'' ∧ vs = vs'
∧ ln ≤ length x3
               using outer-outer-false False run-step-is Local 2(3) Suc
               by (cases ln ≤ length x3) auto
             then obtain n lfilled es-c where local-eqs:s=s' vs=vs' ln ≤ length x3
Lfilled-exact n lfilled ((vs-to-es x3) @ [$Return] @ es-c) es
               using run-step-is run-step-return-imp-lfilled RSReturn
               by fastforce
             then obtain lfilled' where lfilled-int:Lfilled n lfilled' ((vs-to-es x3) @
[$Return]) es
               using lfilled-collapse2[OF Lfilled-exact-imp-Lfilled]
               by fastforce
            obtain lfilled'' where Lfilled n lfilled'' ((drop (length x3 − ln) (vs-to-es
x3)) @ [$Return]) es
                 using lfilled-collapse1[OF lfilled-int] is-const-list-vs-to-es-list[of rev
x3] local-eqs(3)
               by fastforce
```

```
            hence (|[Local ln j vls es]|) ⇝ (|(drop (length x3 − ln) (vs-to-es x3))|)
              using reduce-simple.intros(40) local-eqs(3) is-const-list-vs-to-es-list
              unfolding drop-map
              by fastforce
              hence 1:(|s;vs;[Local ln j vls es]|) ⇝-i (|s';vs';(drop (length x3 − ln)
(vs-to-es x3))|)
              using reduce.intros(1) local-eqs(1,2)
              by fastforce
            have (|s;vs;(vs-to-es ves)@[e]|) ⇝-i (|s';vs';(vs-to-es ves)@(drop (length
x3 − ln) (vs-to-es x3))|)
                using progress-L0[OF 1 is-const-list-vs-to-es-list[of rev ves], of []]
Local
              by fastforce
            thus ?thesis
              using es'-def
              unfolding drop-map rev-take[symmetric]
              by auto
          next
            case (RSNormal x4)
            hence inner-reduce:(|s;vls;es|) ⇝-j (|s'';vls';x4|)
              using 2(2)[OF Local outer-outer-false False] run-step-is Suc
              by auto
            thus ?thesis
              using Local 2(3) Local outer-outer-false False run-step-is Suc
                  reduce.intros(24)[OF inner-reduce] RSNormal
                  progress-L0-left is-const-list-vs-to-es-list[of rev ves]
              by (auto simp del: run-step.simps)
          qed
        qed
      qed
    qed
  qed
 qed
 thus ?thesis
  using assms
  by blast
qed

end
```

# References


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