

Java Source and Bytecode Formalizations in Isabelle: Bali

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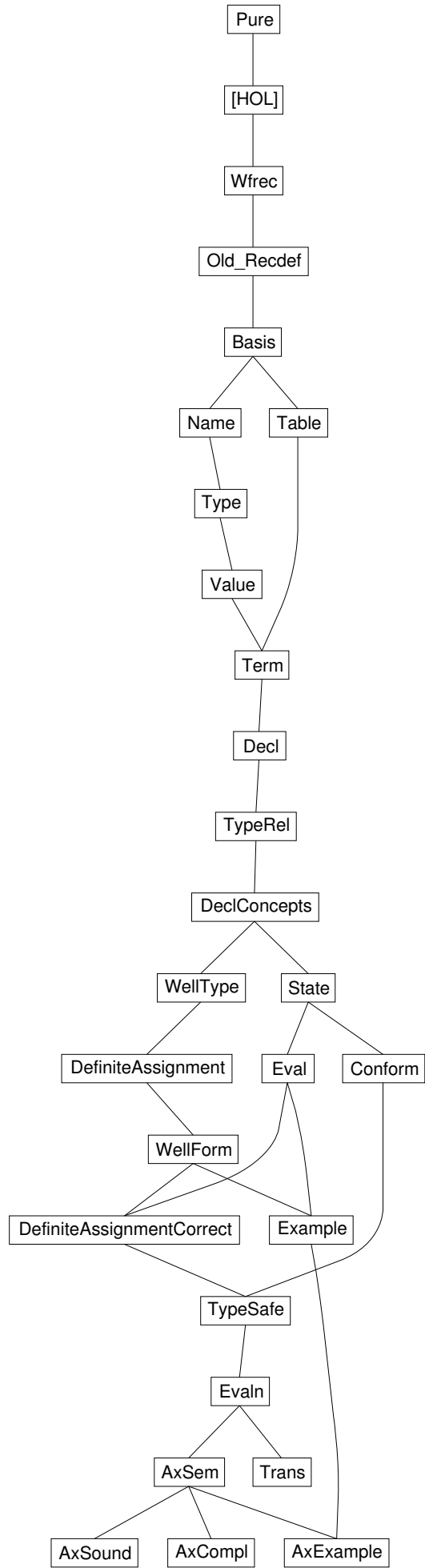
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Chapter 1

Overview

These theories, called Bali, model and analyse different aspects of the JavaCard **source language**. The basis is an abstract model of the JavaCard source language. On it, a type system, an operational semantics and an axiomatic semantics (Hoare logic) are built. The execution of a wellformed program (with respect to the type system) according to the operational semantics is proved to be typesafe. The axiomatic semantics is proved to be sound and relative complete with respect to the operational semantics.

We have modelled large parts of the original JavaCard source language. It models features such as:

- The basic “primitive types” of Java
- Classes and related concepts
- Class fields and methods
- Instance fields and methods
- Interfaces and related concepts
- Arrays
- Static initialisation
- Static overloading of fields and methods
- Inheritance, overriding and hiding of methods, dynamic binding
- All cases of abrupt termination
 - Exception throwing and handling
 - `break`, `continue` and `return`
- Packages
- Access Modifiers (`private`, `protected`, `public`)
- A “definite assignment” check

The following features are missing in Bali wrt. JavaCard:

- Some primitive types (`byte`, `short`)
- Syntactic variants of statements (`do-loop`, `for-loop`)
- Interface fields

- Inner Classes

In addition, features are missing that are not part of the JavaCard language, such as multithreading and garbage collection. No attempt has been made to model peculiarities of JavaCard such as the applet firewall or the transaction mechanism.

Overview of the theories:

Basis Some basic definitions and settings not specific to JavaCard but missing in HOL.

Table Definition and some properties of a lookup table to map various names (like class names or method names) to some content (like classes or methods).

Name Definition of various names (class names, variable names, package names,...)

Value JavaCard expression values (Boolean, Integer, Addresses,...)

Type JavaCard types. Primitive types (Boolean, Integer,...) and reference types (Classes, Interfaces, Arrays,...)

Term JavaCard terms. Variables, expressions and statements.

Decl Class, interface and program declarations. Recursion operators for the class and the interface hierarchy.

TypeRel Various relations on types like the subclass-, subinterface-, widening-, narrowing- and casting-relation.

DeclConcepts Advanced concepts on the class and interface hierarchy like inheritance, overriding, hiding, accessibility of types and members according to the access modifiers, method lookup.

WellType Typesystem on the JavaCard term level.

DefiniteAssignment The definite assignment analysis on the JavaCard term level.

WellForm Typesystem on the JavaCard class, interface and program level.

State The program state (like object store) for the execution of JavaCard. Abrupt completion (exceptions, break, continue, return) is modelled as flag inside the state.

Eval Operational (big step) semantics for JavaCard.

Example An concrete example of a JavaCard program to validate the typesystem and the operational semantics.

Conform Conformance predicate for states. When does an execution state conform to the static types of the program given by the typesystem.

DefiniteAssignmentCorrect Correctness of the definite assignment analysis. If the analysis regards a variable as definitely assigned at a certain program point, the variable will actually be assigned there during execution.

TypeSafe Typesafety proof of the execution of JavaCard. "Welltyped programs don't go wrong" or more technical: The execution of a welltyped JavaCard program preserves the conformance of execution states.

Evaln Copy of the operational semantics given in theory Eval expanded with an annotation for the maximal recursive depth. The semantics is not altered. The annotation is needed for the soundness proof of the axiomatic semantics.

Trans A smallstep operational semantics for JavaCard.

AxSem An axiomatic semantics (Hoare logic) for JavaCard.

AxSound The soundness proof of the axiomatic semantics with respect to the operational semantics.

AxCompl The proof of (relative) completeness of the axiomatic semantics with respect to the operational semantics.

AxExample An concrete example of the axiomatic semantics at work, applied to prove some properties of the JavaCard example given in theory Example.

Chapter 2

Basis

1 Definitions extending HOL as logical basis of Bali

theory *Basis*

imports *Main* $\sim\sim$ /src/HOL/Library/Old-Recdef

begin

misc

declare *split-if-asm* [*split*] *option.split* [*split*] *option.split-asm* [*split*]
 $\langle ML \rangle$

declare *if-weak-cong* [*cong del*] *option.weak-case-cong* [*cong del*]

declare *length-Suc-conv* [*iff*]

lemma *Collect-split-eq*: $\{p. P (split\ f\ p)\} = \{(a,b). P (f\ a\ b)\}$
 $\langle proof \rangle$

lemma *subset-insertD*: $A \subseteq insert\ x\ B \implies A \subseteq B \wedge x \notin A \vee (\exists B'. A = insert\ x\ B' \wedge B' \subseteq B)$
 $\langle proof \rangle$

abbreviation *nat3* :: *nat* (*3*) **where** *3* $\equiv Suc\ 2$

abbreviation *nat4* :: *nat* (*4*) **where** *4* $\equiv Suc\ 3$

lemma *irrefl-tranclI'*: $r^{-1} \cap r^+ = \{\}$ $\implies \forall x. (x, x) \notin r^+$
 $\langle proof \rangle$

lemma *trancl-rtrancl-trancl*: $\llbracket (x, y) \in r^+; (y, z) \in r^* \rrbracket \implies (x, z) \in r^+$
 $\langle proof \rangle$

lemma *rtrancl-into-trancl3*: $\llbracket (a, b) \in r^*; a \neq b \rrbracket \implies (a, b) \in r^+$
 $\langle proof \rangle$

lemma *rtrancl-into-rtrancl2*: $\llbracket (a, b) \in r; (b, c) \in r^* \rrbracket \implies (a, c) \in r^*$
 $\langle proof \rangle$

lemma *triangle-lemma*:

assumes *unique*: $\bigwedge a\ b\ c. \llbracket (a,b) \in r; (a,c) \in r \rrbracket \implies b = c$

and *ax*: $(a,x) \in r^*$ **and** *ay*: $(a,y) \in r^*$

shows $(x,y) \in r^* \vee (y,x) \in r^*$

$\langle proof \rangle$

lemma *rtrancl-cases*:

assumes $(a,b) \in r^*$

obtains (*Refl*) $a = b$

| (*Trancl*) $(a,b) \in r^+$

$\langle proof \rangle$

lemma *Ball-weaken*: $\llbracket Ball\ s\ P; \bigwedge x. P\ x \longrightarrow Q\ x \rrbracket \implies Ball\ s\ Q$

<proof>

lemma *finite-SetCompr2*:

$finite (Collect P) \implies \forall y. P y \longrightarrow finite (range (f y)) \implies$
 $finite \{f y x \mid x y. P y\}$
<proof>

lemma *list-all2-trans*: $\forall a b c. P1 a b \longrightarrow P2 b c \longrightarrow P3 a c \implies$

$\forall xs2 xs3. list-all2 P1 xs1 xs2 \longrightarrow list-all2 P2 xs2 xs3 \longrightarrow list-all2 P3 xs1 xs3$
<proof>

pairs

lemma *surjective-pairing5*:

$p = (fst p, fst (snd p), fst (snd (snd p)), fst (snd (snd (snd p))),$
 $snd (snd (snd (snd p))))$
<proof>

lemma *fst-splitE* [*elim!*]:

assumes $fst s' = x'$
obtains $x s$ **where** $s' = (x, s)$ **and** $x = x'$
<proof>

lemma *fst-in-set-lemma*: $(x, y) : set l \implies x : fst ` set l$

<proof>

quantifiers

lemma *All-Ex-refl-eq2* [*simp*]: $(\forall x. (\exists b. x = f b \wedge Q b) \longrightarrow P x) = (\forall b. Q b \longrightarrow P (f b))$

<proof>

lemma *ex-ex-miniscope1* [*simp*]: $(\exists w v. P w v \wedge Q v) = (\exists v. (\exists w. P w v) \wedge Q v)$

<proof>

lemma *ex-miniscope2* [*simp*]: $(\exists v. P v \wedge Q \wedge R v) = (Q \wedge (\exists v. P v \wedge R v))$

<proof>

lemma *ex-reorder31*: $(\exists z x y. P x y z) = (\exists x y z. P x y z)$

<proof>

lemma *All-Ex-refl-eq1* [*simp*]: $(\forall x. (\exists b. x = f b) \longrightarrow P x) = (\forall b. P (f b))$

<proof>

sums

hide-const *In0 In1*

notation *sum-case* (**infixr** '(+)'80)

primrec *the-Inl* :: 'a + 'b \Rightarrow 'a

where *the-Inl* (*Inl* a) = a

primrec *the-Inr* :: 'a + 'b ⇒ 'b
 where *the-Inr* (Inr b) = b

datatype ('a, 'b, 'c) *sum3* = In1 'a | In2 'b | In3 'c

primrec *the-In1* :: ('a, 'b, 'c) *sum3* ⇒ 'a
 where *the-In1* (In1 a) = a

primrec *the-In2* :: ('a, 'b, 'c) *sum3* ⇒ 'b
 where *the-In2* (In2 b) = b

primrec *the-In3* :: ('a, 'b, 'c) *sum3* ⇒ 'c
 where *the-In3* (In3 c) = c

abbreviation *In1l* :: 'al ⇒ ('al + 'ar, 'b, 'c) *sum3*
 where *In1l* e ≡ In1 (Inl e)

abbreviation *In1r* :: 'ar ⇒ ('al + 'ar, 'b, 'c) *sum3*
 where *In1r* c ≡ In1 (Inr c)

abbreviation *the-In1l* :: ('al + 'ar, 'b, 'c) *sum3* ⇒ 'al
 where *the-In1l* ≡ *the-Inl* ∘ *the-In1*

abbreviation *the-In1r* :: ('al + 'ar, 'b, 'c) *sum3* ⇒ 'ar
 where *the-In1r* ≡ *the-Inr* ∘ *the-In1*

⟨ML⟩

quantifiers for option type

syntax

-*Oall* :: [pttrn, 'a option, bool] ⇒ bool ((∃! -:::/ -) [0,0,10] 10)
 -*Oex* :: [pttrn, 'a option, bool] ⇒ bool ((∃? -:::/ -) [0,0,10] 10)

syntax (symbols)

-*Oall* :: [pttrn, 'a option, bool] ⇒ bool ((∃∀ -∈-:/ -) [0,0,10] 10)
 -*Oex* :: [pttrn, 'a option, bool] ⇒ bool ((∃∃ -∈-:/ -) [0,0,10] 10)

translations

∀x∈A: P ⇒ ∀x∈CONST Option.set A. P
 ∃x∈A: P ⇒ ∃x∈CONST Option.set A. P

Special map update

Deemed too special for theory Map.

definition *chg-map* :: ('b ⇒ 'b) ⇒ 'a ⇒ ('a → 'b) ⇒ ('a → 'b)
 where *chg-map* f a m = (case m a of None ⇒ m | Some b ⇒ m(a→f b))

lemma *chg-map-new[simp]*: m a = None ⇒ *chg-map* f a m = m
 ⟨proof⟩

lemma *chg-map-upd[simp]*: m a = Some b ⇒ *chg-map* f a m = m(a→f b)
 ⟨proof⟩

lemma *chg-map-other* [simp]: $a \neq b \implies \text{chg-map } f \ a \ m \ b = m \ b$
 ⟨proof⟩

unique association lists

definition *unique* :: $('a \times 'b) \text{ list} \Rightarrow \text{bool}$
 where *unique* = *distinct* \circ *map fst*

lemma *uniqueD*: $\text{unique } l \implies (x, y) \in \text{set } l \implies (x', y') \in \text{set } l \implies x = x' \implies y = y'$
 ⟨proof⟩

lemma *unique-Nil* [simp]: *unique* []
 ⟨proof⟩

lemma *unique-Cons* [simp]: $\text{unique } ((x,y)\#l) = (\text{unique } l \wedge (\forall y. (x,y) \notin \text{set } l))$
 ⟨proof⟩

lemma *unique-ConsD*: $\text{unique } (x\#xs) \implies \text{unique } xs$
 ⟨proof⟩

lemma *unique-single* [simp]: $\bigwedge p. \text{unique } [p]$
 ⟨proof⟩

lemma *unique-append* [rule-format (no-asm)]: $\text{unique } l' \implies \text{unique } l \implies$
 $(\forall (x,y) \in \text{set } l. \forall (x',y') \in \text{set } l'. x' \neq x) \longrightarrow \text{unique } (l @ l')$
 ⟨proof⟩

lemma *unique-map-inj*: $\text{unique } l \implies \text{inj } f \implies \text{unique } (\text{map } (\lambda(k,x). (f \ k, \ g \ k \ x)) \ l)$
 ⟨proof⟩

lemma *map-of-SomeI*: $\text{unique } l \implies (k, x) : \text{set } l \implies \text{map-of } l \ k = \text{Some } x$
 ⟨proof⟩

list patterns

definition *lsplit* :: $[['a, 'a \text{ list}] \Rightarrow 'b, 'a \text{ list}] \Rightarrow 'b$
 where *lsplit* = $(\lambda f \ l. f \ (\text{hd } l) \ (\text{tl } l))$

list patterns – extends pre-defined type "pttrn" used in abstractions

syntax

-lpttrn :: $[pttrn, pttrn] \Rightarrow pttrn \quad (-\#/- [901,900] \ 900)$

translations

$\lambda y \ \# \ x \ \# \ xs. \ b \Leftrightarrow \text{CONST } \text{lsplit } (\lambda y \ x \ \# \ xs. \ b)$
 $\lambda x \ \# \ xs. \ b \Leftrightarrow \text{CONST } \text{lsplit } (\lambda x \ xs. \ b)$

lemma *lsplit* [simp]: $\text{lsplit } c \ (x\#xs) = c \ x \ xs$
 ⟨proof⟩

lemma *lsplit2* [simp]: $\text{lsplit } P \ (x\#xs) \ y \ z = P \ x \ xs \ y \ z$

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(proof)

end

Chapter 3

Table

2 Abstract tables and their implementation as lists

theory *Table* **imports** *Basis* **begin**

design issues:

- definition of table: infinite map vs. list vs. finite set list chosen, because:
 - + a priori finite
 - + lookup is more operational than for finite set
 - not very abstract, but function table converts it to abstract mapping
- coding of lookup result: Some/None vs. value/arbitrary Some/None chosen, because:
 - ++ makes definedness check possible (applies also to finite set), which is important for the type standard, hiding/overriding, etc. (though it may perhaps be possible at least for the operational semantics to treat programs as infinite, i.e. where classes, fields, methods etc. of any name are considered to be defined)
 - sometimes awkward case distinctions, alleviated by operator 'the'

type-synonym (*'a*, *'b*) *table* — table with key type *'a* and contents type *'b*
 $= 'a \rightarrow 'b$

type-synonym (*'a*, *'b*) *tables* — non-unique table with key *'a* and contents *'b*
 $= 'a \Rightarrow 'b \text{ set}$

map of / table of

abbreviation

table-of :: (*'a* × *'b*) *list* ⇒ (*'a*, *'b*) *table* — concrete table
where *table-of* ≡ *map-of*

translations

(*type*) (*'a*, *'b*) *table* ≤ (*type*) *'a* → *'b*

lemma *map-add-find-left*[*simp*]: $n \ k = \text{None} \implies (m \ ++ \ n) \ k = m \ k$
 ⟨*proof*⟩

Conditional Override

definition *cond-override* :: (*'b* ⇒ *'b* ⇒ *bool*) ⇒ (*'a*, *'b*)*table* ⇒ (*'a*, *'b*)*table* ⇒ (*'a*, *'b*) *table* **where**

— when merging tables old and new, only override an entry of table old when the condition cond holds
cond-override cond old new =

(λ*k*.
 (case *new k* of
 None ⇒ *old k*
 | *Some new-val* ⇒ (case *old k* of
 None ⇒ *Some new-val*
 | *Some old-val* ⇒ (if *cond new-val old-val*
 then *Some new-val*
 else *Some old-val*))))

lemma *cond-override-empty1*[*simp*]: *cond-override c empty t* = *t*
 ⟨*proof*⟩

lemma *cond-override-empty2*[simp]: *cond-override c t empty = t*
 ⟨proof⟩

lemma *cond-override-None*[simp]:
old k = None \implies (cond-override c old new) k = new k
 ⟨proof⟩

lemma *cond-override-override*:
 $\llbracket \text{old } k = \text{Some } ov; \text{new } k = \text{Some } nv; C \text{ } nv \text{ } ov \rrbracket$
 $\implies (\text{cond-override } C \text{ old new}) k = \text{Some } nv$
 ⟨proof⟩

lemma *cond-override-noOverride*:
 $\llbracket \text{old } k = \text{Some } ov; \text{new } k = \text{Some } nv; \neg (C \text{ } nv \text{ } ov) \rrbracket$
 $\implies (\text{cond-override } C \text{ old new}) k = \text{Some } ov$
 ⟨proof⟩

lemma *dom-cond-override*: *dom (cond-override C s t) \subseteq dom s \cup dom t*
 ⟨proof⟩

lemma *finite-dom-cond-override*:
 $\llbracket \text{finite } (\text{dom } s); \text{finite } (\text{dom } t) \rrbracket \implies \text{finite } (\text{dom } (\text{cond-override } C \text{ } s \text{ } t))$
 ⟨proof⟩

Filter on Tables

definition *filter-tab* :: $('a \Rightarrow 'b \Rightarrow \text{bool}) \Rightarrow ('a, 'b) \text{ table} \Rightarrow ('a, 'b) \text{ table}$
where
*filter-tab c t = (λk . (case t k of
 None \Rightarrow None
 | Some x \Rightarrow if c k x then Some x else None))*

lemma *filter-tab-empty*[simp]: *filter-tab c empty = empty*
 ⟨proof⟩

lemma *filter-tab-True*[simp]: *filter-tab ($\lambda x y$. True) t = t*
 ⟨proof⟩

lemma *filter-tab-False*[simp]: *filter-tab ($\lambda x y$. False) t = empty*
 ⟨proof⟩

lemma *filter-tab-ran-subset*: *ran (filter-tab c t) \subseteq ran t*
 ⟨proof⟩

lemma *filter-tab-range-subset*: *range (filter-tab c t) \subseteq range t \cup {None}*
 ⟨proof⟩

lemma *finite-range-filter-tab*:

$finite\ (range\ t) \implies finite\ (range\ (filter-tab\ c\ t))$
 ⟨proof⟩

lemma *filter-tab-SomeD[dest!]*:

$filter-tab\ c\ t\ k = Some\ x \implies (t\ k = Some\ x) \wedge c\ k\ x$
 ⟨proof⟩

lemma *filter-tab-SomeI*: $\llbracket t\ k = Some\ x; C\ k\ x \rrbracket \implies filter-tab\ C\ t\ k = Some\ x$

⟨proof⟩

lemma *filter-tab-all-True*:

$\forall k\ y. t\ k = Some\ y \longrightarrow p\ k\ y \implies filter-tab\ p\ t = t$
 ⟨proof⟩

lemma *filter-tab-all-True-Some*:

$\llbracket \forall k\ y. t\ k = Some\ y \longrightarrow p\ k\ y; t\ k = Some\ v \rrbracket \implies filter-tab\ p\ t\ k = Some\ v$
 ⟨proof⟩

lemma *filter-tab-all-False*:

$\forall k\ y. t\ k = Some\ y \longrightarrow \neg p\ k\ y \implies filter-tab\ p\ t = empty$
 ⟨proof⟩

lemma *filter-tab-None*: $t\ k = None \implies filter-tab\ p\ t\ k = None$

⟨proof⟩

lemma *filter-tab-dom-subset*: $dom\ (filter-tab\ C\ t) \subseteq dom\ t$

⟨proof⟩

lemma *filter-tab-eq*: $\llbracket a=b \rrbracket \implies filter-tab\ C\ a = filter-tab\ C\ b$

⟨proof⟩

lemma *finite-dom-filter-tab*:

$finite\ (dom\ t) \implies finite\ (dom\ (filter-tab\ C\ t))$
 ⟨proof⟩

lemma *filter-tab-weaken*:

$\llbracket \forall a \in t\ k: \exists b \in s\ k: P\ a\ b; \bigwedge k\ x\ y. \llbracket t\ k = Some\ x; s\ k = Some\ y \rrbracket \implies cond\ k\ x \longrightarrow cond\ k\ y \rrbracket \implies \forall a \in filter-tab\ cond\ t\ k: \exists b \in filter-tab\ cond\ s\ k: P\ a\ b$
 ⟨proof⟩

lemma *cond-override-filter*:

$\llbracket \bigwedge k\ old\ new. \llbracket s\ k = Some\ new; t\ k = Some\ old \rrbracket \implies (\neg\ overC\ new\ old \longrightarrow \neg\ filterC\ k\ new) \wedge (overC\ new\ old \longrightarrow filterC\ k\ old \longrightarrow filterC\ k\ new) \rrbracket \implies$

$cond\text{-}override\ overC\ (filter\text{-}tab\ filterC\ t)\ (filter\text{-}tab\ filterC\ s)$
 $=\ filter\text{-}tab\ filterC\ (cond\text{-}override\ overC\ t\ s)$
 <proof>

Misc

lemma *Ball-set-table*: $(\forall (x,y) \in set\ l.\ P\ x\ y) \implies \forall x.\ \forall y \in map\text{-}of\ l\ x:\ P\ x\ y$
 <proof>

lemma *Ball-set-tableD*:

$\llbracket (\forall (x,y) \in set\ l.\ P\ x\ y); x \in Option.set\ (table\text{-}of\ l\ xa) \rrbracket \implies P\ xa\ x$
 <proof>

declare *map-of-SomeD* [elim]

lemma *table-of-Some-in-set*:

$table\text{-}of\ l\ k = Some\ x \implies (k,x) \in set\ l$
 <proof>

lemma *set-get-eq*:

$unique\ l \implies (k,\ the\ (table\text{-}of\ l\ k)) \in set\ l = (table\text{-}of\ l\ k \neq None)$
 <proof>

lemma *inj-Pair-const2*: $inj\ (\lambda k.\ (k,\ C))$

<proof>

lemma *table-of-mapconst-SomeI*:

$\llbracket table\text{-}of\ t\ k = Some\ y';\ snd\ y=y';\ fst\ y=c \rrbracket \implies$
 $table\text{-}of\ (map\ (\lambda(k,x).\ (k,c,x))\ t)\ k = Some\ y$
 <proof>

lemma *table-of-mapconst-NoneI*:

$\llbracket table\text{-}of\ t\ k = None \rrbracket \implies$
 $table\text{-}of\ (map\ (\lambda(k,x).\ (k,c,x))\ t)\ k = None$
 <proof>

lemmas *table-of-map2-SomeI* = *inj-Pair-const2* [THEN *map-of-mapk-SomeI*]

lemma *table-of-map-SomeI*: $table\text{-}of\ t\ k = Some\ x \implies$

$table\text{-}of\ (map\ (\lambda(k,x).\ (k,\ f\ x))\ t)\ k = Some\ (f\ x)$
 <proof>

lemma *table-of-remap-SomeD*:

$table\text{-}of\ (map\ (\lambda((k,k'),x).\ (k,(k',x)))\ t)\ k = Some\ (k',x) \implies$
 $table\text{-}of\ t\ (k,\ k') = Some\ x$
 <proof>

lemma *table-of-mapf-Some*:

$\forall x\ y.\ f\ x = f\ y \longrightarrow x = y \implies$
 $table\text{-}of\ (map\ (\lambda(k,x).\ (k,f\ x))\ t)\ k = Some\ (f\ x) \implies table\text{-}of\ t\ k = Some\ x$

<proof>

lemma *table-of-mapf-SomeD* [dest!]:

table-of (map ($\lambda(k,x). (k, f x)$) t) k = Some z \implies ($\exists y \in \text{table-of } t \ k: z = f y$)
<proof>

lemma *table-of-mapf-NoneD* [dest!]:

table-of (map ($\lambda(k,x). (k, f x)$) t) k = None \implies (*table-of* t k = None)
<proof>

lemma *table-of-mapkey-SomeD* [dest!]:

table-of (map ($\lambda(k,x). ((k,C),x)$) t) (k,D) = Some x \implies C = D \wedge *table-of* t k = Some x
<proof>

lemma *table-of-mapkey-SomeD2* [dest!]:

table-of (map ($\lambda(k,x). ((k,C),x)$) t) ek = Some x \implies
 C = snd ek \wedge *table-of* t (fst ek) = Some x
<proof>

lemma *table-append-Some-iff*: *table-of* (xs@ys) k = Some z =

(*table-of* xs k = Some z \vee (*table-of* xs k = None \wedge *table-of* ys k = Some z))
<proof>

lemma *table-of-filter-unique-SomeD* [rule-format (no-asm)]:

table-of (filter P xs) k = Some z \implies unique xs \longrightarrow *table-of* xs k = Some z
<proof>

definition *Un-tables* :: ('a, 'b) tables set \Rightarrow ('a, 'b) tables

where *Un-tables* ts = ($\lambda k. \bigcup t \in ts. t \ k$)

definition *overrides-t* :: ('a, 'b) tables \Rightarrow ('a, 'b) tables \Rightarrow ('a, 'b) tables

(infixl $\oplus \oplus$ 100)

where $s \oplus \oplus t = (\lambda k. \text{if } t \ k = \{\} \text{ then } s \ k \text{ else } t \ k)$

definition

hidings-entails :: ('a, 'b) tables \Rightarrow ('a, 'c) tables \Rightarrow ('b \Rightarrow 'c \Rightarrow bool) \Rightarrow bool

(- hidings - entails - 20)

where (*t hidings s entails R*) = ($\forall k. \forall x \in t \ k. \forall y \in s \ k. R \ x \ y$)

definition

— variant for unique table:

hiding-entails :: ('a, 'b) table \Rightarrow ('a, 'c) table \Rightarrow ('b \Rightarrow 'c \Rightarrow bool) \Rightarrow bool

(- hiding - entails - 20)

where (*t hiding s entails R*) = ($\forall k. \forall x \in t \ k: \forall y \in s \ k: R \ x \ y$)

definition

— variant for a unique table and conditional overriding:

cond-hiding-entails :: ('a, 'b) table \Rightarrow ('a, 'c) table

\Rightarrow ('b \Rightarrow 'c \Rightarrow bool) \Rightarrow ('b \Rightarrow 'c \Rightarrow bool) \Rightarrow bool

(- hiding - under - entails - 20)

where (*t hiding s under C entails R*) = ($\forall k. \forall x \in t \ k: \forall y \in s \ k: C \ x \ y \longrightarrow R \ x \ y$)

Untables

lemma *Un-tablesI* [*intro*]: $t \in ts \implies x \in t k \implies x \in \text{Un-tables } ts k$
 ⟨*proof*⟩

lemma *Un-tablesD* [*dest!*]: $x \in \text{Un-tables } ts k \implies \exists t. t \in ts \wedge x \in t k$
 ⟨*proof*⟩

lemma *Un-tables-empty* [*simp*]: $\text{Un-tables } \{\} = (\lambda k. \{\})$
 ⟨*proof*⟩

overrides

lemma *empty-overrides-t* [*simp*]: $(\lambda k. \{\}) \oplus \oplus m = m$
 ⟨*proof*⟩

lemma *overrides-empty-t* [*simp*]: $m \oplus \oplus (\lambda k. \{\}) = m$
 ⟨*proof*⟩

lemma *overrides-t-Some-iff*:
 $(x \in (s \oplus \oplus t) k) = (x \in t k \vee t k = \{\} \wedge x \in s k)$
 ⟨*proof*⟩

lemmas *overrides-t-SomeD* = *overrides-t-Some-iff* [*THEN iffD1, dest!*]

lemma *overrides-t-right-empty* [*simp*]: $n k = \{\} \implies (m \oplus \oplus n) k = m k$
 ⟨*proof*⟩

lemma *overrides-t-find-right* [*simp*]: $n k \neq \{\} \implies (m \oplus \oplus n) k = n k$
 ⟨*proof*⟩

hiding entails

lemma *hiding-entailsD*:
 $t \text{ hiding } s \text{ entails } R \implies t k = \text{Some } x \implies s k = \text{Some } y \implies R x y$
 ⟨*proof*⟩

lemma *empty-hiding-entails* [*simp*]: *empty hiding s entails R*
 ⟨*proof*⟩

lemma *hiding-empty-entails* [*simp*]: *t hiding empty entails R*
 ⟨*proof*⟩

cond hiding entails

lemma *cond-hiding-entailsD*:
 $\llbracket t \text{ hiding } s \text{ under } C \text{ entails } R; t k = \text{Some } x; s k = \text{Some } y; C x y \rrbracket \implies R x y$
 ⟨*proof*⟩

lemma *empty-cond-hiding-entails* [*simp*]: *empty hiding s under C entails R*
 ⟨*proof*⟩

lemma *cond-hiding-empty-entails* [simp]: *t hiding empty under C entails R*
 ⟨proof⟩

lemma *hidings-entailsD*: $\llbracket t \text{ hidings } s \text{ entails } R; x \in t \ k; y \in s \ k \rrbracket \implies R \ x \ y$
 ⟨proof⟩

lemma *hidings-empty-entails* [intro!]: *t hidings* $(\lambda k. \{\})$ *entails R*
 ⟨proof⟩

lemma *empty-hidings-entails* [intro!]:
 $(\lambda k. \{\}) \text{ hidings } s \text{ entails } R$ ⟨proof⟩

primrec *atleast-free* :: $('a \rightsquigarrow 'b) \Rightarrow \text{nat} \Rightarrow \text{bool}$
where

atleast-free *m* 0 = *True*
 | *atleast-free-Suc*: *atleast-free* *m* (*Suc* *n*) = $(\exists a. m \ a = \text{None} \ \& \ (!b. \text{atleast-free} \ (m(a|-\>b)) \ n))$

lemma *atleast-free-weaken* [rule-format (no-asm)]:
 $!m. \text{atleast-free} \ m \ (\text{Suc} \ n) \longrightarrow \text{atleast-free} \ m \ n$
 ⟨proof⟩

lemma *atleast-free-SucI*:
 $\llbracket h \ a = \text{None}; !obj. \text{atleast-free} \ (h(a|-\>obj)) \ n \rrbracket \implies \text{atleast-free} \ h \ (\text{Suc} \ n)$
 ⟨proof⟩

declare *fun-upd-apply* [simp del]

lemma *atleast-free-SucD-lemma* [rule-format (no-asm)]:
 $!m \ a. m \ a = \text{None} \ \longrightarrow \ (!c. \text{atleast-free} \ (m(a|-\>c)) \ n) \ \longrightarrow$
 $(!b \ d. a \rightsquigarrow b \ \longrightarrow \ \text{atleast-free} \ (m(b|-\>d)) \ n)$
 ⟨proof⟩

declare *fun-upd-apply* [simp]

lemma *atleast-free-SucD*: *atleast-free* *h* (*Suc* *n*) $\implies \text{atleast-free} \ (h(a|-\>b)) \ n$
 ⟨proof⟩

declare *atleast-free-Suc* [simp del]

end

Chapter 4

Name

3 Java names

theory *Name* **imports** *Basis* **begin**

typedecl *tnam* — ordinary type name, i.e. class or interface name

typedecl *pname* — package name

typedecl *mname* — method name

typedecl *vname* — variable or field name

typedecl *label* — label as destination of break or continue

datatype *ename* — expression name

= *VNam vname*

| *Res* — special name to model the return value of methods

datatype *lname* — names for local variables and the This pointer

= *ENAME ename*

| *This*

abbreviation *VName* :: *vname* \Rightarrow *lname*

where *VName* *n* == *ENAME* (*VNam n*)

abbreviation *Result* :: *lname*

where *Result* == *ENAME Res*

datatype *xname* — names of standard exceptions

= *Throwable*

| *NullPointerException* | *OutOfMemory* | *ClassCast*

| *NegArrSize* | *IndOutBound* | *ArrStore*

lemma *xn-cases*:

xn = *Throwable* \vee *xn* = *NullPointerException* \vee

xn = *OutOfMemory* \vee *xn* = *ClassCast* \vee

xn = *NegArrSize* \vee *xn* = *IndOutBound* \vee *xn* = *ArrStore*

\langle *proof* \rangle

datatype *tname* — type names for standard classes and other type names

= *Object'*

| *SXcpt'* *xname*

| *TName* *tnam*

record *qtname* = — qualified tname cf. 6.5.3, 6.5.4

pid :: *pname*

tid :: *tname*

class *has-pname* =

fixes *pname* :: '*a* \Rightarrow *pname*

instantiation *pname* :: *has-pname*

begin

definition

pname-pname-def: *pname* (*p*::*pname*) \equiv *p*

instance \langle *proof* \rangle

end

```

class has-tname =
  fixes tname :: 'a  $\Rightarrow$  tname

instantiation tname :: has-tname
begin

definition
  tname-tname-def: tname (t::tname) = t

instance  $\langle$ proof $\rangle$ 

end

definition
  qname-qname-def: qname (q::'a qname-scheme) = q

translations
  (type) qname <= (type) ( $\lfloor$ pid::pname,tid::tname $\rfloor$ )
  (type) 'a qname-scheme <= (type) ( $\lfloor$ pid::pname,tid::tname,...::'a $\rfloor$ )

axiomatization java-lang::pname — package java.lang

definition
  Object :: qname
  where Object = ( $\lfloor$ pid = java-lang, tid = Object $\rfloor$ )

definition SXcpt :: xname  $\Rightarrow$  qname
  where SXcpt = ( $\lambda x$ . ( $\lfloor$ pid = java-lang, tid = SXcpt ' x $\rfloor$ ))

lemma Object-neq-SXcpt [simp]: Object  $\neq$  SXcpt xn
 $\langle$ proof $\rangle$ 

lemma SXcpt-inject [simp]: (SXcpt xn = SXcpt xm) = (xn = xm)
 $\langle$ proof $\rangle$ 

end

```


Chapter 5

Value

4 Java values

theory *Value* **imports** *Type* **begin**

typedecl *loc* — locations, i.e. abstract references on objects

datatype *val*

= *Unit* — dummy result value of void methods
 | *Bool bool* — Boolean value
 | *Intg int* — integer value
 | *Null* — null reference
 | *Addr loc* — addresses, i.e. locations of objects

primrec *the-Bool* :: *val* \Rightarrow *bool*
where *the-Bool* (*Bool b*) = *b*

primrec *the-Intg* :: *val* \Rightarrow *int*
where *the-Intg* (*Intg i*) = *i*

primrec *the-Addr* :: *val* \Rightarrow *loc*
where *the-Addr* (*Addr a*) = *a*

type-synonym *dyn-ty* = *loc* \Rightarrow *ty option*

primrec *typeof* :: *dyn-ty* \Rightarrow *val* \Rightarrow *ty option*
where

typeof dt Unit = *Some (PrimT Void)*
 | *typeof dt (Bool b)* = *Some (PrimT Boolean)*
 | *typeof dt (Intg i)* = *Some (PrimT Integer)*
 | *typeof dt Null* = *Some NT*
 | *typeof dt (Addr a)* = *dt a*

primrec *defpval* :: *prim-ty* \Rightarrow *val* — default value for primitive types
where

defpval Void = *Unit*
 | *defpval Boolean* = *Bool False*
 | *defpval Integer* = *Intg 0*

primrec *default-val* :: *ty* \Rightarrow *val* — default value for all types
where

default-val (PrimT pt) = *defpval pt*
 | *default-val (RefT r)* = *Null*

end

Chapter 6

Type

5 Java types

theory *Type* **imports** *Name* **begin**

simplifications:

- only the most important primitive types
- the null type is regarded as reference type

datatype *prim-ty* — primitive type, cf. 4.2
 = *Void* — result type of void methods
 | *Boolean*
 | *Integer*

datatype *ref-ty* — reference type, cf. 4.3
 = *NullT* — null type, cf. 4.1
 | *IfaceT qname* — interface type
 | *ClassT qname* — class type
 | *ArrayT ty* — array type

and *ty* — any type, cf. 4.1
 = *PrimT prim-ty* — primitive type
 | *RefT ref-ty* — reference type

abbreviation *NT* == *RefT NullT*

abbreviation *Iface I* == *RefT (IfaceT I)*

abbreviation *Class C* == *RefT (ClassT C)*

abbreviation *Array :: ty* \Rightarrow *ty* (-.[[90] 90)
where *T.[* == *RefT (ArrayT T)*

definition

the-Class :: *ty* \Rightarrow *qname*

where *the-Class T* = (*SOME C. T* = *Class C*)

lemma *the-Class-eq [simp]*: *the-Class (Class C)* = *C*
 <proof>

end

Chapter 7

Term

6 Java expressions and statements

theory *Term* **imports** *Value Table* **begin**

design issues:

- invocation frames for local variables could be reduced to special static objects (one per method). This would reduce redundancy, but yield a rather non-standard execution model more difficult to understand.
- method bodies separated from calls to handle assumptions in axiomat. semantics NB: Body is intended to be in the environment of the called method.
- class initialization is regarded as (auxiliary) statement (required for AxSem)
- result expression of method return is handled by a special result variable result variable is treated uniformly with local variables
 - + welltypedness and existence of the result/return expression is ensured without extra effort

simplifications:

- expression statement allowed for any expression
- This is modeled as a special non-assignable local variable
- Super is modeled as a general expression with the same value as This
- access to field x in current class via This.x
- NewA creates only one-dimensional arrays; initialization of further subarrays may be simulated with nested NewAs
- The 'Lit' constructor is allowed to contain a reference value. But this is assumed to be prohibited in the input language, which is enforced by the type-checking rules.
- a call of a static method via a type name may be simulated by a dummy variable
- no nested blocks with inner local variables
- no synchronized statements
- no secondary forms of if, while (e.g. no for) (may be easily simulated)
- no switch (may be simulated with if)
- the *try-catch-finally* statement is divided into the *try-catch* statement and a finally statement, which may be considered as try..finally with empty catch
- the *try-catch* statement has exactly one catch clause; multiple ones can be simulated with instanceof
- the compiler is supposed to add the annotations - during type-checking. This transformation is left out as its result is checked by the type rules anyway

type-synonym *locals* = (*lname, val*) *table* — local variables

datatype *jump*
= *Break label* — break

| *Cont label* — continue
 | *Ret* — return from method

datatype *xcpt* — exception
 = *Loc loc* — location of allocated exception object
 | *Std xname* — intermediate standard exception, see Eval.thy

datatype *error*
 = *AccessViolation* — Access to a member that isn't permitted
 | *CrossMethodJump* — Method exits with a break or continue

datatype *abrupt* — abrupt completion
 = *Xcpt xcpt* — exception
 | *Jump jump* — break, continue, return
 | *Error error* — runtime errors, we wan't to detect and proof absent in welltyped programm

type-synonym

abopt = *abrupt option*

Local variable store and exception. Anticipation of State.thy used by smallstep semantics. For a method call, we save the local variables of the caller in the term Callee to restore them after method return. Also an exception must be restored after the finally statement

translations

$(type) locals \leq (type) (lname, val) table$

datatype *inv-mode* — invocation mode for method calls
 = *Static* — static
 | *SuperM* — super
 | *IntVir* — interface or virtual

record *sig* = — signature of a method, cf. 8.4.2
name :: mname — acutally belongs to Decl.thy
parTs :: ty list

translations

$(type) sig \leq (type) (\{name :: mname, parTs :: ty list\})$
 $(type) sig \leq (type) (\{name :: mname, parTs :: ty list, \dots :: 'a\})$

— function codes for unary operations

datatype *unop* = *UPlus* — + unary plus
 | *UMinus* — - unary minus
 | *UBitNot* — bitwise NOT
 | *UNot* — ! logical complement

— function codes for binary operations

datatype *binop* = *Mul* — * multiplication
 | *Div* — / division
 | *Mod* — % remainder
 | *Plus* — + addition
 | *Minus* — - subtraction
 | *LShift* — << left shift
 | *RShift* — >> signed right shift
 | *RShiftU* — >>> unsigned right shift
 | *Less* — < less than
 | *Le* — <= less than or equal
 | *Greater* — > greater than
 | *Ge* — >= greater than or equal
 | *Eq* — == equal
 | *Neq* — != not equal

```

| BitAnd — & bitwise AND
| And — & boolean AND
| BitXor — ^ bitwise Xor
| Xor — ^ boolean Xor
| BitOr — | bitwise Or
| Or — | boolean Or
| CondAnd — && conditional And
| CondOr — || conditional Or

```

The boolean operators `&` and `|` strictly evaluate both of their arguments. The conditional operators `&&` and `||` only evaluate the second argument if the value of the whole expression isn't already determined by the first argument. e.g.: `false && e` `e` is not evaluated; `true || e` `e` is not evaluated;

datatype *var*

```

= LVar lname — local variable (incl. parameters)
| FVar qname qname bool expr vname ({-,,-}--[10,10,10,85,99]90)
  — class field
  — {accC,statDeclC,stat}e.fn
  — accC: accessing class (static class were
  — the code is declared. Annotation only needed for
  — evaluation to check accessibility)
  — statDeclC: static declaration class of field
  — stat: static or instance field?
  — e: reference to object
  — fn: field name
| AVar expr expr (-.[-][90,10 ]90)
  — array component
  — e1.[e2]: e1 array reference; e2 index
| InsInitV stmt var
  — insertion of initialization before evaluation
  — of var (technical term for smallstep semantics.)

```

and *expr*

```

= NewC qname — class instance creation
| NewA ty expr (New [-][99,10 ]85)
  — array creation
| Cast ty expr — type cast
| Inst expr ref-ty (- InstOf [-[85,99] 85)
  — instanceof
| Lit val — literal value, references not allowed
| UnOp unop expr — unary operation
| BinOp binop expr expr — binary operation

| Super — special Super keyword
| Acc var — variable access
| Ass var expr (-:= [-[90,85 ]85)
  — variable assign
| Cond expr expr expr (- ? - : - [85,85,80]80) — conditional
| Call qname ref-ty inv-mode expr mname (ty list) (expr list)
  ({-,,-}--({-}-')[10,10,10,85,99,10,10]85)
  — method call
  — {accC,statT,mode}e.mn( {pTs}args ) ”
  — accC: accessing class (static class were
  — the call code is declared. Annotation only needed for
  — evaluation to check accessibility)
  — statT: static declaration class/interface of
  — method
  — mode: invocation mode
  — e: reference to object

```

— *mn*: field name
 — *pTs*: types of parameters
 — *args*: the actual parameters/arguments
 | *Methd qname sig* — (folded) method (see below)
 | *Body qname stmt* — (unfolded) method body
 | *InsInitE stmt expr*
 — insertion of initialization before
 — evaluation of *expr* (technical term for smallstep sem.)
 | *Callee locals expr* — save callers locals in callee-Frame
 — (technical term for smallstep semantics)
and *stmt*
 = *Skip* — empty statement
 | *Expr expr* — expression statement
 | *Lab jump stmt* ($\cdot - [99,66]66$)
 — labeled statement; handles break
 | *Comp stmt stmt* ($\cdot - [66,65]65$)
 | *If' expr stmt stmt* (*If'(-)* - *Else* - $[80,79,79]70$)
 | *Loop label expr stmt* (\cdot *While'(-)* - $[99,80,79]70$)
 | *Jmp jump* — break, continue, return
 | *Throw expr*
 | *TryC stmt qname vname stmt* (*Try* - *Catch'(-)* - $[79,99,80,79]70$)
 — *Try c1 Catch(C vn) c2*
 — *c1*: block were exception may be thrown
 — *C*: exception class to catch
 — *vn*: local name for exception used in *c2*
 — *c2*: block to execute when exception is cateched
 | *Fin stmt stmt* (*Finally* - $[79,79]70$)
 | *FinA abopt stmt* — Save abrupton of first statement
 — technical term for smallstep sem.)
 | *Init qname* — class initialization

The expressions *Methd* and *Body* are artificial program constructs, in the sense that they are not used to define a concrete Bali program. In the operational semantic's they are "generated on the fly" to decompose the task to define the behaviour of the *Call* expression. They are crucial for the axiomatic semantics to give a syntactic hook to insert some assertions (cf. *AxSem.thy*, *Eval.thy*). The *Init* statement (to initialize a class on its first use) is inserted in various places by the semantics. *Callee*, *InsInitV*, *InsInitE*, *FinA* are only needed as intermediate steps in the smallstep (transition) semantics (cf. *Trans.thy*). *Callee* is used to save the local variables of the caller for method return. So ve avoid modelling a frame stack. The *InsInitV/E* terms are only used by the smallstep semantics to model the intermediate steps of class-initialisation.

type-synonym *term* = (*expr+stmt,var,expr list*) *sum3*

translations

(*type*) *sig* <= (*type*) *mname* × *ty list*

(*type*) *term* <= (*type*) (*expr+stmt,var,expr list*) *sum3*

abbreviation *this* :: *expr*

where *this* == *Acc (LVar This)*

abbreviation *LAcc* :: *vname* ⇒ *expr* (!!)

where !!*v* == *Acc (LVar (ENAME (VName v)))*

abbreviation

LAss :: *vname* ⇒ *expr* ⇒ *stmt* (\cdot == $[90,85]85$)

where *v::=e* == *Expr (Ass (LVar (ENAME (VName v))) e)*

abbreviation

Return :: *expr* ⇒ *stmt*

where *Return e* == *Expr (Ass (LVar (ENAME Res)) e);; Jmp Ret — Res := e;; Jmp Ret*

abbreviation

```
StatRef :: ref-ty ⇒ expr
where StatRef rt == Cast (RefT rt) (Lit Null)
```

definition

```
is-stmt :: term ⇒ bool
where is-stmt t = (∃ c. t=In1r c)
```

⟨ML⟩

```
declare is-stmt-rews [simp]
```

Here is some syntactic stuff to handle the injections of statements, expressions, variables and expression lists into general terms.

abbreviation (input)

```
expr-inj-term :: expr ⇒ term (⟨-⟩e 1000)
where ⟨e⟩e == In1l e
```

abbreviation (input)

```
stmt-inj-term :: stmt ⇒ term (⟨-⟩s 1000)
where ⟨c⟩s == In1r c
```

abbreviation (input)

```
var-inj-term :: var ⇒ term (⟨-⟩v 1000)
where ⟨v⟩v == In2 v
```

abbreviation (input)

```
lst-inj-term :: expr list ⇒ term (⟨-⟩l 1000)
where ⟨es⟩l == In3 es
```

It seems to be more elegant to have an overloaded injection like the following.

```
class inj-term =
  fixes inj-term:: 'a ⇒ term (⟨-⟩ 1000)
```

How this overloaded injections work can be seen in the theory *DefiniteAssignment*. Other big inductive relations on terms defined in theories *WellType*, *Eval*, *Evaln* and *AxSem* don't follow this convention right now, but introduce subtle syntactic sugar in the relations themselves to make a distinction on expressions, statements and so on. So unfortunately you will encounter a mixture of dealing with these injections. The abbreviations above are used as bridge between the different conventions.

```
instantiation stmt :: inj-term
```

```
begin
```

definition

```
stmt-inj-term-def: ⟨c::stmt⟩ = In1r c
```

```
instance ⟨proof⟩
```

```
end
```

```
lemma stmt-inj-term-simp: ⟨c::stmt⟩ = In1r c
```

```
⟨proof⟩
```

```
lemma stmt-inj-term [iff]: ⟨x::stmt⟩ = ⟨y⟩ ≡ x = y
```

<proof>

instantiation *expr :: inj-term*
begin

definition

expr-inj-term-def: $\langle e::\text{expr} \rangle = \text{In1 } e$

instance *<proof>*

end

lemma *expr-inj-term-simp*: $\langle e::\text{expr} \rangle = \text{In1 } e$

<proof>

lemma *expr-inj-term [iff]*: $\langle x::\text{expr} \rangle = \langle y \rangle \equiv x = y$

<proof>

instantiation *var :: inj-term*

begin

definition

var-inj-term-def: $\langle v::\text{var} \rangle = \text{In2 } v$

instance *<proof>*

end

lemma *var-inj-term-simp*: $\langle v::\text{var} \rangle = \text{In2 } v$

<proof>

lemma *var-inj-term [iff]*: $\langle x::\text{var} \rangle = \langle y \rangle \equiv x = y$

<proof>

class *expr-of =*

fixes *expr-of :: 'a \Rightarrow expr*

instantiation *expr :: expr-of*

begin

definition

expr-of = $(\lambda(e::\text{expr}). e)$

instance *<proof>*

end

instantiation *list :: (expr-of) inj-term*

begin

definition

<es::'a list> = $\text{In3 } (\text{map } \text{expr-of } \text{es})$

instance *<proof>*

end

lemma *expr-list-inj-term-def*:

$\langle es::\text{expr list} \rangle \equiv \text{In3 } es$
 $\langle \text{proof} \rangle$

lemma *expr-list-inj-term-simp*: $\langle es::\text{expr list} \rangle = \text{In3 } es$

$\langle \text{proof} \rangle$

lemma *expr-list-inj-term* [iff]: $\langle x::\text{expr list} \rangle = \langle y \rangle \equiv x = y$

$\langle \text{proof} \rangle$

lemmas *inj-term-simps* = *stmt-inj-term-simp* *expr-inj-term-simp* *var-inj-term-simp*
expr-list-inj-term-simp

lemmas *inj-term-sym-simps* = *stmt-inj-term-simp* [THEN *sym*]
expr-inj-term-simp [THEN *sym*]
var-inj-term-simp [THEN *sym*]
expr-list-inj-term-simp [THEN *sym*]

lemma *stmt-expr-inj-term* [iff]: $\langle t::\text{stmt} \rangle \neq \langle w::\text{expr} \rangle$

$\langle \text{proof} \rangle$

lemma *expr-stmt-inj-term* [iff]: $\langle t::\text{expr} \rangle \neq \langle w::\text{stmt} \rangle$

$\langle \text{proof} \rangle$

lemma *stmt-var-inj-term* [iff]: $\langle t::\text{stmt} \rangle \neq \langle w::\text{var} \rangle$

$\langle \text{proof} \rangle$

lemma *var-stmt-inj-term* [iff]: $\langle t::\text{var} \rangle \neq \langle w::\text{stmt} \rangle$

$\langle \text{proof} \rangle$

lemma *stmt-elist-inj-term* [iff]: $\langle t::\text{stmt} \rangle \neq \langle w::\text{expr list} \rangle$

$\langle \text{proof} \rangle$

lemma *elist-stmt-inj-term* [iff]: $\langle t::\text{expr list} \rangle \neq \langle w::\text{stmt} \rangle$

$\langle \text{proof} \rangle$

lemma *expr-var-inj-term* [iff]: $\langle t::\text{expr} \rangle \neq \langle w::\text{var} \rangle$

$\langle \text{proof} \rangle$

lemma *var-expr-inj-term* [iff]: $\langle t::\text{var} \rangle \neq \langle w::\text{expr} \rangle$

$\langle \text{proof} \rangle$

lemma *expr-elist-inj-term* [iff]: $\langle t::\text{expr} \rangle \neq \langle w::\text{expr list} \rangle$

$\langle \text{proof} \rangle$

lemma *elist-expr-inj-term* [iff]: $\langle t::\text{expr list} \rangle \neq \langle w::\text{expr} \rangle$

$\langle \text{proof} \rangle$

lemma *var-elist-inj-term* [iff]: $\langle t::\text{var} \rangle \neq \langle w::\text{expr list} \rangle$

$\langle \text{proof} \rangle$

lemma *elist-var-inj-term* [iff]: $\langle t::\text{expr list} \rangle \neq \langle w::\text{var} \rangle$

$\langle \text{proof} \rangle$

lemma *term-cases*:

$$\llbracket \bigwedge v. P \langle v \rangle_v; \bigwedge e. P \langle e \rangle_e; \bigwedge c. P \langle c \rangle_s; \bigwedge l. P \langle l \rangle_l \rrbracket \\ \implies P t \\ \langle \text{proof} \rangle$$

Evaluation of unary operations

primrec *eval-unop* :: *unop* \Rightarrow *val* \Rightarrow *val*

where

$$\begin{aligned} & \text{eval-unop } UPlus \ v = \text{Intg } (\text{the-Intg } v) \\ & | \text{eval-unop } UMinus \ v = \text{Intg } (- (\text{the-Intg } v)) \\ & | \text{eval-unop } UBitNot \ v = \text{Intg } 42 \quad \text{--- FIXME: Not yet implemented} \\ & | \text{eval-unop } UNot \ v = \text{Bool } (\neg \text{the-Bool } v) \end{aligned}$$

Evaluation of binary operations

primrec *eval-binop* :: *binop* \Rightarrow *val* \Rightarrow *val* \Rightarrow *val*

where

$$\begin{aligned} & \text{eval-binop } Mul \quad v1 \ v2 = \text{Intg } ((\text{the-Intg } v1) * (\text{the-Intg } v2)) \\ & | \text{eval-binop } Div \quad v1 \ v2 = \text{Intg } ((\text{the-Intg } v1) \text{ div } (\text{the-Intg } v2)) \\ & | \text{eval-binop } Mod \quad v1 \ v2 = \text{Intg } ((\text{the-Intg } v1) \text{ mod } (\text{the-Intg } v2)) \\ & | \text{eval-binop } Plus \quad v1 \ v2 = \text{Intg } ((\text{the-Intg } v1) + (\text{the-Intg } v2)) \\ & | \text{eval-binop } Minus \quad v1 \ v2 = \text{Intg } ((\text{the-Intg } v1) - (\text{the-Intg } v2)) \end{aligned}$$

— Be aware of the explicit coercion of the shift distance to nat

$$\begin{aligned} & | \text{eval-binop } LShift \ v1 \ v2 = \text{Intg } ((\text{the-Intg } v1) * (2^{(\text{nat } (\text{the-Intg } v2))})) \\ & | \text{eval-binop } RShift \ v1 \ v2 = \text{Intg } ((\text{the-Intg } v1) \text{ div } (2^{(\text{nat } (\text{the-Intg } v2))})) \\ & | \text{eval-binop } RShiftU \ v1 \ v2 = \text{Intg } 42 \quad \text{--- FIXME: Not yet implemented} \end{aligned}$$

$$\begin{aligned} & | \text{eval-binop } Less \quad v1 \ v2 = \text{Bool } ((\text{the-Intg } v1) < (\text{the-Intg } v2)) \\ & | \text{eval-binop } Le \quad v1 \ v2 = \text{Bool } ((\text{the-Intg } v1) \leq (\text{the-Intg } v2)) \\ & | \text{eval-binop } Greater \ v1 \ v2 = \text{Bool } ((\text{the-Intg } v2) < (\text{the-Intg } v1)) \\ & | \text{eval-binop } Ge \quad v1 \ v2 = \text{Bool } ((\text{the-Intg } v2) \leq (\text{the-Intg } v1)) \end{aligned}$$

$$\begin{aligned} & | \text{eval-binop } Eq \quad v1 \ v2 = \text{Bool } (v1=v2) \\ & | \text{eval-binop } Neq \quad v1 \ v2 = \text{Bool } (v1 \neq v2) \\ & | \text{eval-binop } BitAnd \ v1 \ v2 = \text{Intg } 42 \quad \text{--- FIXME: Not yet implemented} \\ & | \text{eval-binop } And \quad v1 \ v2 = \text{Bool } ((\text{the-Bool } v1) \wedge (\text{the-Bool } v2)) \\ & | \text{eval-binop } BitXor \ v1 \ v2 = \text{Intg } 42 \quad \text{--- FIXME: Not yet implemented} \\ & | \text{eval-binop } Xor \quad v1 \ v2 = \text{Bool } ((\text{the-Bool } v1) \neq (\text{the-Bool } v2)) \\ & | \text{eval-binop } BitOr \quad v1 \ v2 = \text{Intg } 42 \quad \text{--- FIXME: Not yet implemented} \\ & | \text{eval-binop } Or \quad v1 \ v2 = \text{Bool } ((\text{the-Bool } v1) \vee (\text{the-Bool } v2)) \\ & | \text{eval-binop } CondAnd \ v1 \ v2 = \text{Bool } ((\text{the-Bool } v1) \wedge (\text{the-Bool } v2)) \\ & | \text{eval-binop } CondOr \ v1 \ v2 = \text{Bool } ((\text{the-Bool } v1) \vee (\text{the-Bool } v2)) \end{aligned}$$

definition

$$\begin{aligned} & \text{need-second-arg} :: \text{binop} \Rightarrow \text{val} \Rightarrow \text{bool} \text{ where} \\ & \text{need-second-arg } \text{binop } v1 = (\neg ((\text{binop}=\text{CondAnd} \wedge \neg \text{the-Bool } v1) \vee \\ & \quad (\text{binop}=\text{CondOr} \wedge \text{the-Bool } v1))) \end{aligned}$$

CondAnd and *CondOr* only evaluate the second argument if the value isn't already determined by the first argument

lemma *need-second-arg-CondAnd* [*simp*]: *need-second-arg* *CondAnd* (*Bool* *b*) = *b*
 $\langle \text{proof} \rangle$

lemma *need-second-arg-CondOr* [*simp*]: *need-second-arg* *CondOr* (*Bool* *b*) = (\neg *b*)
 $\langle \text{proof} \rangle$

```
lemma need-second-arg-strict[simp]:  
   $\llbracket \text{binop} \neq \text{CondAnd}; \text{binop} \neq \text{CondOr} \rrbracket \implies \text{need-second-arg binop } b$   
   $\langle \text{proof} \rangle$   
end
```

Chapter 8

Decl

7 Field, method, interface, and class declarations, whole Java programs

theory *Decl*

imports *Term Table*

begin

improvements:

- clarification and correction of some aspects of the package/access concept (Also submitted as bug report to the Java Bug Database: Bug Id: 4485402 and Bug Id: 4493343 <http://developer.java.sun.com>)

simplifications:

- the only field and method modifiers are static and the access modifiers
- no constructors, which may be simulated by new + suitable methods
- there is just one global initializer per class, which can simulate all others
- no throws clause
- a void method is replaced by one that returns Unit (of dummy type Void)
- no interface fields
- every class has an explicit superclass (unused for Object)
- the (standard) methods of Object and of standard exceptions are not specified
- no main method

8 Modifier

Access modifier

datatype *acc-modi*

= *Private* | *Package* | *Protected* | *Public*

We can define a linear order for the access modifiers. With Private yielding the most restrictive access and public the most liberal access policy: Private \leq Package \leq Protected \leq Public

instantiation *acc-modi* :: *linorder*

begin

definition

less-acc-def: $a < b$

\longleftrightarrow (case a of

| *Private* $\Rightarrow (b = \text{Package} \vee b = \text{Protected} \vee b = \text{Public})$

| *Package* $\Rightarrow (b = \text{Protected} \vee b = \text{Public})$

| *Protected* $\Rightarrow (b = \text{Public})$

| *Public* $\Rightarrow \text{False}$)

definition

le-acc-def: $(a :: \text{acc-modi}) \leq b \longleftrightarrow a < b \vee a = b$

instance

<proof>

Static Modifier

type-synonym *stat-modi* = *bool*

9 Declaration (base "class" for member, interface and class declarations)

record *decl* =
 access :: *acc-modi*

translations

(*type*) *decl* <= (*type*) (|*access*::*acc-modi*|)
 (*type*) *decl* <= (*type*) (|*access*::*acc-modi*,...::'*a*'|)

10 Member (field or method)

record *member* = *decl* +
 static :: *stat-modi*

translations

(*type*) *member* <= (*type*) (|*access*::*acc-modi*,*static*::*bool*|)
 (*type*) *member* <= (*type*) (|*access*::*acc-modi*,*static*::*bool*,...::'*a*'|)

11 Field

record *field* = *member* +
 type :: *ty*

translations

(*type*) *field* <= (*type*) (|*access*::*acc-modi*, *static*::*bool*, *type*::*ty*|)
 (*type*) *field* <= (*type*) (|*access*::*acc-modi*, *static*::*bool*, *type*::*ty*,...::'*a*'|)

type-synonym *fdecl*
 = *vname* × *field*

translations

(*type*) *fdecl* <= (*type*) *vname* × *field*

12 Method

record *mhead* = *member* +
 pars :: *vname list*
 resT :: *ty*

record *mbody* =
 lcls:: (*vname* × *ty*) *list*
 stmt:: *stmt*

record *methd* = *mhead* +
 mbody::*mbody*

type-synonym *mdecl* = *sig* × *methd*

translations

(*type*) *mhead* <= (*type*) (|*access*::*acc-modi*, *static*::*bool*,
 pars::*vname list*, *resT*::*ty*|)
 (*type*) *mhead* <= (*type*) (|*access*::*acc-modi*, *static*::*bool*,
 pars::*vname list*, *resT*::*ty*,...::'*a*'|)
 (*type*) *mbody* <= (*type*) (|*lcls*::(*vname* × *ty*) *list*,*stmt*::*stmt*|)
 (*type*) *mbody* <= (*type*) (|*lcls*::(*vname* × *ty*) *list*,*stmt*::*stmt*,...::'*a*'|)

```

(type) methd <= (type) (|access::acc-modi, static::bool,
                        pars::vname list, resT::ty, mbody::mbody|)
(type) methd <= (type) (|access::acc-modi, static::bool,
                        pars::vname list, resT::ty, mbody::mbody, ...::'a|)
(type) mdecl <= (type) sig × methd

```

definition

```

mhead :: methd ⇒ mhead
where mhead m = (|access=access m, static=static m, pars=pars m, resT=resT m|)

```

```

lemma access-mhead [simp]: access (mhead m) = access m
⟨proof⟩

```

```

lemma static-mhead [simp]: static (mhead m) = static m
⟨proof⟩

```

```

lemma pars-mhead [simp]: pars (mhead m) = pars m
⟨proof⟩

```

```

lemma resT-mhead [simp]: resT (mhead m) = resT m
⟨proof⟩

```

To be able to talk uniformly about field and method declarations we introduce the notion of a member declaration (e.g. useful to define accessibility)

```

datatype memberdecl = fdecl fdecl | mdecl mdecl

```

```

datatype memberid = fid vname | mid sig

```

```

class has-memberid =
  fixes memberid :: 'a ⇒ memberid

```

```

instantiation memberdecl :: has-memberid
begin

```

definition

```

memberdecl-memberid-def:
  memberid m = (case m of
                fdecl (vn,f) ⇒ fid vn
                | mdecl (sig,m) ⇒ mid sig)

```

```

instance ⟨proof⟩

```

```

end

```

```

lemma memberid-fdecl-simp [simp]: memberid (fdecl (vn,f)) = fid vn
⟨proof⟩

```

```

lemma memberid-fdecl-simp1: memberid (fdecl f) = fid (fst f)
⟨proof⟩

```

```

lemma memberid-mdecl-simp [simp]: memberid (mdecl (sig,m)) = mid sig

```

$\langle proof \rangle$

lemma *memberid-mdecl-simp1*: $memberid (mdecl\ m) = mid (fst\ m)$

$\langle proof \rangle$

instantiation *prod* :: (*type*, *has-memberid*) *has-memberid*

begin

definition

pair-memberid-def:

$memberid\ p = memberid (snd\ p)$

instance $\langle proof \rangle$

end

lemma *memberid-pair-simp*[*simp*]: $memberid (c,m) = memberid\ m$

$\langle proof \rangle$

lemma *memberid-pair-simp1*: $memberid\ p = memberid (snd\ p)$

$\langle proof \rangle$

definition

is-field :: *qname* \times *memberdecl* \Rightarrow *bool*

where *is-field* *m* = $(\exists\ declC\ f.\ m=(declC,fdecl\ f))$

lemma *is-fieldD*: $is-field\ m \Longrightarrow \exists\ declC\ f.\ m=(declC,fdecl\ f)$

$\langle proof \rangle$

lemma *is-fieldI*: $is-field (C,fdecl\ f)$

$\langle proof \rangle$

definition

is-method :: *qname* \times *memberdecl* \Rightarrow *bool*

where *is-method* *membr* = $(\exists\ declC\ m.\ membr=(declC,mdecl\ m))$

lemma *is-methodD*: $is-method\ membr \Longrightarrow \exists\ declC\ m.\ membr=(declC,mdecl\ m)$

$\langle proof \rangle$

lemma *is-methodI*: $is-method (C,mdecl\ m)$

$\langle proof \rangle$

13 Interface

record *ibody* = *decl* + — interface body

imethods :: (*sig* \times *mhead*) *list* — method heads

record *iface* = *ibody* + — interface

isuperIfs:: *qname list* — superinterface list

type-synonym

idecl — interface declaration, cf. 9.1

= *qname* \times *iface*

translations

$(type) \text{ ibody} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{imethods}::(\text{sig} \times \text{mhead}) \text{ list})$
 $(type) \text{ ibody} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{imethods}::(\text{sig} \times \text{mhead}) \text{ list}, \dots::'a)$
 $(type) \text{ iface} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{imethods}::(\text{sig} \times \text{mhead}) \text{ list},$
 $\quad \text{isuperIfs}::\text{qtname list})$
 $(type) \text{ iface} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{imethods}::(\text{sig} \times \text{mhead}) \text{ list},$
 $\quad \text{isuperIfs}::\text{qtname list}, \dots::'a)$
 $(type) \text{ idecl} \leq (type) \text{ qtname} \times \text{ iface}$

definition

$\text{ibody} :: \text{iface} \Rightarrow \text{ibody}$
where $\text{ibody } i = (\downarrow \text{access}=\text{access } i, \text{imethods}=\text{imethods } i)$

lemma $\text{access-ibody [simp]}$: $(\text{access } (\text{ibody } i)) = \text{access } i$
 $\langle \text{proof} \rangle$

lemma $\text{imethods-ibody [simp]}$: $(\text{imethods } (\text{ibody } i)) = \text{imethods } i$
 $\langle \text{proof} \rangle$

14 Class

record $\text{cbody} = \text{decl} + \quad \text{--- class body}$
 $\text{cfields}:: \text{fdecl list}$
 $\text{methods}:: \text{mdecl list}$
 $\text{init} :: \text{stmt} \quad \text{--- initializer}$

record $\text{class} = \text{cbody} + \quad \text{--- class}$
 $\text{super} :: \text{qtname} \quad \text{--- superclass}$
 $\text{superIfs}:: \text{qtname list} \quad \text{--- implemented interfaces}$

type-synonym

$\text{cdecl} \quad \text{--- class declaration, cf. 8.1}$
 $= \text{qtname} \times \text{class}$

translations

$(type) \text{ cbody} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{cfields}::\text{fdecl list},$
 $\quad \text{methods}::\text{mdecl list}, \text{init}::\text{stmt})$
 $(type) \text{ cbody} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{cfields}::\text{fdecl list},$
 $\quad \text{methods}::\text{mdecl list}, \text{init}::\text{stmt}, \dots::'a)$
 $(type) \text{ class} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{cfields}::\text{fdecl list},$
 $\quad \text{methods}::\text{mdecl list}, \text{init}::\text{stmt},$
 $\quad \text{super}::\text{qtname}, \text{superIfs}::\text{qtname list})$
 $(type) \text{ class} \leq (type) (\downarrow \text{access}::\text{acc-modi}, \text{cfields}::\text{fdecl list},$
 $\quad \text{methods}::\text{mdecl list}, \text{init}::\text{stmt},$
 $\quad \text{super}::\text{qtname}, \text{superIfs}::\text{qtname list}, \dots::'a)$
 $(type) \text{ cdecl} \leq (type) \text{ qtname} \times \text{class}$

definition

$\text{cbody} :: \text{class} \Rightarrow \text{cbody}$
where $\text{cbody } c = (\downarrow \text{access}=\text{access } c, \text{cfields}=\text{cfields } c, \text{methods}=\text{methods } c, \text{init}=\text{init } c)$

lemma $\text{access-cbody [simp]}$: $\text{access } (\text{cbody } c) = \text{access } c$
 $\langle \text{proof} \rangle$

lemma $\text{cfields-cbody [simp]}$: $\text{cfields } (\text{cbody } c) = \text{cfields } c$

<proof>

lemma *methods-cbody* [simp]: $methods\ (cbody\ c) = methods\ c$
<proof>

lemma *init-cbody* [simp]: $init\ (cbody\ c) = init\ c$
<proof>

standard classes

consts

Object-mdecls :: *mdecl list* — methods of Object
SXcpt-mdecls :: *mdecl list* — methods of SXcpts

definition

ObjectC :: *cdecl* — declaration of root class **where**
ObjectC = (*Object*, (*access=Public*, *cfields=[]*, *methods=Object-mdecls*,
init=Skip, *super=undefined*, *superIfs=[]*))

definition

SXcptC :: *xname* \Rightarrow *cdecl* — declarations of throwable classes **where**
SXcptC *xn* = (*SXcpt* *xn*, (*access=Public*, *cfields=[]*, *methods=SXcpt-mdecls*,
init=Skip,
super=if xn = Throwable then Object
else SXcpt Throwable,
superIfs=[]))

lemma *ObjectC-neq-SXcptC* [simp]: $ObjectC \neq SXcptC\ xn$
<proof>

lemma *SXcptC-inject* [simp]: $(SXcptC\ xn = SXcptC\ xm) = (xn = xm)$
<proof>

definition

standard-classes :: *cdecl list* **where**
standard-classes = [*ObjectC*, *SXcptC* *Throwable*,
SXcptC *NullPointer*, *SXcptC* *OutOfMemory*, *SXcptC* *ClassCast*,
SXcptC *NegArrSize*, *SXcptC* *IndOutBound*, *SXcptC* *ArrStore*]

programs

record *prog* =
ifaces :: *idecl list*
classes :: *cdecl list*

translations

(*type*) *prog* <= (*type*) (*ifaces*::*idecl list*, *classes*::*cdecl list*)
(*type*) *prog* <= (*type*) (*ifaces*::*idecl list*, *classes*::*cdecl list*, ...::'*a*)

abbreviation

iface :: *prog* \Rightarrow (*qname*, *iface*) *table*
where *iface* *G* *I* == *table-of* (*ifaces* *G*) *I*

abbreviation

class :: *prog* \Rightarrow (*qname*, *class*) *table*

where *class* $G\ C == \text{table-of (classes } G) C$

abbreviation

is-iface $:: \text{prog} \Rightarrow \text{qname} \Rightarrow \text{bool}$
where *is-iface* $G\ I == \text{iface } G\ I \neq \text{None}$

abbreviation

is-class $:: \text{prog} \Rightarrow \text{qname} \Rightarrow \text{bool}$
where *is-class* $G\ C == \text{class } G\ C \neq \text{None}$

is type

primrec *is-type* $:: \text{prog} \Rightarrow \text{ty} \Rightarrow \text{bool}$

and *isrtype* $:: \text{prog} \Rightarrow \text{ref-ty} \Rightarrow \text{bool}$

where

is-type $G\ (\text{PrimT } pt) = \text{True}$
 $| \text{is-type } G\ (\text{RefT } rt) = \text{isrtype } G\ rt$
 $| \text{isrtype } G\ (\text{NullT}) = \text{True}$
 $| \text{isrtype } G\ (\text{IfaceT } tn) = \text{is-iface } G\ tn$
 $| \text{isrtype } G\ (\text{ClassT } tn) = \text{is-class } G\ tn$
 $| \text{isrtype } G\ (\text{ArrayT } T) = \text{is-type } G\ T$

lemma *type-is-iface*: $\text{is-type } G\ (\text{Iface } I) \Longrightarrow \text{is-iface } G\ I$

<proof>

lemma *type-is-class*: $\text{is-type } G\ (\text{Class } C) \Longrightarrow \text{is-class } G\ C$

<proof>

subinterface and subclass relation, in anticipation of TypeRel.thy**definition**

subint1 $:: \text{prog} \Rightarrow (\text{qname} \times \text{qname}) \text{ set} \text{ — direct subinterface}$
where *subint1* $G = \{(I, J). \exists i \in \text{iface } G\ I: J \in \text{set (isuperIfs } i)\}$

definition

subcls1 $:: \text{prog} \Rightarrow (\text{qname} \times \text{qname}) \text{ set} \text{ — direct subclass}$
where *subcls1* $G = \{(C, D). C \neq \text{Object} \wedge (\exists c \in \text{class } G\ C: \text{super } c = D)\}$

abbreviation

subcls1-syntax $:: \text{prog} \Rightarrow [\text{qname}, \text{qname}] \Rightarrow \text{bool} \text{ (|-<:C1- [71,71,71] 70)}$
where $G|-C <:C1\ D == (C, D) \in \text{subcls1 } G$

abbreviation

subclseq-syntax $:: \text{prog} \Rightarrow [\text{qname}, \text{qname}] \Rightarrow \text{bool} \text{ (|-<=:C -[71,71,71] 70)}$
where $G|-C <=:C\ D == (C, D) \in (\text{subcls1 } G)^*$

abbreviation

subcls-syntax $:: \text{prog} \Rightarrow [\text{qname}, \text{qname}] \Rightarrow \text{bool} \text{ (|-<:C -[71,71,71] 70)}$
where $G|-C <:C\ D == (C, D) \in (\text{subcls1 } G)^+$

notation (*xsymbols*)

subcls1-syntax $(|-<_{C1} - [71,71,71] 70)$ **and**
subclseq-syntax $(|-<_C - [71,71,71] 70)$ **and**
subcls-syntax $(|-<_C - [71,71,71] 70)$

lemma *subint1I*: $\llbracket \text{iface } G\ I = \text{Some } i; J \in \text{set (isuperIfs } i) \rrbracket$

$\implies (I,J) \in \text{subint1 } G$
 ⟨proof⟩

lemma subcls1I: $\llbracket \text{class } G \ C = \text{Some } c; C \neq \text{Object} \rrbracket \implies (C, (\text{super } c)) \in \text{subcls1 } G$
 ⟨proof⟩

lemma subint1D: $(I,J) \in \text{subint1 } G \implies \exists i \in \text{iface } G \ I: J \in \text{set } (\text{isuperIfs } i)$
 ⟨proof⟩

lemma subcls1D:
 $(C,D) \in \text{subcls1 } G \implies C \neq \text{Object} \wedge (\exists c. \text{class } G \ C = \text{Some } c \wedge (\text{super } c = D))$
 ⟨proof⟩

lemma subint1-def2:
 $\text{subint1 } G = (\text{SIGMA } I: \{I. \text{is-iface } G \ I\}. \text{set } (\text{isuperIfs } (\text{the } (\text{iface } G \ I))))$
 ⟨proof⟩

lemma subcls1-def2:
 $\text{subcls1 } G =$
 $(\text{SIGMA } C: \{C. \text{is-class } G \ C\}. \{D. C \neq \text{Object} \wedge \text{super } (\text{the } (\text{class } G \ C)) = D\})$
 ⟨proof⟩

lemma subcls-is-class:
 $\llbracket G \vdash C \prec_C D \rrbracket \implies \exists c. \text{class } G \ C = \text{Some } c$
 ⟨proof⟩

lemma no-subcls1-Object: $G \vdash \text{Object} \prec_C D \implies P$
 ⟨proof⟩

lemma no-subcls-Object: $G \vdash \text{Object} \prec_C D \implies P$
 ⟨proof⟩

well-structured programs

definition

$\text{ws-idecl} :: \text{prog} \Rightarrow \text{qname} \Rightarrow \text{qname list} \Rightarrow \text{bool}$
where $\text{ws-idecl } G \ I \ si = (\forall J \in \text{set } si. \text{is-iface } G \ J \ \wedge \ (J,I) \notin (\text{subint1 } G) \wedge +)$

definition

$\text{ws-cdecl} :: \text{prog} \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$
where $\text{ws-cdecl } G \ C \ sc = (C \neq \text{Object} \longrightarrow \text{is-class } G \ sc \wedge (sc,C) \notin (\text{subcls1 } G) \wedge +)$

definition

$\text{ws-prog} :: \text{prog} \Rightarrow \text{bool}$ **where**
 $\text{ws-prog } G = ((\forall (I,i) \in \text{set } (\text{ifaces } G). \text{ws-idecl } G \ I \ (\text{isuperIfs } i)) \wedge$
 $(\forall (C,c) \in \text{set } (\text{classes } G). \text{ws-cdecl } G \ C \ (\text{super } c)))$

lemma ws-progI:

$$\begin{aligned} & \llbracket \forall (I,i) \in \text{set } (\text{ifaces } G). \forall J \in \text{set } (\text{isuperIfs } i). \text{is-iface } G J \wedge \\ & \quad (J,I) \notin (\text{subint1 } G)^{+}; \\ & \quad \forall (C,c) \in \text{set } (\text{classes } G). C \neq \text{Object} \longrightarrow \text{is-class } G (\text{super } c) \wedge \\ & \quad ((\text{super } c), C) \notin (\text{subcls1 } G)^{+} \\ & \rrbracket \implies \text{ws-prog } G \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ws-prog-ideclD*:

$$\begin{aligned} & \llbracket \text{iface } G I = \text{Some } i; J \in \text{set } (\text{isuperIfs } i); \text{ws-prog } G \rrbracket \implies \\ & \quad \text{is-iface } G J \wedge (J,I) \notin (\text{subint1 } G)^{+} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ws-prog-cdeclD*:

$$\begin{aligned} & \llbracket \text{class } G C = \text{Some } c; C \neq \text{Object}; \text{ws-prog } G \rrbracket \implies \\ & \quad \text{is-class } G (\text{super } c) \wedge (\text{super } c, C) \notin (\text{subcls1 } G)^{+} \\ & \langle \text{proof} \rangle \end{aligned}$$

well-foundedness

lemma *finite-is-iface*: $\text{finite } \{I. \text{is-iface } G I\}$
 $\langle \text{proof} \rangle$

lemma *finite-is-class*: $\text{finite } \{C. \text{is-class } G C\}$
 $\langle \text{proof} \rangle$

lemma *finite-subint1*: $\text{finite } (\text{subint1 } G)$
 $\langle \text{proof} \rangle$

lemma *finite-subcls1*: $\text{finite } (\text{subcls1 } G)$
 $\langle \text{proof} \rangle$

lemma *subint1-irrefl-lemma1*:

$$\text{ws-prog } G \implies (\text{subint1 } G)^{-1} \cap (\text{subint1 } G)^{+} = \{\}$$
 $\langle \text{proof} \rangle$

lemma *subcls1-irrefl-lemma1*:

$$\text{ws-prog } G \implies (\text{subcls1 } G)^{-1} \cap (\text{subcls1 } G)^{+} = \{\}$$
 $\langle \text{proof} \rangle$

lemmas *subint1-irrefl-lemma2* = *subint1-irrefl-lemma1* [THEN *irrefl-tranclI*']

lemmas *subcls1-irrefl-lemma2* = *subcls1-irrefl-lemma1* [THEN *irrefl-tranclI*']

lemma *subint1-irrefl*: $\llbracket (x, y) \in \text{subint1 } G; \text{ws-prog } G \rrbracket \implies x \neq y$
 $\langle \text{proof} \rangle$

lemma *subcls1-irrefl*: $\llbracket (x, y) \in \text{subcls1 } G; \text{ws-prog } G \rrbracket \implies x \neq y$
 $\langle \text{proof} \rangle$

lemmas *subint1-acyclic* = *subint1-irrefl-lemma2* [THEN *acyclicI*]

lemmas *subcls1-acyclic* = *subcls1-irrefl-lemma2* [THEN *acyclicI*]

lemma *wf-subint1*: $ws\text{-prog } G \Longrightarrow wf ((subint1\ G)^{-1})$
 ⟨proof⟩

lemma *wf-subcls1*: $ws\text{-prog } G \Longrightarrow wf ((subcls1\ G)^{-1})$
 ⟨proof⟩

lemma *subint1-induct*:
 $\llbracket ws\text{-prog } G; \bigwedge x. \forall y. (x, y) \in subint1\ G \longrightarrow P\ y \Longrightarrow P\ x \rrbracket \Longrightarrow P\ a$
 ⟨proof⟩

lemma *subcls1-induct* [*consumes 1*]:
 $\llbracket ws\text{-prog } G; \bigwedge x. \forall y. (x, y) \in subcls1\ G \longrightarrow P\ y \Longrightarrow P\ x \rrbracket \Longrightarrow P\ a$
 ⟨proof⟩

lemma *ws-subint1-induct*:
 $\llbracket is\text{-iface } G\ I; ws\text{-prog } G; \bigwedge I\ i. \llbracket iface\ G\ I = Some\ i \wedge$
 $(\forall J \in set\ (isuperIfs\ i). (I, J) \in subint1\ G \wedge P\ J \wedge is\text{-iface } G\ J) \rrbracket \Longrightarrow P\ I$
 $\rrbracket \Longrightarrow P\ I$
 ⟨proof⟩

lemma *ws-subcls1-induct*: $\llbracket is\text{-class } G\ C; ws\text{-prog } G;$
 $\bigwedge C\ c. \llbracket class\ G\ C = Some\ c;$
 $(C \neq Object \longrightarrow (C, (super\ c)) \in subcls1\ G \wedge$
 $P\ (super\ c) \wedge is\text{-class } G\ (super\ c)) \rrbracket \Longrightarrow P\ C$
 $\rrbracket \Longrightarrow P\ C$
 ⟨proof⟩

lemma *ws-class-induct* [*consumes 2, case-names Object Subcls*]:
 $\llbracket class\ G\ C = Some\ c; ws\text{-prog } G;$
 $\bigwedge co. class\ G\ Object = Some\ co \Longrightarrow P\ Object;$
 $\bigwedge C\ c. \llbracket class\ G\ C = Some\ c; C \neq Object; P\ (super\ c) \rrbracket \Longrightarrow P\ C$
 $\rrbracket \Longrightarrow P\ C$
 ⟨proof⟩

lemma *ws-class-induct'* [*consumes 2, case-names Object Subcls*]:
 $\llbracket is\text{-class } G\ C; ws\text{-prog } G;$
 $\bigwedge co. class\ G\ Object = Some\ co \Longrightarrow P\ Object;$
 $\bigwedge C\ c. \llbracket class\ G\ C = Some\ c; C \neq Object; P\ (super\ c) \rrbracket \Longrightarrow P\ C$
 $\rrbracket \Longrightarrow P\ C$
 ⟨proof⟩

lemma *ws-class-induct''* [*consumes 2, case-names Object Subcls*]:
 $\llbracket class\ G\ C = Some\ c; ws\text{-prog } G;$
 $\bigwedge co. class\ G\ Object = Some\ co \Longrightarrow P\ Object\ co;$
 $\bigwedge C\ c\ sc. \llbracket class\ G\ C = Some\ c; class\ G\ (super\ c) = Some\ sc;$
 $C \neq Object; P\ (super\ c)\ sc \rrbracket \Longrightarrow P\ C\ c$

$\llbracket \cdot \rrbracket \Longrightarrow P C c$
 ⟨proof⟩

lemma *ws-interface-induct* [consumes 2, case-names Step]:

assumes *is-if-I*: *is-iface* *G I* **and**

ws: *ws-prog* *G* **and**

hyp-sub: $\bigwedge I i. \llbracket \text{iface } G I = \text{Some } i; \forall J \in \text{set } (\text{isuperIfs } i).$

$(I, J) \in \text{subint1 } G \wedge P J \wedge \text{is-iface } G J \rrbracket \Longrightarrow P I$

shows *P I*

⟨proof⟩

general recursion operators for the interface and class hierarchies

function *iface-rec* :: *prog* \Rightarrow *qname* \Rightarrow (*qname* \Rightarrow *iface* \Rightarrow 'a *set* \Rightarrow 'a) \Rightarrow 'a

where

[simp del]: *iface-rec* *G I f* =

(case *iface* *G I* of

None \Rightarrow *undefined*

| *Some i* \Rightarrow if *ws-prog* *G*

then *f I i*

(($\lambda J. \text{iface-rec } G J f$) 'set (*isuperIfs i*))

else *undefined*)

⟨proof⟩

termination

⟨proof⟩

lemma *iface-rec*:

$\llbracket \text{iface } G I = \text{Some } i; \text{ws-prog } G \rrbracket \Longrightarrow$

iface-rec *G I f* = *f I i* (($\lambda J. \text{iface-rec } G J f$) 'set (*isuperIfs i*))

⟨proof⟩

function

class-rec :: *prog* \Rightarrow *qname* \Rightarrow 'a \Rightarrow (*qname* \Rightarrow *class* \Rightarrow 'a \Rightarrow 'a) \Rightarrow 'a

where

[simp del]: *class-rec* *G C t f* =

(case *class* *G C* of

None \Rightarrow *undefined*

| *Some c* \Rightarrow if *ws-prog* *G*

then *f C c*

(if *C* = *Object* then *t*

else *class-rec* *G* (*super c*) *t f*)

else *undefined*)

⟨proof⟩

termination

⟨proof⟩

lemma *class-rec*: $\llbracket \text{class } G C = \text{Some } c; \text{ws-prog } G \rrbracket \Longrightarrow$

class-rec *G C t f* =

f C c (if *C* = *Object* then *t* else *class-rec* *G* (*super c*) *t f*)

⟨proof⟩

definition

imethds :: *prog* \Rightarrow *qname* \Rightarrow (*sig*, *qname* \times *mhead*) *tables* **where**

— methods of an interface, with overriding and inheritance, cf. 9.2

imethds $G\ I = \text{iface-rec } G\ I$

$(\lambda I\ i\ ts. (\text{Un-tables } ts) \oplus \oplus$

$(\text{Option.set} \circ \text{table-of } (\text{map } (\lambda(s,m). (s,I,m)) (\text{imethds } i))))$

end

Chapter 9

TypeRel

15 The relations between Java types

theory *TypeRel* **imports** *Decl* **begin**

simplifications:

- subinterface, subclass and widening relation includes identity

improvements over Java Specification 1.0:

- narrowing reference conversion also in cases where the return types of a pair of methods common to both types are in widening (rather identity) relation
- one could add similar constraints also for other cases

design issues:

- the type relations do not require *is-type* for their arguments
- the *subint1* and *subcls1* relations imply *is-iface/is-class* for their first arguments, which is required for their finiteness

definition

implmt1 :: *prog* => (*qname* × *qname*) *set* — direct implementation
 — direct implementation, cf. 8.1.3
where *implmt1* *G* = {(*C*,*I*). *C* ≠ *Object* ∧ (∃ *c* ∈ *class G C*: *I* ∈ *set (superIfs c)*)}

abbreviation

subint1-syntax :: *prog* => [*qname*, *qname*] => *bool* (|-<:I1- [71,71,71] 70)
where *G*|-*I* <:I1 *J* == (*I*,*J*) ∈ *subint1 G*

abbreviation

subint-syntax :: *prog* => [*qname*, *qname*] => *bool* (|-<=:I- [71,71,71] 70)
where *G*|-*I* <=:I *J* == (*I*,*J*) ∈ (*subint1 G*)^{*} — cf. 9.1.3

abbreviation

implmt1-syntax :: *prog* => [*qname*, *qname*] => *bool* (|-~>I- [71,71,71] 70)
where *G*|-*C* ~>I *I* == (*C*,*I*) ∈ *implmt1 G*

notation (*xsymbols*)

subint1-syntax (|-<:I1- [71,71,71] 70) **and**
subint-syntax (|-<=:I- [71,71,71] 70) **and**
implmt1-syntax (|-~>I- [71,71,71] 70)

subclass and subinterface relations

lemmas *subcls-direct* = *subcls1I* [THEN *r-into-rtrancl*]

lemma *subcls-direct1*:

[*class G C* = *Some c*; *C* ≠ *Object*; *D* = *super c*] ==> *G* ⊢ *C* ≤_{*C*} *D*
 ⟨*proof*⟩

lemma *subcls1I1*:

[*class G C* = *Some c*; *C* ≠ *Object*; *D* = *super c*] ==> *G* ⊢ *C* <_{*C*} 1 *D*
 ⟨*proof*⟩

lemma *subcls-direct2*:

$\llbracket \text{class } G \ C = \text{Some } c; C \neq \text{Object}; D = \text{super } c \rrbracket \implies G \vdash C \prec_C D$
 $\langle \text{proof} \rangle$

lemma *subclseq-trans*: $\llbracket G \vdash A \preceq_C B; G \vdash B \preceq_C C \rrbracket \implies G \vdash A \preceq_C C$

$\langle \text{proof} \rangle$

lemma *subcls-trans*: $\llbracket G \vdash A \prec_C B; G \vdash B \prec_C C \rrbracket \implies G \vdash A \prec_C C$

$\langle \text{proof} \rangle$

lemma *SXcpt-subcls-Throwable-lemma*:

$\llbracket \text{class } G \ (SXcpt \ x) = \text{Some } xc;$
 $\text{super } xc = (\text{if } x = \text{Throwable} \text{ then } \text{Object} \text{ else } SXcpt \ \text{Throwable}) \rrbracket$
 $\implies G \vdash SXcpt \ x \preceq_C SXcpt \ \text{Throwable}$
 $\langle \text{proof} \rangle$

lemma *subcls-ObjectI*: $\llbracket \text{is-class } G \ C; \text{ws-prog } G \rrbracket \implies G \vdash C \preceq_C \text{Object}$

$\langle \text{proof} \rangle$

lemma *subclseq-ObjectD* [dest!]: $G \vdash \text{Object} \preceq_C C \implies C = \text{Object}$

$\langle \text{proof} \rangle$

lemma *subcls-ObjectD* [dest!]: $G \vdash \text{Object} \prec_C C \implies \text{False}$

$\langle \text{proof} \rangle$

lemma *subcls-ObjectI1* [intro!]:

$\llbracket C \neq \text{Object}; \text{is-class } G \ C; \text{ws-prog } G \rrbracket \implies G \vdash C \prec_C \text{Object}$
 $\langle \text{proof} \rangle$

lemma *subcls-is-class*: $(C, D) \in (\text{subcls1 } G)^+ \implies \text{is-class } G \ C$

$\langle \text{proof} \rangle$

lemma *subcls-is-class2* [rule-format (no-asm)]:

$G \vdash C \preceq_C D \implies \text{is-class } G \ D \longrightarrow \text{is-class } G \ C$
 $\langle \text{proof} \rangle$

lemma *single-inheritance*:

$\llbracket G \vdash A \prec_{C1} B; G \vdash A \prec_{C1} C \rrbracket \implies B = C$
 $\langle \text{proof} \rangle$

lemma *subcls-compareable*:

$\llbracket G \vdash A \preceq_C X; G \vdash A \preceq_C Y$
 $\rrbracket \implies G \vdash X \preceq_C Y \vee G \vdash Y \preceq_C X$
 $\langle \text{proof} \rangle$

lemma *subcls1-irrefl*: $\llbracket G \vdash C \prec_{C1} D; \text{ws-prog } G \rrbracket$

$\implies C \neq D$
 $\langle \text{proof} \rangle$

lemma *no-subcls-Object*: $G \vdash C \prec_C D \implies C \neq \text{Object}$
 $\langle \text{proof} \rangle$

lemma *subcls-acyclic*: $\llbracket G \vdash C \prec_C D; \text{ws-prog } G \rrbracket \implies \neg G \vdash D \prec_C C$
 $\langle \text{proof} \rangle$

lemma *subclseq-cases*:
assumes $G \vdash C \preceq_C D$
obtains $(Eq) C = D \mid (Subcls) G \vdash C \prec_C D$
 $\langle \text{proof} \rangle$

lemma *subclseq-acyclic*:
 $\llbracket G \vdash C \preceq_C D; G \vdash D \preceq_C C; \text{ws-prog } G \rrbracket \implies C = D$
 $\langle \text{proof} \rangle$

lemma *subcls-irrefl*: $\llbracket G \vdash C \prec_C D; \text{ws-prog } G \rrbracket$
 $\implies C \neq D$
 $\langle \text{proof} \rangle$

lemma *invert-subclseq*:
 $\llbracket G \vdash C \preceq_C D; \text{ws-prog } G \rrbracket$
 $\implies \neg G \vdash D \prec_C C$
 $\langle \text{proof} \rangle$

lemma *invert-subcls*:
 $\llbracket G \vdash C \prec_C D; \text{ws-prog } G \rrbracket$
 $\implies \neg G \vdash D \preceq_C C$
 $\langle \text{proof} \rangle$

lemma *subcls-superD*:
 $\llbracket G \vdash C \prec_C D; \text{class } G \ C = \text{Some } c \rrbracket \implies G \vdash (\text{super } c) \preceq_C D$
 $\langle \text{proof} \rangle$

lemma *subclseq-superD*:
 $\llbracket G \vdash C \preceq_C D; C \neq D; \text{class } G \ C = \text{Some } c \rrbracket \implies G \vdash (\text{super } c) \preceq_C D$
 $\langle \text{proof} \rangle$

implementation relation

lemma *implmt1D*: $G \vdash C \rightsquigarrow 1I \implies C \neq \text{Object} \wedge (\exists c \in \text{class } G \ C: I \in \text{set } (\text{superIfs } c))$
 $\langle \text{proof} \rangle$

inductive — implementation, cf. 8.1.4

implmt :: *prog* \Rightarrow *qname* \Rightarrow *qname* \Rightarrow *bool* ($\vdash \rightsquigarrow \vdash$ [71,71,71] 70)

for *G* :: *prog*

where

direct: $G \vdash C \rightsquigarrow 1J \implies G \vdash C \rightsquigarrow J$
| *subint*: $G \vdash C \rightsquigarrow 1I \implies G \vdash I \preceq I J \implies G \vdash C \rightsquigarrow J$
| *subcls1*: $G \vdash C \prec_C 1D \implies G \vdash D \rightsquigarrow J \implies G \vdash C \rightsquigarrow J$

lemma *implmtD*: $G \vdash C \rightsquigarrow J \implies (\exists I. G \vdash C \rightsquigarrow 1I \wedge G \vdash I \preceq I J) \vee (\exists D. G \vdash C \prec_C 1D \wedge G \vdash D \rightsquigarrow J)$
⟨proof⟩

lemma *implmt-ObjectE* [elim!]: $G \vdash \text{Object} \rightsquigarrow I \implies R$
⟨proof⟩

lemma *subcls-implmt* [rule-format (no-asm)]: $G \vdash A \preceq_C B \implies G \vdash B \rightsquigarrow K \longrightarrow G \vdash A \rightsquigarrow K$
⟨proof⟩

lemma *implmt-subint2*: $\llbracket G \vdash A \rightsquigarrow J; G \vdash J \preceq I K \rrbracket \implies G \vdash A \rightsquigarrow K$
⟨proof⟩

lemma *implmt-is-class*: $G \vdash C \rightsquigarrow I \implies \text{is-class } G \ C$
⟨proof⟩

widening relation

inductive

— widening, viz. method invocation conversion, cf. 5.3 i.e. kind of syntactic subtyping

widen :: *prog* \Rightarrow *ty* \Rightarrow *ty* \Rightarrow *bool* (+-_- [71,71,71] 70)

for *G* :: *prog*

where

refl: $G \vdash T \preceq T$ — identity conversion, cf. 5.1.1
| *subint*: $G \vdash I \preceq I J \implies G \vdash \text{Iface } I \preceq \text{Iface } J$ — wid.ref.conv.,cf. 5.1.4
| *int-obj*: $G \vdash \text{Iface } I \preceq \text{Class } \text{Object}$
| *subcls*: $G \vdash C \preceq_C D \implies G \vdash \text{Class } C \preceq \text{Class } D$
| *implmt*: $G \vdash C \rightsquigarrow I \implies G \vdash \text{Class } C \preceq \text{Iface } I$
| *null*: $G \vdash \text{NT} \preceq \text{RefT } R$
| *arr-obj*: $G \vdash T.\llbracket \rrbracket \preceq \text{Class } \text{Object}$
| *array*: $G \vdash \text{RefT } S \preceq \text{RefT } T \implies G \vdash \text{RefT } S.\llbracket \rrbracket \preceq \text{RefT } T.\llbracket \rrbracket$

declare *widen.refl* [intro!]

declare *widen.intros* [simp]

lemma *widen-PrimT*: $G \vdash \text{PrimT } x \preceq T \implies (\exists y. T = \text{PrimT } y)$
⟨proof⟩

lemma *widen-PrimT2*: $G \vdash S \preceq \text{PrimT } x \implies \exists y. S = \text{PrimT } y$
⟨proof⟩

These widening lemmata hold in Bali but are too strong for ordinary Java. They would not work for real Java Integral Types, like short, long, int. These lemmata are just for documentation and are not used.

lemma *widen-PrimT-strong*: $G \vdash \text{PrimT } x \preceq T \implies T = \text{PrimT } x$
⟨proof⟩

lemma *widen-PrimT2-strong*: $G \vdash S \preceq_{\text{PrimT}} x \implies S = \text{PrimT } x$
 ⟨proof⟩

Specialized versions for booleans also would work for real Java

lemma *widen-Boolean*: $G \vdash \text{PrimT } \text{Boolean} \preceq T \implies T = \text{PrimT } \text{Boolean}$
 ⟨proof⟩

lemma *widen-Boolean2*: $G \vdash S \preceq_{\text{PrimT}} \text{Boolean} \implies S = \text{PrimT } \text{Boolean}$
 ⟨proof⟩

lemma *widen-RefT*: $G \vdash \text{RefT } R \preceq T \implies \exists t. T = \text{RefT } t$
 ⟨proof⟩

lemma *widen-RefT2*: $G \vdash S \preceq_{\text{RefT}} R \implies \exists t. S = \text{RefT } t$
 ⟨proof⟩

lemma *widen-Iface*: $G \vdash \text{Iface } I \preceq T \implies T = \text{Class } \text{Object} \vee (\exists J. T = \text{Iface } J)$
 ⟨proof⟩

lemma *widen-Iface2*: $G \vdash S \preceq \text{Iface } J \implies S = \text{NT} \vee (\exists I. S = \text{Iface } I) \vee (\exists D. S = \text{Class } D)$
 ⟨proof⟩

lemma *widen-Iface-Iface*: $G \vdash \text{Iface } I \preceq \text{Iface } J \implies G \vdash I \preceq I J$
 ⟨proof⟩

lemma *widen-Iface-Iface-eq [simp]*: $G \vdash \text{Iface } I \preceq \text{Iface } J = G \vdash I \preceq I J$
 ⟨proof⟩

lemma *widen-Class*: $G \vdash \text{Class } C \preceq T \implies (\exists D. T = \text{Class } D) \vee (\exists I. T = \text{Iface } I)$
 ⟨proof⟩

lemma *widen-Class2*: $G \vdash S \preceq \text{Class } C \implies C = \text{Object} \vee S = \text{NT} \vee (\exists D. S = \text{Class } D)$
 ⟨proof⟩

lemma *widen-Class-Class*: $G \vdash \text{Class } C \preceq \text{Class } cm \implies G \vdash C \preceq_C cm$
 ⟨proof⟩

lemma *widen-Class-Class-eq [simp]*: $G \vdash \text{Class } C \preceq \text{Class } cm = G \vdash C \preceq_C cm$
 ⟨proof⟩

lemma *widen-Class-Iface*: $G \vdash \text{Class } C \preceq \text{Iface } I \implies G \vdash C \rightsquigarrow I$
 ⟨proof⟩

lemma *widen-Class-Iface-eq [simp]*: $G \vdash \text{Class } C \preceq \text{Iface } I = G \vdash C \rightsquigarrow I$
 ⟨proof⟩

lemma *widen-Array*: $G \vdash S.\boxed{\preceq} T \implies T = \text{Class Object} \vee (\exists T'. T = T'.\boxed{\preceq} \wedge G \vdash S \preceq T')$
 ⟨proof⟩

lemma *widen-Array2*: $G \vdash S \preceq T.\boxed{\preceq} \implies S = NT \vee (\exists S'. S = S'.\boxed{\preceq} \wedge G \vdash S' \preceq T)$
 ⟨proof⟩

lemma *widen-ArrayPrimT*: $G \vdash \text{PrimT } t.\boxed{\preceq} T \implies T = \text{Class Object} \vee T = \text{PrimT } t.\boxed{\preceq}$
 ⟨proof⟩

lemma *widen-ArrayRefT*:
 $G \vdash \text{RefT } t.\boxed{\preceq} T \implies T = \text{Class Object} \vee (\exists s. T = \text{RefT } s.\boxed{\preceq} \wedge G \vdash \text{RefT } t \preceq \text{RefT } s)$
 ⟨proof⟩

lemma *widen-ArrayRefT-ArrayRefT-eq* [simp]:
 $G \vdash \text{RefT } T.\boxed{\preceq} \text{RefT } T'.\boxed{\preceq} = G \vdash \text{RefT } T \preceq \text{RefT } T'$
 ⟨proof⟩

lemma *widen-Array-Array*: $G \vdash T.\boxed{\preceq} T'.\boxed{\preceq} \implies G \vdash T \preceq T'$
 ⟨proof⟩

lemma *widen-Array-Class*: $G \vdash S.\boxed{\preceq} \text{Class } C \implies C = \text{Object}$
 ⟨proof⟩

lemma *widen-NT2*: $G \vdash S \preceq NT \implies S = NT$
 ⟨proof⟩

lemma *widen-Object*:
 assumes *isrtype* G T and *ws-prog* G
 shows $G \vdash \text{RefT } T \preceq \text{Class Object}$
 ⟨proof⟩

lemma *widen-trans-lemma* [rule-format (no-asm)]:
 $\llbracket G \vdash S \preceq U; \forall C. \text{is-class } G \ C \longrightarrow G \vdash C \preceq_C \text{Object} \rrbracket \implies \forall T. G \vdash U \preceq T \longrightarrow G \vdash S \preceq T$
 ⟨proof⟩

lemma *ws-widen-trans*: $\llbracket G \vdash S \preceq U; G \vdash U \preceq T; \text{ws-prog } G \rrbracket \implies G \vdash S \preceq T$
 ⟨proof⟩

lemma *widen-antisym-lemma* [rule-format (no-asm)]: $\llbracket G \vdash S \preceq T;$
 $\forall I J. G \vdash I \preceq I J \wedge G \vdash J \preceq I I \longrightarrow I = J;$
 $\forall C D. G \vdash C \preceq_C D \wedge G \vdash D \preceq_C C \longrightarrow C = D;$
 $\forall I. G \vdash \text{Object} \rightsquigarrow I \longrightarrow \text{False} \rrbracket \implies G \vdash T \preceq S \longrightarrow S = T$
 ⟨proof⟩

lemmas *subint-antisym* =
 subint1-acyclic [THEN *acyclic-impl-antisym-rtrancl*]
lemmas *subcls-antisym* =
 subcls1-acyclic [THEN *acyclic-impl-antisym-rtrancl*]

lemma *widen-antisym*: $\llbracket G \vdash S \preceq T; G \vdash T \preceq S; \text{ws-prog } G \rrbracket \implies S = T$
 ⟨proof⟩

lemma *widen-ObjectD* [*dest!*]: $G \vdash \text{Class Object} \preceq T \implies T = \text{Class Object}$
 ⟨proof⟩

definition

widens :: *prog* \Rightarrow [*ty list*, *ty list*] \Rightarrow *bool* ($\text{-} \text{-} [\preceq] \text{-}$ [71,71,71] 70)
where $G \vdash Ts [\preceq] Ts' = \text{list-all2 } (\lambda T T'. G \vdash T \preceq T') Ts Ts'$

lemma *widens-Nil* [*simp*]: $G \vdash [] [\preceq] []$
 ⟨proof⟩

lemma *widens-Cons* [*simp*]: $G \vdash (S \# Ss) [\preceq] (T \# Ts) = (G \vdash S \preceq T \wedge G \vdash Ss [\preceq] Ts)$
 ⟨proof⟩

narrowing relation

inductive — narrowing reference conversion, cf. 5.1.5

narrow :: *prog* \Rightarrow *ty* \Rightarrow *ty* \Rightarrow *bool* ($\text{-} \text{-} \text{-} \text{-}$ [71,71,71] 70)

for $G :: \text{prog}$

where

| *subcls*: $G \vdash C \preceq_C D \implies G \vdash \text{Class } D \succ \text{Class } C$
 | *implmt*: $\neg G \vdash C \rightsquigarrow I \implies G \vdash \text{Class } C \succ \text{Iface } I$
 | *obj-arr*: $G \vdash \text{Class Object} \succ T. []$
 | *int-cls*: $G \vdash \text{Iface } I \succ \text{Class } C$
 | *subint*: *imethds* $G I$ *hidings* *imethds* $G J$ *entails*
 $(\lambda (md, mh \) (md', mh')). G \vdash \text{mrt } mh \preceq \text{mrt } mh' \implies$
 $\neg G \vdash I \preceq I J \implies G \vdash \text{Iface } I \succ \text{Iface } J$
 | *array*: $G \vdash \text{RefT } S \succ \text{RefT } T \implies G \vdash \text{RefT } S. [] \succ \text{RefT } T. []$

lemma *narrow-RefT*: $G \vdash \text{RefT } R \succ T \implies \exists t. T = \text{RefT } t$
 ⟨proof⟩

lemma *narrow-RefT2*: $G \vdash S \succ \text{RefT } R \implies \exists t. S = \text{RefT } t$
 ⟨proof⟩

lemma *narrow-PrimT*: $G \vdash \text{PrimT } pt \succ T \implies \exists t. T = \text{PrimT } t$
 ⟨proof⟩

lemma *narrow-PrimT2*: $G \vdash S \succ \text{PrimT } pt \implies$
 $\exists t. S = \text{PrimT } t \wedge G \vdash \text{PrimT } t \preceq \text{PrimT } pt$
 ⟨proof⟩

These narrowing lemmata hold in Bali but are too strong for ordinary Java. They would not work for real Java Integral Types, like short, long, int. These lemmata are just for documentation and are not used.

lemma *narrow-PrimT-strong*: $G \vdash \text{PrimT } pt \succ T \implies T = \text{PrimT } pt$
 ⟨proof⟩

lemma *narrow-PrimT2-strong*: $G \vdash S \succ \text{PrimT } pt \implies S = \text{PrimT } pt$
 ⟨proof⟩

Specialized versions for booleans also would work for real Java

lemma *narrow-Boolean*: $G \vdash \text{PrimT } \text{Boolean} \succ T \implies T = \text{PrimT } \text{Boolean}$
 ⟨proof⟩

lemma *narrow-Boolean2*: $G \vdash S \succ \text{PrimT } \text{Boolean} \implies S = \text{PrimT } \text{Boolean}$
 ⟨proof⟩

casting relation

inductive — casting conversion, cf. 5.5

cast :: $\text{prog} \Rightarrow \text{ty} \Rightarrow \text{ty} \Rightarrow \text{bool}$ (-|-<=? - [71,71,71] 70)

for G :: prog

where

widen: $G \vdash S \preceq T \implies G \vdash S \preceq? T$

| *narrow*: $G \vdash S \succ T \implies G \vdash S \preceq? T$

lemma *cast-RefT*: $G \vdash \text{RefT } R \preceq? T \implies \exists t. T = \text{RefT } t$
 ⟨proof⟩

lemma *cast-RefT2*: $G \vdash S \preceq? \text{RefT } R \implies \exists t. S = \text{RefT } t$
 ⟨proof⟩

lemma *cast-PrimT*: $G \vdash \text{PrimT } pt \preceq? T \implies \exists t. T = \text{PrimT } t$
 ⟨proof⟩

lemma *cast-PrimT2*: $G \vdash S \preceq? \text{PrimT } pt \implies \exists t. S = \text{PrimT } t \wedge G \vdash \text{PrimT } t \preceq \text{PrimT } pt$
 ⟨proof⟩

lemma *cast-Boolean*:

assumes *bool-cast*: $G \vdash \text{PrimT } \text{Boolean} \preceq? T$

shows $T = \text{PrimT } \text{Boolean}$

⟨proof⟩

lemma *cast-Boolean2*:

assumes *bool-cast*: $G \vdash S \preceq? \text{PrimT } \text{Boolean}$

shows $S = \text{PrimT } \text{Boolean}$

⟨proof⟩

end

Chapter 10

DeclConcepts

16 Advanced concepts on Java declarations like overriding, inheritance, dynamic method lookup

theory *DeclConcepts* imports *TypeRel* begin

access control (cf. 6.6), overriding and hiding (cf. 8.4.6.1)

definition *is-public* :: *prog* \Rightarrow *qname* \Rightarrow *bool* **where**

$$\begin{aligned} \textit{is-public } G \textit{ qn} &= (\textit{case class } G \textit{ qn of} \\ &\quad \textit{None} \quad \Rightarrow (\textit{case iface } G \textit{ qn of} \\ &\quad \quad \textit{None} \quad \Rightarrow \textit{False} \\ &\quad \quad | \textit{Some } i \Rightarrow \textit{access } i = \textit{Public}) \\ &| \textit{Some } c \Rightarrow \textit{access } c = \textit{Public}) \end{aligned}$$

17 accessibility of types (cf. 6.6.1)

Primitive types are always accessible, interfaces and classes are accessible in their package or if they are defined public, an array type is accessible if its element type is accessible

primrec

accessible-in :: *prog* \Rightarrow *ty* \Rightarrow *pname* \Rightarrow *bool* (- \vdash - *accessible'-in* - [61,61,61] 60) **and**
rt-accessible-in :: *prog* \Rightarrow *ref-ty* \Rightarrow *pname* \Rightarrow *bool* (- \vdash - *accessible'-in'* - [61,61,61] 60)

where

$$\begin{aligned} &G \vdash (\textit{PrimT } p) \textit{ accessible-in pack} = \textit{True} \\ &| \textit{accessible-in-RefT-simp}: \\ &G \vdash (\textit{RefT } r) \textit{ accessible-in pack} = G \vdash r \textit{ accessible-in' pack} \\ &| G \vdash (\textit{NullT}) \textit{ accessible-in' pack} = \textit{True} \\ &| G \vdash (\textit{IfaceT } I) \textit{ accessible-in' pack} = ((\textit{pid } I = \textit{pack}) \vee \textit{is-public } G \textit{ I}) \\ &| G \vdash (\textit{ClassT } C) \textit{ accessible-in' pack} = ((\textit{pid } C = \textit{pack}) \vee \textit{is-public } G \textit{ C}) \\ &| G \vdash (\textit{ArrayT } ty) \textit{ accessible-in' pack} = G \vdash ty \textit{ accessible-in pack} \end{aligned}$$

declare *accessible-in-RefT-simp* [*simp del*]

definition

is-acc-class :: *prog* \Rightarrow *pname* \Rightarrow *qname* \Rightarrow *bool*
where *is-acc-class* *G P C* = (*is-class* *G C* \wedge $G \vdash (\textit{Class } C) \textit{ accessible-in } P$)

definition

is-acc-iface :: *prog* \Rightarrow *pname* \Rightarrow *qname* \Rightarrow *bool*
where *is-acc-iface* *G P I* = (*is-iface* *G I* \wedge $G \vdash (\textit{Iface } I) \textit{ accessible-in } P$)

definition

is-acc-type :: *prog* \Rightarrow *pname* \Rightarrow *ty* \Rightarrow *bool*
where *is-acc-type* *G P T* = (*is-type* *G T* \wedge $G \vdash T \textit{ accessible-in } P$)

definition

is-acc-reftype :: *prog* \Rightarrow *pname* \Rightarrow *ref-ty* \Rightarrow *bool*
where *is-acc-reftype* *G P T* = (*isrtype* *G T* \wedge $G \vdash T \textit{ accessible-in' } P$)

lemma *is-acc-classD*:

is-acc-class *G P C* \Longrightarrow *is-class* *G C* \wedge $G \vdash (\textit{Class } C) \textit{ accessible-in } P$
 $\langle \textit{proof} \rangle$

lemma *is-acc-class-is-class*: *is-acc-class* *G P C* \Longrightarrow *is-class* *G C*

$\langle \textit{proof} \rangle$

lemma *is-acc-ifaceD*:

is-acc-iface $G P I \implies is\text{-iface } G I \wedge G \vdash (I\text{face } I) \text{ accessible-in } P$
 ⟨proof⟩

lemma *is-acc-typeD*:

is-acc-type $G P T \implies is\text{-type } G T \wedge G \vdash T \text{ accessible-in } P$
 ⟨proof⟩

lemma *is-acc-reftypeD*:

is-acc-reftype $G P T \implies is\text{rtype } G T \wedge G \vdash T \text{ accessible-in' } P$
 ⟨proof⟩

18 accessibility of members

The accessibility of members is more involved as the accessibility of types. We have to distinguish several cases to model the different effects of accessibility during inheritance, overriding and ordinary member access

Various technical conversion and selection functions

overloaded selector *accmodi* to select the access modifier out of various HOL types

class *has-accmodi* =

fixes *accmodi*:: 'a $\Rightarrow acc\text{-modi}$

instantiation *acc-modi* :: *has-accmodi*

begin

definition

acc-modi-accmodi-def: *accmodi* (*a*::*acc-modi*) = *a*

instance ⟨proof⟩

end

lemma *acc-modi-accmodi-simp*[*simp*]: *accmodi* (*a*::*acc-modi*) = *a*

⟨proof⟩

instantiation *decl-ext* :: (*type*) *has-accmodi*

begin

definition

decl-acc-modi-def: *accmodi* (*d*::('a::*type*) *decl-scheme*) = *access d*

instance ⟨proof⟩

end

lemma *decl-acc-modi-simp*[*simp*]: *accmodi* (*d*::('a::*type*) *decl-scheme*) = *access d*

⟨proof⟩

instantiation *prod* :: (*type*, *has-accmodi*) *has-accmodi*

begin

definition

pair-acc-modi-def: $accmodi\ p = accmodi\ (snd\ p)$

instance $\langle proof \rangle$

end

lemma *pair-acc-modi-simp*[simp]: $accmodi\ (x,a) = (accmodi\ a)$
 $\langle proof \rangle$

instantiation *memberdecl* :: *has-accmodi*
begin

definition

memberdecl-acc-modi-def: $accmodi\ m = (case\ m\ of$
 $\quad fdecl\ f \Rightarrow accmodi\ f$
 $\quad | mdecl\ m \Rightarrow accmodi\ m)$

instance $\langle proof \rangle$

end

lemma *memberdecl-fdecl-acc-modi-simp*[simp]:
 $accmodi\ (fdecl\ m) = accmodi\ m$
 $\langle proof \rangle$

lemma *memberdecl-mdecl-acc-modi-simp*[simp]:
 $accmodi\ (mdecl\ m) = accmodi\ m$
 $\langle proof \rangle$

overloaded selector *declclass* to select the declaring class out of various HOL types

class *has-declclass* =
fixes *declclass*:: 'a \Rightarrow *qname*

instantiation *qname-ext* :: (*type*) *has-declclass*
begin

definition

declclass $q = (\mid pid = pid\ q, tid = tid\ q \mid)$

instance $\langle proof \rangle$

end

lemma *qname-declclass-def*:
 $declclass\ q \equiv (q::qname)$
 $\langle proof \rangle$

lemma *qname-declclass-simp*[simp]: $declclass\ (q::qname) = q$
 $\langle proof \rangle$

instantiation *prod* :: (*has-declclass*, *type*) *has-declclass*
begin

definition

pair-declclass-def: $\text{declclass } p = \text{declclass } (\text{fst } p)$

instance $\langle \text{proof} \rangle$

end

lemma *pair-declclass-simp*[simp]: $\text{declclass } (c,x) = \text{declclass } c$
 $\langle \text{proof} \rangle$

overloaded selector *is-static* to select the static modifier out of various HOL types

class *has-static* =
fixes *is-static* :: 'a \Rightarrow bool

instantiation *decl-ext* :: (has-static) has-static
begin

instance $\langle \text{proof} \rangle$

end

instantiation *member-ext* :: (type) has-static
begin

instance $\langle \text{proof} \rangle$

end

axiomatization where

static-field-type-is-static-def: $\text{is-static } (m::('a \text{ member-scheme})) \equiv \text{static } m$

lemma *member-is-static-simp*: $\text{is-static } (m::('a \text{ member-scheme})) = \text{static } m$
 $\langle \text{proof} \rangle$

instantiation *prod* :: (type, has-static) has-static
begin

definition

pair-is-static-def: $\text{is-static } p = \text{is-static } (\text{snd } p)$

instance $\langle \text{proof} \rangle$

end

lemma *pair-is-static-simp* [simp]: $\text{is-static } (x,s) = \text{is-static } s$
 $\langle \text{proof} \rangle$

lemma *pair-is-static-simp1*: $\text{is-static } p = \text{is-static } (\text{snd } p)$
 $\langle \text{proof} \rangle$

instantiation *memberdecl* :: has-static
begin

definition

memberdecl-is-static-def:
 $\text{is-static } m = (\text{case } m \text{ of}$

$$\begin{array}{l} fdecl\ f \Rightarrow is-static\ f \\ | mdecl\ m \Rightarrow is-static\ m \end{array}$$

instance $\langle proof \rangle$

end

lemma *memberdecl-is-static-fdecl-simp*[simp]:
 $is-static\ (fdecl\ f) = is-static\ f$
 $\langle proof \rangle$

lemma *memberdecl-is-static-mdecl-simp*[simp]:
 $is-static\ (mdecl\ m) = is-static\ m$
 $\langle proof \rangle$

lemma *mhead-static-simp* [simp]: $is-static\ (mhead\ m) = is-static\ m$
 $\langle proof \rangle$

definition

$decliface :: qname \times 'a\ decl-scheme \Rightarrow qname$ **where**
 $decliface = fst$ — get the interface component

definition

$mbr :: qname \times memberdecl \Rightarrow memberdecl$ **where**
 $mbr = snd$ — get the memberdecl component

definition

$mthd :: 'b \times 'a \Rightarrow 'a$ **where**
 $mthd = snd$ — get the method component
— also used for mdecl, mhead

definition

$fld :: 'b \times 'a\ decl-scheme \Rightarrow 'a\ decl-scheme$ **where**
 $fld = snd$ — get the field component
— also used for $((vname \times qname) \times field)$

— some mnemonic selectors for $(vname \times qname)$

definition

$fname :: vname \times 'a \Rightarrow vname$
where $fname = fst$
— also used for fdecl

definition

$declclassf :: (vname \times qname) \Rightarrow qname$
where $declclassf = snd$

lemma *decliface-simp*[simp]: $decliface\ (I, m) = I$
 $\langle proof \rangle$

lemma *mbr-simp*[simp]: $mbr\ (C, m) = m$
 $\langle proof \rangle$

lemma *access-mbr-simp* [simp]: $(\text{accmodi } (\text{mbr } m)) = \text{accmodi } m$
 ⟨proof⟩

lemma *mthd-simp*[simp]: $\text{mthd } (C, m) = m$
 ⟨proof⟩

lemma *fld-simp*[simp]: $\text{fld } (C, f) = f$
 ⟨proof⟩

lemma *accmodi-simp*[simp]: $\text{accmodi } (C, m) = \text{access } m$
 ⟨proof⟩

lemma *access-mthd-simp* [simp]: $(\text{access } (\text{mthd } m)) = \text{accmodi } m$
 ⟨proof⟩

lemma *access-fld-simp* [simp]: $(\text{access } (\text{fld } f)) = \text{accmodi } f$
 ⟨proof⟩

lemma *static-mthd-simp*[simp]: $\text{static } (\text{mthd } m) = \text{is-static } m$
 ⟨proof⟩

lemma *mthd-is-static-simp* [simp]: $\text{is-static } (\text{mthd } m) = \text{is-static } m$
 ⟨proof⟩

lemma *static-fld-simp*[simp]: $\text{static } (\text{fld } f) = \text{is-static } f$
 ⟨proof⟩

lemma *ext-field-simp* [simp]: $(\text{declclass } f, \text{fld } f) = f$
 ⟨proof⟩

lemma *ext-method-simp* [simp]: $(\text{declclass } m, \text{mthd } m) = m$
 ⟨proof⟩

lemma *ext-mbr-simp* [simp]: $(\text{declclass } m, \text{mbr } m) = m$
 ⟨proof⟩

lemma *fname-simp*[simp]: $\text{fname } (n, c) = n$
 ⟨proof⟩

lemma *declclassf-simp*[simp]: $\text{declclassf } (n, c) = c$
 ⟨proof⟩

definition

$\text{fldname} :: \text{vname} \times \text{qname} \Rightarrow \text{vname}$
 where $\text{fldname} = \text{fst}$

definition

$fldclass :: vname \times qname \Rightarrow qname$
where $fldclass = snd$

lemma $fldname-simp[simp]$: $fldname (n,c) = n$
 $\langle proof \rangle$

lemma $fldclass-simp[simp]$: $fldclass (n,c) = c$
 $\langle proof \rangle$

lemma $ext-fieldname-simp[simp]$: $(fldname f, fldclass f) = f$
 $\langle proof \rangle$

Convert a qualified method declaration (qualified with its declaring class) to a qualified member declaration: $methdMembr$

definition

$methdMembr :: qname \times mdecl \Rightarrow qname \times memberdecl$
where $methdMembr m = (fst m, mdecl (snd m))$

lemma $methdMembr-simp[simp]$: $methdMembr (c,m) = (c,mdecl m)$
 $\langle proof \rangle$

lemma $accmodi-methdMembr-simp[simp]$: $accmodi (methdMembr m) = accmodi m$
 $\langle proof \rangle$

lemma $is-static-methdMembr-simp[simp]$: $is-static (methdMembr m) = is-static m$
 $\langle proof \rangle$

lemma $declclass-methdMembr-simp[simp]$: $declclass (methdMembr m) = declclass m$
 $\langle proof \rangle$

Convert a qualified method (qualified with its declaring class) to a qualified member declaration: $method$

definition

$method :: sig \Rightarrow (qname \times method) \Rightarrow (qname \times memberdecl)$
where $method sig m = (declclass m, mdecl (sig, mthd m))$

lemma $method-simp[simp]$: $method sig (C,m) = (C,mdecl (sig,m))$
 $\langle proof \rangle$

lemma $accmodi-method-simp[simp]$: $accmodi (method sig m) = accmodi m$
 $\langle proof \rangle$

lemma $declclass-method-simp[simp]$: $declclass (method sig m) = declclass m$
 $\langle proof \rangle$

lemma *is-static-method-simp*[simp]: *is-static* (method sig m) = *is-static* m
 ⟨proof⟩

lemma *mbr-method-simp*[simp]: *mbr* (method sig m) = *mdecl* (sig,mthd m)
 ⟨proof⟩

lemma *memberid-method-simp*[simp]: *memberid* (method sig m) = *mid* sig
 ⟨proof⟩

definition

fieldm :: *vname* ⇒ (*qname* × *field*) ⇒ (*qname* × *memberdecl*)
where *fieldm* n f = (*declclass* f, *fdecl* (n, fld f))

lemma *fieldm-simp*[simp]: *fieldm* n (C,f) = (C,*fdecl* (n,f))
 ⟨proof⟩

lemma *accmodi-fieldm-simp*[simp]: *accmodi* (*fieldm* n f) = *accmodi* f
 ⟨proof⟩

lemma *declclass-fieldm-simp*[simp]: *declclass* (*fieldm* n f) = *declclass* f
 ⟨proof⟩

lemma *is-static-fieldm-simp*[simp]: *is-static* (*fieldm* n f) = *is-static* f
 ⟨proof⟩

lemma *mbr-fieldm-simp*[simp]: *mbr* (*fieldm* n f) = *fdecl* (n,fld f)
 ⟨proof⟩

lemma *memberid-fieldm-simp*[simp]: *memberid* (*fieldm* n f) = *fid* n
 ⟨proof⟩

Select the signature out of a qualified method declaration: *msig*

definition

msig :: (*qname* × *mdecl*) ⇒ *sig*
where *msig* m = *fst* (*snd* m)

lemma *msig-simp*[simp]: *msig* (c,(s,m)) = s
 ⟨proof⟩

Convert a qualified method (qualified with its declaring class) to a qualified method declaration:
qmdecl

definition

qmdecl :: *sig* ⇒ (*qname* × *method*) ⇒ (*qname* × *mdecl*)
where *qmdecl* sig m = (*declclass* m, (*sig*,*mthd* m))

lemma *qmdecl-simp*[simp]: *qmdecl* sig (C,m) = (C,(sig,m))
 ⟨proof⟩

lemma *declclass-qmdecl-simp*[simp]: *declclass (qmdecl sig m) = declclass m*
 ⟨proof⟩

lemma *accmodi-qmdecl-simp*[simp]: *accmodi (qmdecl sig m) = accmodi m*
 ⟨proof⟩

lemma *is-static-qmdecl-simp*[simp]: *is-static (qmdecl sig m) = is-static m*
 ⟨proof⟩

lemma *msig-qmdecl-simp*[simp]: *msig (qmdecl sig m) = sig*
 ⟨proof⟩

lemma *mdecl-qmdecl-simp*[simp]:
mdecl (mthd (qmdecl sig new)) = mdecl (sig, mthd new)
 ⟨proof⟩

lemma *methdMembr-qmdecl-simp* [simp]:
methdMembr (qmdecl sig old) = method sig old
 ⟨proof⟩

overloaded selector *resTy* to select the result type out of various HOL types

class *has-resTy* =
fixes *resTy*:: 'a ⇒ ty

instantiation *decl-ext* :: (*has-resTy*) *has-resTy*
begin

instance ⟨proof⟩

end

instantiation *member-ext* :: (*has-resTy*) *has-resTy*
begin

instance ⟨proof⟩

end

instantiation *mhead-ext* :: (*type*) *has-resTy*
begin

instance ⟨proof⟩

end

axiomatization where

mhead-ext-type-resTy-def: *resTy (m::('b mhead-scheme)) ≡ resT m*

lemma *mhead-resTy-simp*: *resTy (m::'a mhead-scheme) = resT m*
 ⟨proof⟩

lemma *resTy-mhead* [simp]: $\text{resTy } (\text{mhead } m) = \text{resTy } m$
 ⟨proof⟩

instantiation *prod* :: (type, has-resTy) has-resTy
begin

definition

pair-resTy-def: $\text{resTy } p = \text{resTy } (\text{snd } p)$

instance ⟨proof⟩

end

lemma *pair-resTy-simp*[simp]: $\text{resTy } (x, m) = \text{resTy } m$
 ⟨proof⟩

lemma *qmdecl-resTy-simp* [simp]: $\text{resTy } (\text{qmdecl } \text{sig } m) = \text{resTy } m$
 ⟨proof⟩

lemma *resTy-mthd* [simp]: $\text{resTy } (\text{mthd } m) = \text{resTy } m$
 ⟨proof⟩

inheritable-in

$G \vdash m$ *inheritable-in* P : m can be inherited by classes in package P if:

- the declaration class of m is accessible in P and
- the member m is declared with protected or public access or if it is declared with default (package) access, the package of the declaration class of m is also P . If the member m is declared with private access it is not accessible for inheritance at all.

definition

inheritable-in :: $\text{prog} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{pname} \Rightarrow \text{bool}$ (- \vdash - *inheritable'-in* - [61,61,61] 60)

where

$G \vdash \text{membr}$ *inheritable-in* $\text{pack} =$
 (case (accmodi membr) of
 | *Private* \Rightarrow *False*
 | *Package* \Rightarrow ($\text{pid } (\text{declclass } \text{membr})$) = pack
 | *Protected* \Rightarrow *True*
 | *Public* \Rightarrow *True*)

abbreviation

Method-inheritable-in-syntax::

$\text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{pname} \Rightarrow \text{bool}$
 (- \vdash *Method* - *inheritable'-in* - [61,61,61] 60)

where $G \vdash \text{Method } m$ *inheritable-in* $p == G \vdash \text{methdMembr } m$ *inheritable-in* p

abbreviation

Methd-inheritable-in::

$\text{prog} \Rightarrow \text{sig} \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow \text{pname} \Rightarrow \text{bool}$
 (- \vdash *Methd* - *inheritable'-in* - [61,61,61,61] 60)

where $G \vdash \text{Methd } s \ m$ *inheritable-in* $p == G \vdash (\text{method } s \ m)$ *inheritable-in* p

declared-in/undeclared-in

definition

cdeclaredmethd :: prog \Rightarrow qname \Rightarrow (sig, methd) table **where**
cdeclaredmethd G C =
 (case class G C of
 None \Rightarrow λ sig. None
 | Some c \Rightarrow table-of (methods c))

definition

cdeclaredfield :: prog \Rightarrow qname \Rightarrow (vname, field) table **where**
cdeclaredfield G C =
 (case class G C of
 None \Rightarrow λ sig. None
 | Some c \Rightarrow table-of (cfields c))

definition

declared-in :: prog \Rightarrow memberdecl \Rightarrow qname \Rightarrow bool (\vdash - declared'-in - [61,61,61] 60)

where

$G \vdash m$ declared-in C = (case m of
 fdecl (fn, f) \Rightarrow *cdeclaredfield* G C fn = Some f
 | mdecl (sig, m) \Rightarrow *cdeclaredmethd* G C sig = Some m)

abbreviation

method-declared-in:: prog \Rightarrow (qname \times mdecl) \Rightarrow qname \Rightarrow bool
 (\vdash Method - declared'-in - [61,61,61] 60)

where $G \vdash$ Method m declared-in C == $G \vdash$ mdecl (methd m) declared-in C

abbreviation

methd-declared-in:: prog \Rightarrow sig \Rightarrow (qname \times methd) \Rightarrow qname \Rightarrow bool
 (\vdash Methd - - declared'-in - [61,61,61,61] 60)

where $G \vdash$ Methd s m declared-in C == $G \vdash$ mdecl (s, methd m) declared-in C

lemma *declared-in-classD*:

$G \vdash m$ declared-in C \Longrightarrow is-class G C
 <proof>

definition

undeclared-in :: prog \Rightarrow memberid \Rightarrow qname \Rightarrow bool (\vdash - undeclared'-in - [61,61,61] 60)

where

$G \vdash m$ undeclared-in C = (case m of
 fid fn \Rightarrow *cdeclaredfield* G C fn = None
 | mid sig \Rightarrow *cdeclaredmethd* G C sig = None)

members**inductive**

members :: prog \Rightarrow (qname \times memberdecl) \Rightarrow qname \Rightarrow bool
 (\vdash - member'-of - [61,61,61] 60)

for G :: prog

where

Immediate: $\llbracket G \vdash mbr$ m declared-in C; declclass m = C $\rrbracket \Longrightarrow G \vdash m$ member-of C
 | *Inherited*: $\llbracket G \vdash m$ inheritable-in (pid C); $G \vdash$ memberid m undeclared-in C;
 $G \vdash C <_C 1$ S; $G \vdash$ (Class S) accessible-in (pid C); $G \vdash m$ member-of S
 $\rrbracket \Longrightarrow G \vdash m$ member-of C

Note that in the case of an inherited member only the members of the direct superclass are concerned. If a member of a superclass of the direct superclass isn't inherited in the direct superclass (not member of the direct superclass) than it can't be a member of the class. E.g. If a member of a class A is defined with package access it isn't member of a subclass S if S isn't in the same package as A.

Any further subclasses of S will not inherit the member, regardless if they are in the same package as A or not.

abbreviation

$$\text{method-member-of} :: \text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Method} - \text{member'-of} - [61,61,61] 60)$$

where $G \vdash \text{Method } m \text{ member-of } C == G \vdash (\text{methdMembr } m) \text{ member-of } C$

abbreviation

$$\text{methd-member-of} :: \text{prog} \Rightarrow \text{sig} \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Methd} - - \text{member'-of} - [61,61,61,61] 60)$$

where $G \vdash \text{Methd } s \text{ m member-of } C == G \vdash (\text{method } s \text{ m}) \text{ member-of } C$

abbreviation

$$\text{fieldm-member-of} :: \text{prog} \Rightarrow \text{vname} \Rightarrow (\text{qname} \times \text{field}) \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Field} - - \text{member'-of} - [61,61,61] 60)$$

where $G \vdash \text{Field } n \text{ f member-of } C == G \vdash \text{fieldm } n \text{ f member-of } C$

definition

$$\text{inherits} :: \text{prog} \Rightarrow \text{qname} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{bool} \quad (- \vdash - \text{inherits} - [61,61,61] 60)$$

where

$$G \vdash C \text{ inherits } m =$$

$$(G \vdash m \text{ inheritable-in } (\text{pid } C) \wedge G \vdash \text{memberid } m \text{ undeclared-in } C \wedge$$

$$(\exists S. G \vdash C \prec_C 1 S \wedge G \vdash (\text{Class } S) \text{ accessible-in } (\text{pid } C) \wedge G \vdash m \text{ member-of } S))$$

lemma *inherits-member*: $G \vdash C \text{ inherits } m \implies G \vdash m \text{ member-of } C$

<proof>

definition

$$\text{member-in} :: \text{prog} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{qname} \Rightarrow \text{bool} \quad (- \vdash - \text{member'-in} - [61,61,61] 60)$$

where $G \vdash m \text{ member-in } C = (\exists \text{ provC}. G \vdash C \preceq_C \text{ provC} \wedge G \vdash m \text{ member-of } \text{ provC})$

A member is in a class if it is member of the class or a superclass. If a member is in a class we can select this member. This additional notion is necessary since not all members are inherited to subclasses. So such members are not member-of the subclass but member-in the subclass.

abbreviation

$$\text{method-member-in} :: \text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Method} - \text{member'-in} - [61,61,61] 60)$$

where $G \vdash \text{Method } m \text{ member-in } C == G \vdash (\text{methdMembr } m) \text{ member-in } C$

abbreviation

$$\text{methd-member-in} :: \text{prog} \Rightarrow \text{sig} \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Methd} - - \text{member'-in} - [61,61,61,61] 60)$$

where $G \vdash \text{Methd } s \text{ m member-in } C == G \vdash (\text{method } s \text{ m}) \text{ member-in } C$

lemma *member-inD*: $G \vdash m \text{ member-in } C$

$\implies \exists \text{ provC}. G \vdash C \preceq_C \text{ provC} \wedge G \vdash m \text{ member-of } \text{ provC}$

<proof>

lemma *member-inI*: $\llbracket G \vdash m \text{ member-of } \text{ provC}; G \vdash C \preceq_C \text{ provC} \rrbracket \implies G \vdash m \text{ member-in } C$

<proof>

lemma *member-of-to-member-in*: $G \vdash m \text{ member-of } C \implies G \vdash m \text{ member-in } C$

<proof>

overriding

Unfortunately the static notion of overriding (used during the typecheck of the compiler) and the dynamic notion of overriding (used during execution in the JVM) are not exactly the same.

Static overriding (used during the typecheck of the compiler)

inductive

$$\text{stat-overridesR} :: \text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{bool}$$

$$(- \vdash - \text{overrides}_S - [61,61,61] 60)$$

for $G :: \text{prog}$

where

Direct: $\llbracket \neg \text{is-static new}; \text{msig new} = \text{msig old};$
 $G \vdash \text{Method new declared-in (declclass new)};$
 $G \vdash \text{Method old declared-in (declclass old)};$
 $G \vdash \text{Method old inheritable-in pid (declclass new)};$
 $G \vdash (\text{declclass new}) \prec_C 1 \text{ superNew};$
 $G \vdash \text{Method old member-of superNew}$
 $\rrbracket \implies G \vdash \text{new overrides}_S \text{ old}$

| *Indirect:* $\llbracket G \vdash \text{new overrides}_S \text{ intr}; G \vdash \text{intr overrides}_S \text{ old} \rrbracket$
 $\implies G \vdash \text{new overrides}_S \text{ old}$

Dynamic overriding (used during the typecheck of the compiler)

inductive

$$\text{overridesR} :: \text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{bool}$$

$$(- \vdash - \text{overrides} - [61,61,61] 60)$$

for $G :: \text{prog}$

where

Direct: $\llbracket \neg \text{is-static new}; \neg \text{is-static old}; \text{accmodi new} \neq \text{Private};$
 $\text{msig new} = \text{msig old};$
 $G \vdash (\text{declclass new}) \prec_C (\text{declclass old});$
 $G \vdash \text{Method new declared-in (declclass new)};$
 $G \vdash \text{Method old declared-in (declclass old)};$
 $G \vdash \text{Method old inheritable-in pid (declclass new)};$
 $G \vdash \text{resTy new} \preceq \text{resTy old}$
 $\rrbracket \implies G \vdash \text{new overrides old}$

| *Indirect:* $\llbracket G \vdash \text{new overrides intr}; G \vdash \text{intr overrides old} \rrbracket$
 $\implies G \vdash \text{new overrides old}$

abbreviation (input)

sig-stat-overrides::

$$\text{prog} \Rightarrow \text{sig} \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow \text{bool}$$

$$(-, \vdash - \text{overrides}_S - [61,61,61,61] 60)$$

where $G, s \vdash \text{new overrides}_S \text{ old} == G \vdash (\text{qmdecl } s \text{ new}) \text{ overrides}_S (\text{qmdecl } s \text{ old})$

abbreviation (input)

sig-overrides:: $\text{prog} \Rightarrow \text{sig} \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow \text{bool}$
 $(-, \vdash - \text{overrides} - [61,61,61,61] 60)$

where $G, s \vdash \text{new overrides old} == G \vdash (\text{qmdecl } s \text{ new}) \text{ overrides} (\text{qmdecl } s \text{ old})$

Hiding

definition

$$\text{hides} :: \text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{bool} \quad (- \vdash - \text{hides} - [61,61,61] 60)$$

where

$G \vdash \text{new hides old} =$

$$\begin{aligned}
& (is-static\ new \wedge msig\ new = msig\ old \wedge \\
& \quad G \vdash (declclass\ new) \prec_C (declclass\ old) \wedge \\
& \quad G \vdash Method\ new\ declared-in\ (declclass\ new) \wedge \\
& \quad G \vdash Method\ old\ declared-in\ (declclass\ old) \wedge \\
& \quad G \vdash Method\ old\ inheritable-in\ pid\ (declclass\ new))
\end{aligned}$$
abbreviation

$$sig-hides::\ prog \Rightarrow sig \Rightarrow (qname \times methd) \Rightarrow (qname \times methd) \Rightarrow bool$$

$$(-, \vdash -\ hides - [61, 61, 61, 61] 60)$$

where $G, s \vdash new\ hides\ old == G \vdash (qmdecl\ s\ new)\ hides\ (qmdecl\ s\ old)$

lemma *hidesI*:
$$\begin{aligned}
& \llbracket is-static\ new; msig\ new = msig\ old; \\
& \quad G \vdash (declclass\ new) \prec_C (declclass\ old); \\
& \quad G \vdash Method\ new\ declared-in\ (declclass\ new); \\
& \quad G \vdash Method\ old\ declared-in\ (declclass\ old); \\
& \quad G \vdash Method\ old\ inheritable-in\ pid\ (declclass\ new) \\
& \rrbracket \Longrightarrow G \vdash new\ hides\ old \\
& \langle proof \rangle
\end{aligned}$$
lemma *hidesD*:
$$\begin{aligned}
& \llbracket G \vdash new\ hides\ old \rrbracket \Longrightarrow \\
& \quad declclass\ new \neq Object \wedge is-static\ new \wedge msig\ new = msig\ old \wedge \\
& \quad G \vdash (declclass\ new) \prec_C (declclass\ old) \wedge \\
& \quad G \vdash Method\ new\ declared-in\ (declclass\ new) \wedge \\
& \quad G \vdash Method\ old\ declared-in\ (declclass\ old) \\
& \langle proof \rangle
\end{aligned}$$
lemma *overrides-commonD*:
$$\begin{aligned}
& \llbracket G \vdash new\ overrides\ old \rrbracket \Longrightarrow \\
& \quad declclass\ new \neq Object \wedge \neg is-static\ new \wedge \neg is-static\ old \wedge \\
& \quad accmodi\ new \neq Private \wedge \\
& \quad msig\ new = msig\ old \wedge \\
& \quad G \vdash (declclass\ new) \prec_C (declclass\ old) \wedge \\
& \quad G \vdash Method\ new\ declared-in\ (declclass\ new) \wedge \\
& \quad G \vdash Method\ old\ declared-in\ (declclass\ old) \\
& \langle proof \rangle
\end{aligned}$$
lemma *ws-overrides-commonD*:
$$\begin{aligned}
& \llbracket G \vdash new\ overrides\ old; ws-prog\ G \rrbracket \Longrightarrow \\
& \quad declclass\ new \neq Object \wedge \neg is-static\ new \wedge \neg is-static\ old \wedge \\
& \quad accmodi\ new \neq Private \wedge G \vdash resTy\ new \preceq resTy\ old \wedge \\
& \quad msig\ new = msig\ old \wedge \\
& \quad G \vdash (declclass\ new) \prec_C (declclass\ old) \wedge \\
& \quad G \vdash Method\ new\ declared-in\ (declclass\ new) \wedge \\
& \quad G \vdash Method\ old\ declared-in\ (declclass\ old) \\
& \langle proof \rangle
\end{aligned}$$
lemma *overrides-eq-sigD*:
$$\llbracket G \vdash new\ overrides\ old \rrbracket \Longrightarrow msig\ old = msig\ new$$

$\langle proof \rangle$

lemma *hides-eq-sigD*:

$\llbracket G \vdash \text{new hides old} \rrbracket \implies \text{msig old} = \text{msig new}$
 (proof)

permits access

definition

$\text{permits-acc} :: \text{prog} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool} \text{ (- } \vdash \text{ - in - permits'-acc'-from - [61,61,61,61] 60)}$

where

$G \vdash \text{membr in cls permits-acc-from accclass} =$
 (case (accmodi membr) of
 | *Private* $\Rightarrow (\text{declclass membr} = \text{accclass})$
 | *Package* $\Rightarrow (\text{pid} (\text{declclass membr}) = \text{pid accclass})$
 | *Protected* $\Rightarrow (\text{pid} (\text{declclass membr}) = \text{pid accclass})$
 \vee
 $(G \vdash \text{accclass} \prec_C \text{declclass membr}$
 $\wedge (G \vdash \text{cls} \preceq_C \text{accclass} \vee \text{is-static membr}))$
 | *Public* $\Rightarrow \text{True}$)

The subcondition of the *Protected* case: $G \vdash \text{accclass} \prec_C \text{declclass membr}$ could also be relaxed to: $G \vdash \text{accclass} \preceq_C \text{declclass membr}$ since in case both classes are the same the other condition $\text{pid} (\text{declclass membr}) = \text{pid accclass}$ holds anyway.

Like in case of overriding, the static and dynamic accessibility of members is not uniform.

- Statically the class/interface of the member must be accessible for the member to be accessible. During runtime this is not necessary. For Example, if a class is accessible and we are allowed to access a member of this class (statically) we expect that we can access this member in an arbitrary subclass (during runtime). It's not intended to restrict the access to accessible subclasses during runtime.
- Statically the member we want to access must be "member of" the class. Dynamically it must only be "member in" the class.

inductive

$\text{accessible-fromR} :: \text{prog} \Rightarrow \text{qname} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{qname} \Rightarrow \text{bool}$
and $\text{accessible-from} :: \text{prog} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$
 (- \vdash - of - accessible'-from - [61,61,61,61] 60)
and $\text{method-accessible-from} :: \text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$
 (- \vdash Method - of - accessible'-from - [61,61,61,61] 60)
for $G :: \text{prog}$ **and** $\text{accclass} :: \text{qname}$

where

$G \vdash \text{membr of cls accessible-from accclass} \equiv \text{accessible-fromR } G \text{ accclass membr cls}$

| $G \vdash \text{Method } m \text{ of cls accessible-from accclass} \equiv \text{accessible-fromR } G \text{ accclass (methdMembr } m) \text{ cls}$

| *Immediate*: !!membr class.

$\llbracket G \vdash \text{membr member-of class};$
 $G \vdash (\text{Class class}) \text{ accessible-in (pid accclass)};$
 $G \vdash \text{membr in class permits-acc-from accclass}$
 $\rrbracket \implies G \vdash \text{membr of class accessible-from accclass}$

| *Overriding*: $\text{!!membr class } C \text{ new old supr.}$

$\llbracket G \vdash \text{membr member-of class};$
 $G \vdash (\text{Class class}) \text{ accessible-in (pid accclass)};$
 $\text{membr} = (C, \text{mdecl new});$
 $G \vdash (C, \text{new}) \text{ overrides}_S \text{ old};$
 $G \vdash \text{class} \prec_C \text{ supr};$
 $G \vdash \text{Method old of supr accessible-from accclass}$

$$\boxed{\implies} G\vdash \text{memb}r \text{ of class accessible-from } \text{accclass}$$
abbreviation

methd-accessible-from::

$$\text{prog} \Rightarrow \text{sig} \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Methd} \text{ - - of - accessible'-from - } [61,61,61,61,61] \ 60)$$
where

$$G\vdash \text{Methd } s \ m \ \text{ of cls accessible-from } \text{accclass} ==$$

$$G\vdash (\text{method } s \ m) \ \text{ of cls accessible-from } \text{accclass}$$
abbreviation

field-accessible-from::

$$\text{prog} \Rightarrow \text{vname} \Rightarrow (\text{qname} \times \text{field}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Field} \text{ - - of - accessible'-from - } [61,61,61,61,61] \ 60)$$
where

$$G\vdash \text{Field } \text{fn } f \ \text{ of } C \ \text{ accessible-from } \text{accclass} ==$$

$$G\vdash (\text{fieldm } \text{fn } f) \ \text{ of } C \ \text{ accessible-from } \text{accclass}$$
inductive

$$\text{dyn-accessible-fromR} :: \text{prog} \Rightarrow \text{qname} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{qname} \Rightarrow \text{bool}$$

and *dyn-accessible-from'* :: $\text{prog} \Rightarrow (\text{qname} \times \text{memberdecl}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$

$$(- \vdash \text{ - in - dyn'-accessible'-from - } [61,61,61,61] \ 60)$$

and *method-dyn-accessible-from* :: $\text{prog} \Rightarrow (\text{qname} \times \text{mdecl}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$

$$(- \vdash \text{Method - in - dyn'-accessible'-from - } [61,61,61,61] \ 60)$$

for $G :: \text{prog}$ **and** $\text{accclass} :: \text{qname}$

where

$$G\vdash \text{memb}r \ \text{ in } C \ \text{ dyn-accessible-from } \text{accC} \equiv \text{dyn-accessible-fromR } G \ \text{accC} \ \text{memb}r \ C$$

$$| \ G\vdash \text{Method } m \ \text{ in } C \ \text{ dyn-accessible-from } \text{accC} \equiv \text{dyn-accessible-fromR } G \ \text{accC} \ (\text{methdMembr } m) \ C$$

$$| \ \text{Immediate: } !!\text{class. } \boxed{\implies} G\vdash \text{memb}r \ \text{ member-in } \text{class};$$

$$G\vdash \text{memb}r \ \text{ in } \text{class} \ \text{permits-acc-from } \text{accclass}$$

$$\boxed{\implies} G\vdash \text{memb}r \ \text{ in } \text{class} \ \text{dyn-accessible-from } \text{accclass}$$

$$| \ \text{Overriding: } !!\text{class. } \boxed{\implies} G\vdash \text{memb}r \ \text{ member-in } \text{class};$$

$$\text{memb}r = (C, \text{mdecl } \text{new});$$

$$G\vdash (C, \text{new}) \ \text{overrides } \text{old};$$

$$G\vdash \text{class} \prec_C \ \text{supr};$$

$$G\vdash \text{Method } \text{old} \ \text{ in } \text{supr} \ \text{dyn-accessible-from } \text{accclass}$$

$$\boxed{\implies} G\vdash \text{memb}r \ \text{ in } \text{class} \ \text{dyn-accessible-from } \text{accclass}$$
abbreviation

methd-dyn-accessible-from::

$$\text{prog} \Rightarrow \text{sig} \Rightarrow (\text{qname} \times \text{methd}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Methd} \text{ - - in - dyn'-accessible'-from - } [61,61,61,61,61] \ 60)$$
where

$$G\vdash \text{Methd } s \ m \ \text{ in } C \ \text{ dyn-accessible-from } \text{accC} ==$$

$$G\vdash (\text{method } s \ m) \ \text{ in } C \ \text{ dyn-accessible-from } \text{accC}$$
abbreviation

field-dyn-accessible-from::

$$\text{prog} \Rightarrow \text{vname} \Rightarrow (\text{qname} \times \text{field}) \Rightarrow \text{qname} \Rightarrow \text{qname} \Rightarrow \text{bool}$$

$$(- \vdash \text{Field} \text{ - - in - dyn'-accessible'-from - } [61,61,61,61,61] \ 60)$$
where

$$G\vdash \text{Field } \text{fn } f \ \text{ in } \text{dynC} \ \text{ dyn-accessible-from } \text{accC} ==$$

$$G\vdash (\text{fieldm } \text{fn } f) \ \text{ in } \text{dynC} \ \text{ dyn-accessible-from } \text{accC}$$

lemma *accessible-from-commonD*: $G \vdash m$ of C accessible-from S
 $\implies G \vdash m$ member-of $C \wedge G \vdash (\text{Class } C)$ accessible-in ($\text{pid } S$)
 ⟨proof⟩

lemma *unique-declaration*:
 $\llbracket G \vdash m$ declared-in C ; $G \vdash n$ declared-in C ; memberid $m = \text{memberid } n \rrbracket$
 $\implies m = n$
 ⟨proof⟩

lemma *declared-not-undeclared*:
 $G \vdash m$ declared-in $C \implies \neg G \vdash$ memberid m undeclared-in C
 ⟨proof⟩

lemma *undeclared-not-declared*:
 $G \vdash$ memberid m undeclared-in $C \implies \neg G \vdash m$ declared-in C
 ⟨proof⟩

lemma *not-undeclared-declared*:
 $\neg G \vdash$ membr-id undeclared-in $C \implies (\exists m. G \vdash m$ declared-in $C \wedge$
 $\text{membr-id} = \text{memberid } m)$
 ⟨proof⟩

lemma *unique-declared-in*:
 $\llbracket G \vdash m$ declared-in C ; $G \vdash n$ declared-in C ; memberid $m = \text{memberid } n \rrbracket$
 $\implies m = n$
 ⟨proof⟩

lemma *unique-member-of*:
assumes n : $G \vdash n$ member-of C **and**
 m : $G \vdash m$ member-of C **and**
 eqid : memberid $n = \text{memberid } m$
shows $n = m$
 ⟨proof⟩

lemma *member-of-is-classD*: $G \vdash m$ member-of $C \implies \text{is-class } G C$
 ⟨proof⟩

lemma *member-of-declC*:
 $G \vdash m$ member-of C
 $\implies G \vdash \text{mbr } m$ declared-in ($\text{declclass } m$)
 ⟨proof⟩

lemma *member-of-member-of-declC*:
 $G \vdash m$ member-of C
 $\implies G \vdash m$ member-of ($\text{declclass } m$)
 ⟨proof⟩

lemma *member-of-class-relation*:
 $G \vdash m$ member-of $C \implies G \vdash C \preceq_C \text{ declclass } m$

$\langle \text{proof} \rangle$

lemma *member-in-class-relation*:

$G \vdash m \text{ member-in } C \implies G \vdash C \preceq_C \text{ declclass } m$
 $\langle \text{proof} \rangle$

lemma *stat-override-declclasses-relation*:

$\llbracket G \vdash (\text{declclass } \text{new}) \prec_C 1 \text{ superNew}; G \vdash \text{Method } \text{old} \text{ member-of } \text{superNew} \rrbracket$
 $\implies G \vdash (\text{declclass } \text{new}) \prec_C (\text{declclass } \text{old})$
 $\langle \text{proof} \rangle$

lemma *stat-overrides-commonD*:

$\llbracket G \vdash \text{new overrides}_S \text{ old} \rrbracket \implies$
 $\text{declclass } \text{new} \neq \text{Object} \wedge \neg \text{is-static } \text{new} \wedge \text{msig } \text{new} = \text{msig } \text{old} \wedge$
 $G \vdash (\text{declclass } \text{new}) \prec_C (\text{declclass } \text{old}) \wedge$
 $G \vdash \text{Method } \text{new} \text{ declared-in } (\text{declclass } \text{new}) \wedge$
 $G \vdash \text{Method } \text{old} \text{ declared-in } (\text{declclass } \text{old})$
 $\langle \text{proof} \rangle$

lemma *member-of-Package*:

assumes $G \vdash m \text{ member-of } C$
and $\text{accmodi } m = \text{Package}$
shows $\text{pid } (\text{declclass } m) = \text{pid } C$
 $\langle \text{proof} \rangle$

lemma *member-in-declC*: $G \vdash m \text{ member-in } C \implies G \vdash m \text{ member-in } (\text{declclass } m)$

$\langle \text{proof} \rangle$

lemma *dyn-accessible-from-commonD*: $G \vdash m \text{ in } C \text{ dyn-accessible-from } S$

$\implies G \vdash m \text{ member-in } C$
 $\langle \text{proof} \rangle$

lemma *no-Private-stat-override*:

$\llbracket G \vdash \text{new overrides}_S \text{ old} \rrbracket \implies \text{accmodi } \text{old} \neq \text{Private}$
 $\langle \text{proof} \rangle$

lemma *no-Private-override*: $\llbracket G \vdash \text{new overrides } \text{old} \rrbracket \implies \text{accmodi } \text{old} \neq \text{Private}$

$\langle \text{proof} \rangle$

lemma *permits-acc-inheritance*:

$\llbracket G \vdash m \text{ in } \text{stat}C \text{ permits-acc-from } \text{acc}C; G \vdash \text{dyn}C \preceq_C \text{stat}C$
 $\rrbracket \implies G \vdash m \text{ in } \text{dyn}C \text{ permits-acc-from } \text{acc}C$
 $\langle \text{proof} \rangle$

lemma *permits-acc-static-declC*:

$\llbracket G \vdash m \text{ in } C \text{ permits-acc-from } \text{acc}C; G \vdash m \text{ member-in } C; \text{is-static } m$
 $\rrbracket \implies G \vdash m \text{ in } (\text{declclass } m) \text{ permits-acc-from } \text{acc}C$
 $\langle \text{proof} \rangle$

lemma *dyn-accessible-from-static-declC*:

assumes *acc-C*: $G \vdash m$ in C *dyn-accessible-from* *accC* **and**
static: *is-static* m

shows $G \vdash m$ in (*declclass* m) *dyn-accessible-from* *accC*

<proof>

lemma *field-accessible-fromD*:

$\llbracket G \vdash \text{membr of } C \text{ accessible-from } accC; \text{is-field membr} \rrbracket$

$\implies G \vdash \text{membr member-of } C \wedge$

$G \vdash (\text{Class } C) \text{ accessible-in } (pid \text{ } accC) \wedge$

$G \vdash \text{membr in } C \text{ permits-acc-from } accC$

<proof>

lemma *field-accessible-from-permits-acc-inheritance*:

$\llbracket G \vdash \text{membr of } statC \text{ accessible-from } accC; \text{is-field membr}; G \vdash dynC \preceq_C statC \rrbracket$

$\implies G \vdash \text{membr in } dynC \text{ permits-acc-from } accC$

<proof>

lemma *accessible-fieldD*:

$\llbracket G \vdash \text{membr of } C \text{ accessible-from } accC; \text{is-field membr} \rrbracket$

$\implies G \vdash \text{membr member-of } C \wedge$

$G \vdash (\text{Class } C) \text{ accessible-in } (pid \text{ } accC) \wedge$

$G \vdash \text{membr in } C \text{ permits-acc-from } accC$

<proof>

lemma *member-of-Private*:

$\llbracket G \vdash m \text{ member-of } C; \text{accmodi } m = \text{Private} \rrbracket \implies \text{declclass } m = C$

<proof>

lemma *member-of-subclseq-declC*:

$G \vdash m \text{ member-of } C \implies G \vdash C \preceq_C \text{ declclass } m$

<proof>

lemma *member-of-inheritance*:

assumes m : $G \vdash m$ *member-of* D **and**

subclseq-D-C: $G \vdash D \preceq_C C$ **and**

subclseq-C-m: $G \vdash C \preceq_C \text{ declclass } m$ **and**

ws: *ws-prog* G

shows $G \vdash m$ *member-of* C

<proof>

lemma *member-of-subcls*:

assumes *old*: $G \vdash \text{old}$ *member-of* C **and**

new: $G \vdash \text{new}$ *member-of* D **and**

eqid: *memberid* *new* = *memberid* *old* **and**

subclseq-D-C: $G \vdash D \preceq_C C$ **and**

subcls-new-old: $G \vdash \text{declclass new} \prec_C \text{declclass old}$ **and**
 $ws: ws\text{-prog } G$
shows $G \vdash D \prec_C C$
 ⟨proof⟩

corollary *member-of-overrides-subcls*:
 $\llbracket G \vdash \text{Methd sig old member-of } C; G \vdash \text{Methd sig new member-of } D; G \vdash D \preceq_C C;$
 $G, \text{sig} \vdash \text{new overrides old}; ws\text{-prog } G \rrbracket$
 $\implies G \vdash D \prec_C C$
 ⟨proof⟩

corollary *member-of-stat-overrides-subcls*:
 $\llbracket G \vdash \text{Methd sig old member-of } C; G \vdash \text{Methd sig new member-of } D; G \vdash D \preceq_C C;$
 $G, \text{sig} \vdash \text{new overrides}_S \text{ old}; ws\text{-prog } G \rrbracket$
 $\implies G \vdash D \prec_C C$
 ⟨proof⟩

lemma *inherited-field-access*:
assumes *stat-acc*: $G \vdash \text{memb of stat} C \text{ accessible-from } acc C$ **and**
is-field: *is-field membr* **and**
subclseq: $G \vdash \text{dyn} C \preceq_C \text{stat} C$
shows $G \vdash \text{memb in dyn} C \text{ dyn-accessible-from } acc C$
 ⟨proof⟩

lemma *accessible-inheritance*:
assumes *stat-acc*: $G \vdash m \text{ of stat} C \text{ accessible-from } acc C$ **and**
subclseq: $G \vdash \text{dyn} C \preceq_C \text{stat} C$ **and**
member-dynC: $G \vdash m \text{ member-of } \text{dyn} C$ **and**
dynC-acc: $G \vdash (\text{Class } \text{dyn} C) \text{ accessible-in } (pid \text{ } acc C)$
shows $G \vdash m \text{ of } \text{dyn} C \text{ accessible-from } acc C$
 ⟨proof⟩

fields and methods

type-synonym
 $f\text{spec} = v\text{name} \times q\text{name}$

translations
 $(\text{type}) f\text{spec} \leq (\text{type}) v\text{name} \times q\text{name}$

definition
 $imethods :: \text{prog} \Rightarrow q\text{name} \Rightarrow (\text{sig}, q\text{name} \times m\text{head}) \text{ tables}$ **where**
 $imethods \ G \ I =$
 $iface\text{-rec } G \ I \ (\lambda I \ i \ ts. (Un\text{-tables } ts) \oplus \oplus$
 $(Option.set \circ table\text{-of } (map \ (\lambda (s,m). (s, I, m)) \ (imethods \ i))))$

methods of an interface, with overriding and inheritance, cf. 9.2

definition
 $accimethods :: \text{prog} \Rightarrow p\text{name} \Rightarrow q\text{name} \Rightarrow (\text{sig}, q\text{name} \times m\text{head}) \text{ tables}$ **where**
 $accimethods \ G \ pack \ I =$
 $(if \ G \vdash \text{Iface } I \text{ accessible-in } pack$
 $then \ imethods \ G \ I$
 $else \ (\lambda k. \ {}))$

only returns imethods if the interface is accessible

definition

$$\begin{aligned}
\mathit{methd} &:: \mathit{prog} \Rightarrow \mathit{qname} \Rightarrow (\mathit{sig}, \mathit{qname} \times \mathit{methd}) \mathit{table} \mathbf{where} \\
\mathit{methd} \ G \ C &= \\
&\mathit{class-rec} \ G \ C \ \mathit{empty} \\
&\quad (\lambda C \ c \ \mathit{subcls-mthds}. \\
&\quad \quad \mathit{filter-tab} \ (\lambda \mathit{sig} \ m. \ G \vdash C \ \mathit{inherits} \ \mathit{method} \ \mathit{sig} \ m) \\
&\quad \quad \quad \mathit{subcls-mthds} \\
&\quad ++ \\
&\quad \mathit{table-of} \ (\mathit{map} \ (\lambda (s,m). \ (s, C, m)) \ (\mathit{methods} \ c))
\end{aligned}$$

$\mathit{methd} \ G \ C$: methods of a class C (statically visible from C), with inheritance and hiding cf. 8.4.6; Overriding is captured by $\mathit{dynmethd}$. Every new method with the same signature coalesces the method of a superclass.

definition

$$\begin{aligned}
\mathit{accmethd} &:: \mathit{prog} \Rightarrow \mathit{qname} \Rightarrow \mathit{qname} \Rightarrow (\mathit{sig}, \mathit{qname} \times \mathit{methd}) \mathit{table} \mathbf{where} \\
\mathit{accmethd} \ G \ S \ C &= \\
&\mathit{filter-tab} \ (\lambda \mathit{sig} \ m. \ G \vdash \mathit{method} \ \mathit{sig} \ m \ \mathit{of} \ C \ \mathit{accessible-from} \ S) \ (\mathit{methd} \ G \ C)
\end{aligned}$$

$\mathit{accmethd} \ G \ S \ C$: only those methods of $\mathit{methd} \ G \ C$, accessible from S

Note the class component in the accessibility filter. The class where method m is declared ($\mathit{decl}C$) isn't necessarily accessible from the current scope S . The method can be made accessible through inheritance, too. So we must test accessibility of method m of class C (not $\mathit{declclass} \ m$)

definition

$$\begin{aligned}
\mathit{dynmethd} &:: \mathit{prog} \Rightarrow \mathit{qname} \Rightarrow \mathit{qname} \Rightarrow (\mathit{sig}, \mathit{qname} \times \mathit{methd}) \mathit{table} \mathbf{where} \\
\mathit{dynmethd} \ G \ \mathit{stat}C \ \mathit{dyn}C &= \\
&(\lambda \mathit{sig}. \\
&\quad (\mathit{if} \ G \vdash \mathit{dyn}C \preceq_C \ \mathit{stat}C \\
&\quad \quad \mathit{then} \ (\mathit{case} \ \mathit{methd} \ G \ \mathit{stat}C \ \mathit{sig} \ \mathit{of} \\
&\quad \quad \quad \mathit{None} \Rightarrow \mathit{None} \\
&\quad \quad \quad | \ \mathit{Some} \ \mathit{stat}M \\
&\quad \quad \quad \Rightarrow (\mathit{class-rec} \ G \ \mathit{dyn}C \ \mathit{empty} \\
&\quad \quad \quad \quad (\lambda C \ c \ \mathit{subcls-mthds}. \\
&\quad \quad \quad \quad \quad \mathit{subcls-mthds} \\
&\quad \quad \quad \quad ++ \\
&\quad \quad \quad \quad (\mathit{filter-tab} \\
&\quad \quad \quad \quad \quad (\lambda - \ \mathit{dyn}M. \ G, \mathit{sig} \vdash \mathit{dyn}M \ \mathit{overrides} \ \mathit{stat}M \ \vee \ \mathit{dyn}M = \mathit{stat}M) \\
&\quad \quad \quad \quad \quad (\mathit{methd} \ G \ C) \)) \\
&\quad \quad \quad \quad) \ \mathit{sig} \\
&\quad \quad \quad) \\
&\quad \quad \mathit{else} \ \mathit{None}))
\end{aligned}$$

$\mathit{dynmethd} \ G \ \mathit{stat}C \ \mathit{dyn}C$: dynamic method lookup of a reference with dynamic class $\mathit{dyn}C$ and static class $\mathit{stat}C$

Note some kind of duality between methd and $\mathit{dynmethd}$ in the $\mathit{class-rec}$ arguments. Whereas methd filters the subclass methods (to get only the inherited ones), $\mathit{dynmethd}$ filters the new methods (to get only those methods which actually override the methods of the static class)

definition

$$\begin{aligned}
\mathit{dynimethd} &:: \mathit{prog} \Rightarrow \mathit{qname} \Rightarrow \mathit{qname} \Rightarrow (\mathit{sig}, \mathit{qname} \times \mathit{methd}) \mathit{table} \mathbf{where} \\
\mathit{dynimethd} \ G \ I \ \mathit{dyn}C &= \\
&(\lambda \mathit{sig}. \ \mathit{if} \ \mathit{imethds} \ G \ I \ \mathit{sig} \neq \{\} \\
&\quad \mathit{then} \ \mathit{methd} \ G \ \mathit{dyn}C \ \mathit{sig} \\
&\quad \mathit{else} \ \mathit{dynmethd} \ G \ \mathit{Object} \ \mathit{dyn}C \ \mathit{sig})
\end{aligned}$$

$\mathit{dynimethd} \ G \ I \ \mathit{dyn}C$: dynamic method lookup of a reference with dynamic class $\mathit{dyn}C$ and static interface type I

When calling an interface method, we must distinguish if the method signature was defined in the interface or if it must be an Object method in the other case. If it was an interface method we search the class hierarchy starting at the dynamic class of the object up to Object to find the first matching method (*methd*). Since all interface methods have public access the method can't be coalesced due to some odd visibility effects like in case of *dynmethd*. The method will be inherited or overridden in all classes from the first class implementing the interface down to the actual dynamic class.

definition

dynlookup :: *prog* \Rightarrow *ref-ty* \Rightarrow *qname* \Rightarrow (*sig,qname* \times *methd*) *table* **where**
dynlookup *G statT dynC* =
 (*case statT of*
 NullT \Rightarrow *empty*
 | *IfaceT I* \Rightarrow *dynimethd G I dynC*
 | *ClassT statC* \Rightarrow *dynmethd G statC dynC*
 | *ArrayT ty* \Rightarrow *dynmethd G Object dynC*)

dynlookup G statT dynC: dynamic lookup of a method within the static reference type *statT* and the dynamic class *dynC*. In a wellformd context *statT* will not be *NullT* and in case *statT* is an array type, *dynC*=Object

definition

fields :: *prog* \Rightarrow *qname* \Rightarrow ((*vname* \times *qname*) \times *field*) *list* **where**
fields G C =
class-rec G C [] ($\lambda C c ts. \text{map } (\lambda(n,t). ((n,C),t)) (cfields c) @ ts$)

DeclConcepts.fields G C list of fields of a class, including all the fields of the superclasses (private, inherited and hidden ones) not only the accessible ones (an instance of a object allocates all these fields)

definition

accfield :: *prog* \Rightarrow *qname* \Rightarrow *qname* \Rightarrow (*vname, qname* \times *field*) *table* **where**
accfield G S C =
 (*let field-tab* = *table-of*((*map* ($\lambda((n,d),f).((n,(d,f))))$) (*fields G C*))
 in filter-tab ($\lambda n (declC,f). G \vdash (declC,fdecl (n,f)) \text{ of } C \text{ accessible-from } S$)
 field-tab)

accfield G C S: fields of a class *C* which are accessible from scope of class *S* with inheritance and hiding, cf. 8.3

note the class component in the accessibility filter (see also *methd*). The class declaring field *f* (*declC*) isn't necessarily accessible from scope *S*. The field can be made visible through inheritance, too. So we must test accessibility of field *f* of class *C* (not *declclass f*)

definition

is-methd :: *prog* \Rightarrow *qname* \Rightarrow *sig* \Rightarrow *bool*
where *is-methd G* = ($\lambda C sig. is-class G C \wedge methd G C sig \neq None$)

definition

efname :: ((*vname* \times *qname*) \times *field*) \Rightarrow (*vname* \times *qname*)
where *efname* = *fst*

lemma *efname-simp[simp]:efname (n,f) = n*

<proof>

19 imethds

lemma *imethds-rec: [iface G I = Some i; ws-prog G] \implies*

imethds G I = Un-tables (($\lambda J. imethds G J$) 'set (isuperIfs i)) $\oplus \oplus$
(Option.set \circ table-of (map ($\lambda(s,mh). (s,I,mh)$) (imethods i)))

$\langle \text{proof} \rangle$

lemma *imethds-norec*:

$\llbracket \text{iface } G \text{ md} = \text{Some } i; \text{ws-prog } G; \text{table-of } (\text{imethds } i) \text{ sig} = \text{Some } mh \rrbracket \implies$
 $(\text{md}, mh) \in \text{imethds } G \text{ md sig}$
 $\langle \text{proof} \rangle$

lemma *imethds-declI*: $\llbracket m \in \text{imethds } G \text{ I sig}; \text{ws-prog } G; \text{is-iface } G \text{ I} \rrbracket \implies$

$(\exists i. \text{iface } G (\text{decliface } m) = \text{Some } i \wedge$
 $\text{table-of } (\text{imethds } i) \text{ sig} = \text{Some } (\text{mthd } m)) \wedge$
 $(I, \text{decliface } m) \in (\text{subint1 } G)^{\wedge*} \wedge m \in \text{imethds } G (\text{decliface } m) \text{ sig}$
 $\langle \text{proof} \rangle$

lemma *imethds-cases*:

assumes *im*: $im \in \text{imethds } G \text{ I sig}$
and *ifI*: $\text{iface } G \text{ I} = \text{Some } i$
and *ws*: $\text{ws-prog } G$
obtains $(\text{NewMethod}) \text{table-of } (\text{map } (\lambda(s, mh). (s, I, mh)) (\text{imethds } i)) \text{ sig} = \text{Some } im$
 $| (\text{InheritedMethod}) J$ **where** $J \in \text{set } (\text{isuperIfs } i)$ **and** $im \in \text{imethds } G \text{ J sig}$
 $\langle \text{proof} \rangle$

20 accimethd

lemma *accimethds-simp* [*simp*]:

$G \vdash \text{Iface } I \text{ accessible-in pack} \implies \text{accimethds } G \text{ pack } I = \text{imethds } G \text{ I}$
 $\langle \text{proof} \rangle$

lemma *accimethdsD*:

$im \in \text{accimethds } G \text{ pack } I \text{ sig}$
 $\implies im \in \text{imethds } G \text{ I sig} \wedge G \vdash \text{Iface } I \text{ accessible-in pack}$
 $\langle \text{proof} \rangle$

lemma *accimethdsI*:

$\llbracket im \in \text{imethds } G \text{ I sig}; G \vdash \text{Iface } I \text{ accessible-in pack} \rrbracket$
 $\implies im \in \text{accimethds } G \text{ pack } I \text{ sig}$
 $\langle \text{proof} \rangle$

21 methd

lemma *methd-rec*: $\llbracket \text{class } G \text{ C} = \text{Some } c; \text{ws-prog } G \rrbracket \implies$

$\text{methd } G \text{ C}$
 $= (\text{if } C = \text{Object}$
 then empty
 $\text{else filter-tab } (\lambda \text{sig } m. G \vdash C \text{ inherits method sig } m)$
 $\text{(methd } G (\text{super } c)))$
 $++ \text{table-of } (\text{map } (\lambda(s, m). (s, C, m)) (\text{methods } c))$
 $\langle \text{proof} \rangle$

lemma *methd-norec*:

$\llbracket \text{class } G \text{ declC} = \text{Some } c; \text{ws-prog } G; \text{table-of } (\text{methods } c) \text{ sig} = \text{Some } m \rrbracket$

$\implies \text{methd } G \text{ declC sig} = \text{Some } (\text{declC}, m)$
 ⟨proof⟩

lemma *methd-declC*:

$\llbracket \text{methd } G \text{ C sig} = \text{Some } m; \text{ws-prog } G; \text{is-class } G \text{ C} \rrbracket \implies$
 $(\exists d. \text{class } G \text{ (declclass } m) = \text{Some } d \wedge \text{table-of } (\text{methods } d) \text{ sig} = \text{Some } (\text{methd } m)) \wedge$
 $G \vdash C \preceq_C (\text{declclass } m) \wedge \text{methd } G \text{ (declclass } m) \text{ sig} = \text{Some } m$
 ⟨proof⟩

lemma *methd-inheritedD*:

$\llbracket \text{class } G \text{ C} = \text{Some } c; \text{ws-prog } G; \text{methd } G \text{ C sig} = \text{Some } m \rrbracket$
 $\implies (\text{declclass } m \neq C \longrightarrow G \vdash C \text{ inherits method sig } m)$
 ⟨proof⟩

lemma *methd-diff-cls*:

$\llbracket \text{ws-prog } G; \text{is-class } G \text{ C}; \text{is-class } G \text{ D};$
 $\text{methd } G \text{ C sig} = m; \text{methd } G \text{ D sig} = n; m \neq n$
 $\rrbracket \implies C \neq D$
 ⟨proof⟩

lemma *method-declared-inI*:

$\llbracket \text{table-of } (\text{methods } c) \text{ sig} = \text{Some } m; \text{class } G \text{ C} = \text{Some } c \rrbracket$
 $\implies G \vdash \text{mdecl } (\text{sig}, m) \text{ declared-in } C$
 ⟨proof⟩

lemma *methd-declared-in-declclass*:

$\llbracket \text{methd } G \text{ C sig} = \text{Some } m; \text{ws-prog } G; \text{is-class } G \text{ C} \rrbracket$
 $\implies G \vdash \text{Methd sig } m \text{ declared-in } (\text{declclass } m)$
 ⟨proof⟩

lemma *member-methd*:

assumes *member-of*: $G \vdash \text{Methd sig } m \text{ member-of } C$ **and**
 $\text{ws: ws-prog } G$
shows $\text{methd } G \text{ C sig} = \text{Some } m$
 ⟨proof⟩

lemma *finite-methd:ws-prog G* $\implies \text{finite } \{\text{methd } G \text{ C sig} \mid \text{sig } C. \text{is-class } G \text{ C}\}$
 ⟨proof⟩

lemma *finite-dom-methd*:

$\llbracket \text{ws-prog } G; \text{is-class } G \text{ C} \rrbracket \implies \text{finite } (\text{dom } (\text{methd } G \text{ C}))$
 ⟨proof⟩

22 accmethd

lemma *accmethd-SomeD*:

$\text{accmethd } G \text{ S C sig} = \text{Some } m$
 $\implies \text{methd } G \text{ C sig} = \text{Some } m \wedge G \vdash \text{method sig } m \text{ of } C \text{ accessible-from } S$
 ⟨proof⟩

lemma *accmethod-SomeI*:

$\llbracket \text{methd } G \ C \ \text{sig} = \text{Some } m; \text{G} \vdash \text{method } \text{sig } m \text{ of } C \text{ accessible-from } S \rrbracket$
 $\implies \text{accmethod } G \ S \ C \ \text{sig} = \text{Some } m$
 ⟨proof⟩

lemma *accmethod-declC*:

$\llbracket \text{accmethod } G \ S \ C \ \text{sig} = \text{Some } m; \text{ws-prog } G; \text{is-class } G \ C \rrbracket \implies$
 $(\exists d. \text{class } G \ (\text{declclass } m) = \text{Some } d \wedge$
 $\text{table-of } (\text{methods } d) \ \text{sig} = \text{Some } (\text{methd } m)) \wedge$
 $\text{G} \vdash C \preceq_C (\text{declclass } m) \wedge \text{methd } G \ (\text{declclass } m) \ \text{sig} = \text{Some } m \wedge$
 $\text{G} \vdash \text{method } \text{sig } m \text{ of } C \text{ accessible-from } S$
 ⟨proof⟩

lemma *finite-dom-accmethod*:

$\llbracket \text{ws-prog } G; \text{is-class } G \ C \rrbracket \implies \text{finite } (\text{dom } (\text{accmethod } G \ S \ C))$
 ⟨proof⟩

23 dynmethod

lemma *dynmethod-rec*:

$\llbracket \text{class } G \ \text{dynC} = \text{Some } c; \text{ws-prog } G \rrbracket \implies$
 $\text{dynmethod } G \ \text{statC} \ \text{dynC} \ \text{sig}$
 $= (\text{if } \text{G} \vdash \text{dynC} \preceq_C \ \text{statC}$
 $\text{then } (\text{case } \text{methd } G \ \text{statC} \ \text{sig} \text{ of}$
 $\text{None} \Rightarrow \text{None}$
 $\mid \text{Some } \text{statM}$
 $\Rightarrow (\text{case } \text{methd } G \ \text{dynC} \ \text{sig} \text{ of}$
 $\text{None} \Rightarrow \text{dynmethod } G \ \text{statC} \ (\text{super } c) \ \text{sig}$
 $\mid \text{Some } \text{dynM} \Rightarrow$
 $(\text{if } G, \text{sig} \vdash \text{dynM} \text{ overrides } \text{statM} \vee \text{dynM} = \text{statM}$
 $\text{then } \text{Some } \text{dynM}$
 $\text{else } (\text{dynmethod } G \ \text{statC} \ (\text{super } c) \ \text{sig})$
 $)))$
 $\text{else } \text{None})$
 $(\text{is } - \implies - \implies ?\text{Dynmethod-def } \text{dynC} \ \text{sig} = ?\text{Dynmethod-rec } \text{dynC} \ c \ \text{sig})$
 ⟨proof⟩

lemma *dynmethod-C-C*: $\llbracket \text{is-class } G \ C; \text{ws-prog } G \rrbracket$

$\implies \text{dynmethod } G \ C \ C \ \text{sig} = \text{methd } G \ C \ \text{sig}$
 ⟨proof⟩

lemma *dynmethodSomeD*:

$\llbracket \text{dynmethod } G \ \text{statC} \ \text{dynC} \ \text{sig} = \text{Some } \text{dynM}; \text{is-class } G \ \text{dynC}; \text{ws-prog } G \rrbracket$
 $\implies \text{G} \vdash \text{dynC} \preceq_C \ \text{statC} \wedge (\exists \text{statM}. \text{methd } G \ \text{statC} \ \text{sig} = \text{Some } \text{statM})$
 ⟨proof⟩

lemma *dynmethod-Some-cases*:

assumes *dynM*: $\text{dynmethod } G \ \text{statC} \ \text{dynC} \ \text{sig} = \text{Some } \text{dynM}$
and *is-cls-dynC*: $\text{is-class } G \ \text{dynC}$
and *ws*: $\text{ws-prog } G$
obtains *(Static)* $\text{methd } G \ \text{statC} \ \text{sig} = \text{Some } \text{dynM}$

| (Overrides) $statM$
where $methd\ G\ statC\ sig = Some\ statM$
and $dynM \neq statM$
and $G, sig \vdash dynM$ overrides $statM$
⟨proof⟩

lemma *no-override-in-Object*:

assumes $dynM: dynmethd\ G\ statC\ dynC\ sig = Some\ dynM$ **and**
 $is-clc-dynC: is-class\ G\ dynC$ **and**
 $ws: ws-prog\ G$ **and**
 $statM: methd\ G\ statC\ sig = Some\ statM$ **and**
 $neq-dynM-statM: dynM \neq statM$
shows $dynC \neq Object$
⟨proof⟩

lemma *dynmethd-Some-rec-cases*:

assumes $dynM: dynmethd\ G\ statC\ dynC\ sig = Some\ dynM$
and $clsDynC: class\ G\ dynC = Some\ c$
and $ws: ws-prog\ G$
obtains (Static) $methd\ G\ statC\ sig = Some\ dynM$
| (Override) $statM$ **where** $methd\ G\ statC\ sig = Some\ statM$
and $methd\ G\ dynC\ sig = Some\ dynM$ **and** $statM \neq dynM$
and $G, sig \vdash dynM$ overrides $statM$
| (Recursion) $dynC \neq Object$ **and** $dynmethd\ G\ statC\ (super\ c)\ sig = Some\ dynM$
⟨proof⟩

lemma *dynmethd-declC*:

[[$dynmethd\ G\ statC\ dynC\ sig = Some\ m;$
 $is-class\ G\ statC; ws-prog\ G$
]] \implies
 $(\exists d. class\ G\ (declclass\ m) = Some\ d \wedge table-of\ (methods\ d)\ sig = Some\ (methd\ m)) \wedge$
 $G \vdash dynC \preceq_C (declclass\ m) \wedge methd\ G\ (declclass\ m)\ sig = Some\ m$
⟨proof⟩

lemma *methd-Some-dynmethd-Some*:

assumes $statM: methd\ G\ statC\ sig = Some\ statM$ **and**
 $subclseq: G \vdash dynC \preceq_C statC$ **and**
 $is-clc-statC: is-class\ G\ statC$ **and**
 $ws: ws-prog\ G$
shows $\exists dynM. dynmethd\ G\ statC\ dynC\ sig = Some\ dynM$
(is ?P dynC)
⟨proof⟩

lemma *dynmethd-cases*:

assumes $statM: methd\ G\ statC\ sig = Some\ statM$
and $subclseq: G \vdash dynC \preceq_C statC$
and $is-clc-statC: is-class\ G\ statC$
and $ws: ws-prog\ G$
obtains (Static) $dynmethd\ G\ statC\ dynC\ sig = Some\ statM$
| (Overrides) $dynM$ **where** $dynmethd\ G\ statC\ dynC\ sig = Some\ dynM$
and $dynM \neq statM$ **and** $G, sig \vdash dynM$ overrides $statM$
⟨proof⟩

lemma *ws-dynmethod*:

assumes $statM: methd\ G\ statC\ sig = Some\ statM$ **and**
 $subclseq: G \vdash dynC \preceq_C statC$ **and**
 $is-cls-statC: is-class\ G\ statC$ **and**
 $ws: ws-prog\ G$

shows

$\exists\ dynM. dynmethod\ G\ statC\ dynC\ sig = Some\ dynM \wedge$
 $is-static\ dynM = is-static\ statM \wedge G \vdash resTy\ dynM \preceq_{resTy}\ statM$

<proof>

24 dynlookup

lemma *dynlookup-cases*:

assumes $dynlookup\ G\ statT\ dynC\ sig = x$
obtains $(NullT)\ statT = NullT$ **and** $empty\ sig = x$
 $| (IfaceT)\ I$ **where** $statT = IfaceT\ I$ **and** $dynimethd\ G\ I\ dynC\ sig = x$
 $| (ClassT)\ statC$ **where** $statT = ClassT\ statC$ **and** $dynmethod\ G\ statC\ dynC\ sig = x$
 $| (ArrayT)\ ty$ **where** $statT = ArrayT\ ty$ **and** $dynmethod\ G\ Object\ dynC\ sig = x$

<proof>

25 fields

lemma *fields-rec*: $\llbracket class\ G\ C = Some\ c; ws-prog\ G \rrbracket \implies$

$fields\ G\ C = map\ (\lambda(fn,ft). ((fn,C),ft))\ (cfields\ c)\ @$
 $(if\ C = Object\ then\ []\ else\ fields\ G\ (super\ c))$

<proof>

lemma *fields-norec*:

$\llbracket class\ G\ fd = Some\ c; ws-prog\ G; table-of\ (cfields\ c)\ fn = Some\ f \rrbracket$
 $\implies table-of\ (fields\ G\ fd)\ (fn,fd) = Some\ f$

<proof>

lemma *table-of-fieldsD*:

$table-of\ (map\ (\lambda(fn,ft). ((fn,C),ft))\ (cfields\ c))\ efn = Some\ f$
 $\implies (declclassf\ efn) = C \wedge table-of\ (cfields\ c)\ (fname\ efn) = Some\ f$

<proof>

lemma *fields-declC*:

$\llbracket table-of\ (fields\ G\ C)\ efn = Some\ f; ws-prog\ G; is-class\ G\ C \rrbracket \implies$
 $(\exists\ d. class\ G\ (declclassf\ efn) = Some\ d \wedge$
 $table-of\ (cfields\ d)\ (fname\ efn) = Some\ f) \wedge$
 $G \vdash C \preceq_C (declclassf\ efn) \wedge table-of\ (fields\ G\ (declclassf\ efn))\ efn = Some\ f$

<proof>

lemma *fields-emptyI*: $\bigwedge y. \llbracket ws-prog\ G; class\ G\ C = Some\ c; cfields\ c = [] \rrbracket;$

$C \neq Object \longrightarrow class\ G\ (super\ c) = Some\ y \wedge fields\ G\ (super\ c) = [] \implies$
 $fields\ G\ C = []$

<proof>

lemma *fields-mono-lemma*:

$\llbracket x \in \text{set} (\text{fields } G \ C); G \vdash D \preceq_C \ C; \text{ws-prog } G \rrbracket$
 $\implies x \in \text{set} (\text{fields } G \ D)$
 <proof>

lemma *ws-unique-fields-lemma*:

$\llbracket (efn,fd) \in \text{set} (\text{fields } G \ (\text{super } c)); fc \in \text{set} (c\text{fields } c); \text{ws-prog } G;$
 $f\text{name } efn = f\text{name } fc; \text{declclassf } efn = C;$
 $\text{class } G \ C = \text{Some } c; C \neq \text{Object}; \text{class } G \ (\text{super } c) = \text{Some } d \rrbracket \implies R$
 <proof>

lemma *ws-unique-fields*: $\llbracket \text{is-class } G \ C; \text{ws-prog } G;$

$\bigwedge C \ c. \llbracket \text{class } G \ C = \text{Some } c \rrbracket \implies \text{unique} (c\text{fields } c) \rrbracket \implies$
 $\text{unique} (\text{fields } G \ C)$

<proof>

26 accfield

lemma *accfield-fields*:

$\text{accfield } G \ S \ C \ fn = \text{Some } f$
 $\implies \text{table-of} (\text{fields } G \ C) (fn, \text{declclass } f) = \text{Some} (fd \ f)$
 <proof>

lemma *accfield-declC-is-class*:

$\llbracket \text{is-class } G \ C; \text{accfield } G \ S \ C \ en = \text{Some} (fd, f); \text{ws-prog } G \rrbracket \implies$
 $\text{is-class } G \ fd$
 <proof>

lemma *accfield-accessibleD*:

$\text{accfield } G \ S \ C \ fn = \text{Some } f \implies G \vdash \text{Field } fn \ f \text{ of } C \text{ accessible-from } S$
 <proof>

27 is methd

lemma *is-methdI*:

$\llbracket \text{class } G \ C = \text{Some } y; \text{methd } G \ C \ sig = \text{Some } b \rrbracket \implies \text{is-methd } G \ C \ sig$
 <proof>

lemma *is-methdD*:

$\text{is-methd } G \ C \ sig \implies \text{class } G \ C \neq \text{None} \wedge \text{methd } G \ C \ sig \neq \text{None}$
 <proof>

lemma *finite-is-methd*:

$\text{ws-prog } G \implies \text{finite} (\text{Collect} (\text{split} (\text{is-methd } G)))$
 <proof>

calculation of the superclasses of a class

definition

$\text{superclasses} :: \text{prog} \Rightarrow \text{qname} \Rightarrow \text{qname set}$ **where**
 $\text{superclasses } G \ C = \text{class-rec } G \ C \ \{\}$
 $(\lambda \ C \ c \ \text{supercls}. (\text{if } C = \text{Object}$

then {}
else insert (*super c*) *superclass*)

lemma *superclasses-rec*: $\llbracket \text{class } G \ C = \text{Some } c; \text{ ws-prog } G \rrbracket \implies$
superclasses $G \ C$
 $=$ (*if* ($C = \text{Object}$)
then {}
else insert (*super c*) (*superclasses* G (*super c*)))
 ⟨*proof*⟩

lemma *superclasses-mono*:
assumes *clsrel*: $G \vdash C \prec_C D$
and *ws*: *ws-prog* G
and *cls-C*: *class* $G \ C = \text{Some } c$
and *wf*: $\bigwedge C \ c. \llbracket \text{class } G \ C = \text{Some } c; C \neq \text{Object} \rrbracket$
 $\implies \exists sc. \text{class } G \ (\text{super } c) = \text{Some } sc$
and *x*: $x \in \text{superclasses } G \ D$
shows $x \in \text{superclasses } G \ C$ ⟨*proof*⟩

lemma *subclsEval*:
assumes *clsrel*: $G \vdash C \prec_C D$
and *ws*: *ws-prog* G
and *cls-C*: *class* $G \ C = \text{Some } c$
and *wf*: $\bigwedge C \ c. \llbracket \text{class } G \ C = \text{Some } c; C \neq \text{Object} \rrbracket$
 $\implies \exists sc. \text{class } G \ (\text{super } c) = \text{Some } sc$
shows $D \in \text{superclasses } G \ C$ ⟨*proof*⟩

end

Chapter 11

WellType

28 Well-typedness of Java programs

theory *WellType*
imports *DeclConcepts*
begin

improvements over Java Specification 1.0:

- methods of Object can be called upon references of interface or array type

simplifications:

- the type rules include all static checks on statements and expressions, e.g. definedness of names (of parameters, locals, fields, methods)

design issues:

- unified type judgment for statements, variables, expressions, expression lists
- statements are typed like expressions with dummy type Void
- the typing rules take an extra argument that is capable of determining the dynamic type of objects. Therefore, they can be used for both checking static types and determining runtime types in transition semantics.

type-synonym *lenv*
 = (*lname*, *ty*) *table* — local variables, including This and Result

record *env* =
 prg:: *prog* — program
 cls:: *qname* — current package and class name
 lcl:: *lenv* — local environment

translations

(*type*) *lenv* <= (*type*) (*lname*, *ty*) *table*
 (*type*) *lenv* <= (*type*) *lname* \Rightarrow *ty option*
 (*type*) *env* <= (*type*) (*prg*::*prog*, *cls*::*qname*, *lcl*::*lenv*)
 (*type*) *env* <= (*type*) (*prg*::*prog*, *cls*::*qname*, *lcl*::*lenv*, ... :: '*a*)

abbreviation

pkg :: *env* \Rightarrow *pname* — select the current package from an environment
where *pkg e* == *pid (cls e)*

Static overloading: maximally specific methods

type-synonym
emhead = *ref-ty* \times *mhead*

— Some mnemonic selectors for *emhead*

definition
declrefT :: *emhead* \Rightarrow *ref-ty*
where *declrefT* = *fst*

definition
mhd :: *emhead* \Rightarrow *mhead*
where *mhd* \equiv *snd*

lemma *declrefT-simp*[simp]: *declrefT* (r,m) = r
 ⟨proof⟩

lemma *mhd-simp*[simp]: *mhd* (r,m) = m
 ⟨proof⟩

lemma *static-mhd-simp*[simp]: *static* (mhd m) = *is-static* m
 ⟨proof⟩

lemma *mhd-resTy-simp* [simp]: *resTy* (mhd m) = *resTy* m
 ⟨proof⟩

lemma *mhd-is-static-simp* [simp]: *is-static* (mhd m) = *is-static* m
 ⟨proof⟩

lemma *mhd-accmodi-simp* [simp]: *accmodi* (mhd m) = *accmodi* m
 ⟨proof⟩

definition

cmheads :: *prog* ⇒ *qname* ⇒ *qname* ⇒ *sig* ⇒ *emhead set*
where *cmheads* G S C = (λsig. (λ(Cls,mthd). (ClassT Cls,(mhead mthd)))) ‘ *Option.set* (*accmethd* G S C sig)

definition

Objectmheads :: *prog* ⇒ *qname* ⇒ *sig* ⇒ *emhead set* **where**
Objectmheads G S =
 (λsig. (λ(Cls,mthd). (ClassT Cls,(mhead mthd))))
 ‘ *Option.set* (*filter-tab* (λsig m. *accmodi* m ≠ *Private*) (*accmethd* G S *Object*) sig)

definition

accObjectmheads :: *prog* ⇒ *qname* ⇒ *ref-ty* ⇒ *sig* ⇒ *emhead set*
where
accObjectmheads G S T =
 (if G ⊢ *RefT* T *accessible-in* (*pid* S)
 then *Objectmheads* G S
 else (λsig. {}))

primrec *mheads* :: *prog* ⇒ *qname* ⇒ *ref-ty* ⇒ *sig* ⇒ *emhead set*

where

mheads G S *NullT* = (λsig. {})
 | *mheads* G S (*IfaceT* I) = (λsig. (λ(I,h).(IfaceT I,h))
 ‘ *accimethds* G (*pid* S) I sig ∪
 accObjectmheads G S (*IfaceT* I) sig)
 | *mheads* G S (*ClassT* C) = *cmheads* G S C
 | *mheads* G S (*ArrayT* T) = *accObjectmheads* G S (*ArrayT* T)

definition

— applicable methods, cf. 15.11.2.1

appl-methds :: *prog* ⇒ *qname* ⇒ *ref-ty* ⇒ *sig* ⇒ (*emhead* × *ty list*) *set* **where**
appl-methds G S rt = (λ sig.
 {(mh,pTs') | mh pTs'. mh ∈ *mheads* G S rt (|name=name sig,parTs=pTs') ∧
 G ⊢ (*parTs* sig)[⊆]pTs'})

definition

— more specific methods, cf. 15.11.2.2

$more-spec :: prog \Rightarrow emhead \times ty\ list \Rightarrow emhead \times ty\ list \Rightarrow bool$ **where**
 $more-spec\ G = (\lambda(mh,pTs). \lambda(mh',pTs'). G \vdash pTs[\preceq]pTs')$

definition

— maximally specific methods, cf. 15.11.2.2

$max-spec :: prog \Rightarrow qtname \Rightarrow ref-ty \Rightarrow sig \Rightarrow (emhead \times ty\ list)\ set$ **where**
 $max-spec\ G\ S\ rt\ sig = \{m. m \in appl-methods\ G\ S\ rt\ sig \wedge$
 $(\forall m' \in appl-methods\ G\ S\ rt\ sig. more-spec\ G\ m'\ m \longrightarrow m'=m)\}$

lemma $max-spec2appl-methods$:

$x \in max-spec\ G\ S\ T\ sig \implies x \in appl-methods\ G\ S\ T\ sig$
 $\langle proof \rangle$

lemma $appl-methodsD$: $(mh,pTs') \in appl-methods\ G\ S\ T\ (\lambda name=mn, parTs=pTs) \implies$

$mh \in mheads\ G\ S\ T\ (\lambda name=mn, parTs=pTs') \wedge G \vdash pTs[\preceq]pTs'$
 $\langle proof \rangle$

lemma $max-spec2mheads$:

$max-spec\ G\ S\ rt\ (\lambda name=mn, parTs=pTs) = insert\ (mh, pTs')\ A$
 $\implies mh \in mheads\ G\ S\ rt\ (\lambda name=mn, parTs=pTs') \wedge G \vdash pTs[\preceq]pTs'$
 $\langle proof \rangle$

definition

$empty-dt :: dyn-ty$
where $empty-dt = (\lambda a. None)$

definition

$invmode :: ('a::type)member-scheme \Rightarrow expr \Rightarrow inv-mode$ **where**
 $invmode\ m\ e = (if\ is-static\ m$
 $\quad then\ Static$
 $\quad else\ if\ e=Super\ then\ SuperM\ else\ IntVir)$

lemma $invmode-nonstatic$ [simp]:

$invmode\ (\lambda access=a, static=False, \dots =x)\ (Acc\ (LVar\ e)) = IntVir$
 $\langle proof \rangle$

lemma $invmode-Static-eq$ [simp]: $(invmode\ m\ e = Static) = is-static\ m$

$\langle proof \rangle$

lemma $invmode-IntVir-eq$: $(invmode\ m\ e = IntVir) = (\neg(is-static\ m) \wedge e \neq Super)$

$\langle proof \rangle$

lemma $Null-staticD$:

$a'=Null \longrightarrow (is-static\ m) \implies invmode\ m\ e = IntVir \longrightarrow a' \neq Null$
 $\langle proof \rangle$

Typing for unary operations

primrec *unop-type* :: *unop* \Rightarrow *prim-ty*

where

unop-type *UPlus* = *Integer*
 | *unop-type* *UMinus* = *Integer*
 | *unop-type* *UBitNot* = *Integer*
 | *unop-type* *UNot* = *Boolean*

primrec *wt-unop* :: *unop* \Rightarrow *ty* \Rightarrow *bool*

where

wt-unop *UPlus* *t* = (*t* = *PrimT Integer*)
 | *wt-unop* *UMinus* *t* = (*t* = *PrimT Integer*)
 | *wt-unop* *UBitNot* *t* = (*t* = *PrimT Integer*)
 | *wt-unop* *UNot* *t* = (*t* = *PrimT Boolean*)

Typing for binary operations

primrec *binop-type* :: *binop* \Rightarrow *prim-ty*

where

binop-type *Mul* = *Integer*
 | *binop-type* *Div* = *Integer*
 | *binop-type* *Mod* = *Integer*
 | *binop-type* *Plus* = *Integer*
 | *binop-type* *Minus* = *Integer*
 | *binop-type* *LShift* = *Integer*
 | *binop-type* *RShift* = *Integer*
 | *binop-type* *RShiftU* = *Integer*
 | *binop-type* *Less* = *Boolean*
 | *binop-type* *Le* = *Boolean*
 | *binop-type* *Greater* = *Boolean*
 | *binop-type* *Ge* = *Boolean*
 | *binop-type* *Eq* = *Boolean*
 | *binop-type* *Neq* = *Boolean*
 | *binop-type* *BitAnd* = *Integer*
 | *binop-type* *And* = *Boolean*
 | *binop-type* *BitXor* = *Integer*
 | *binop-type* *Xor* = *Boolean*
 | *binop-type* *BitOr* = *Integer*
 | *binop-type* *Or* = *Boolean*
 | *binop-type* *CondAnd* = *Boolean*
 | *binop-type* *CondOr* = *Boolean*

primrec *wt-binop* :: *prog* \Rightarrow *binop* \Rightarrow *ty* \Rightarrow *ty* \Rightarrow *bool*

where

wt-binop *G Mul* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Div* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Mod* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Plus* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Minus* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G LShift* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G RShift* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G RShiftU* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Less* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Le* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Greater* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Ge* *t1 t2* = ((*t1* = *PrimT Integer*) \wedge (*t2* = *PrimT Integer*))
 | *wt-binop* *G Eq* *t1 t2* = (*G* \vdash *t1* \preceq *t2* \vee *G* \vdash *t2* \preceq *t1*)
 | *wt-binop* *G Neq* *t1 t2* = (*G* \vdash *t1* \preceq *t2* \vee *G* \vdash *t2* \preceq *t1*)

$| wt\text{-binop } G \text{ BitAnd } t1 \ t2 = ((t1 = \text{PrimT Integer}) \wedge (t2 = \text{PrimT Integer}))$
 $| wt\text{-binop } G \text{ And } t1 \ t2 = ((t1 = \text{PrimT Boolean}) \wedge (t2 = \text{PrimT Boolean}))$
 $| wt\text{-binop } G \text{ BitXor } t1 \ t2 = ((t1 = \text{PrimT Integer}) \wedge (t2 = \text{PrimT Integer}))$
 $| wt\text{-binop } G \text{ Xor } t1 \ t2 = ((t1 = \text{PrimT Boolean}) \wedge (t2 = \text{PrimT Boolean}))$
 $| wt\text{-binop } G \text{ BitOr } t1 \ t2 = ((t1 = \text{PrimT Integer}) \wedge (t2 = \text{PrimT Integer}))$
 $| wt\text{-binop } G \text{ Or } t1 \ t2 = ((t1 = \text{PrimT Boolean}) \wedge (t2 = \text{PrimT Boolean}))$
 $| wt\text{-binop } G \text{ CondAnd } t1 \ t2 = ((t1 = \text{PrimT Boolean}) \wedge (t2 = \text{PrimT Boolean}))$
 $| wt\text{-binop } G \text{ CondOr } t1 \ t2 = ((t1 = \text{PrimT Boolean}) \wedge (t2 = \text{PrimT Boolean}))$

Typing for terms

type-synonym $tys = ty + ty \text{ list}$
translations

$(type) \ tys \leq (type) \ ty + ty \text{ list}$

inductive $wt :: env \Rightarrow dyn\text{-ty} \Rightarrow [term, tys] \Rightarrow bool \ (-, \models :: - [51, 51, 51, 51] \ 50)$
and $wt\text{-stmt} :: env \Rightarrow dyn\text{-ty} \Rightarrow stmt \Rightarrow bool \ (-, \models :: \surd [51, 51, 51] \ 50)$
and $ty\text{-expr} :: env \Rightarrow dyn\text{-ty} \Rightarrow [expr, ty] \Rightarrow bool \ (-, \models :: - [51, 51, 51, 51] \ 50)$
and $ty\text{-var} :: env \Rightarrow dyn\text{-ty} \Rightarrow [var, ty] \Rightarrow bool \ (-, \models :: = [51, 51, 51, 51] \ 50)$
and $ty\text{-exprs} :: env \Rightarrow dyn\text{-ty} \Rightarrow [expr \text{ list}, ty \text{ list}] \Rightarrow bool$
 $(-, \models :: \doteq [51, 51, 51, 51] \ 50)$

where

$E, dt \models s :: \surd \equiv E, dt \models In1r \ s :: Inl \ (\text{PrimT } \text{Void})$
 $| E, dt \models e :: - T \equiv E, dt \models In1l \ e :: Inl \ T$
 $| E, dt \models e :: = T \equiv E, dt \models In2 \ e :: Inl \ T$
 $| E, dt \models e :: \doteq T \equiv E, dt \models In3 \ e :: Inr \ T$

— well-typed statements

$| \text{Skip}: \quad E, dt \models \text{Skip} :: \surd$

$| \text{Expr}: \llbracket E, dt \models e :: - T \rrbracket \Longrightarrow E, dt \models \text{Expr } e :: \surd$

— cf. 14.6

$| \text{Lab}: \ E, dt \models c :: \surd \Longrightarrow E, dt \models l \cdot c :: \surd$

$| \text{Comp}: \llbracket E, dt \models c1 :: \surd; E, dt \models c2 :: \surd \rrbracket \Longrightarrow E, dt \models c1 ;; c2 :: \surd$

— cf. 14.8

$| \text{If}: \llbracket E, dt \models e :: - \text{PrimT Boolean}; E, dt \models c1 :: \surd; E, dt \models c2 :: \surd \rrbracket \Longrightarrow E, dt \models \text{If}(e) \ c1 \ \text{Else } c2 :: \surd$

— cf. 14.10

$| \text{Loop}: \llbracket E, dt \models e :: - \text{PrimT Boolean}; E, dt \models c :: \surd \rrbracket \Longrightarrow E, dt \models l \cdot \text{While}(e) \ c :: \surd$

— cf. 14.13, 14.15, 14.16

$| \text{Jmp}: \quad E, dt \models \text{Jmp } \text{jump} :: \surd$

— cf. 14.16

$| \text{Throw}: \llbracket E, dt \models e :: - \text{Class } tn; \text{prg } E \vdash tn \preceq_C \text{ SXcpt } \text{Throwable} \rrbracket \Longrightarrow$

$$E, dt \models \text{Throw } e :: \checkmark$$

— cf. 14.18

$$\begin{aligned} | \text{Try: } \llbracket E, dt \models c1 :: \checkmark; \text{ prg } E \vdash tn \preceq_C \text{ SXcpt Throwable}; \\ \text{lcl } E \text{ (VName } vn) = \text{None}; E \text{ (lcl := lcl } E \text{ (VName } vn \mapsto \text{Class } tn)) \rrbracket, dt \models c2 :: \checkmark \rrbracket \\ \implies \end{aligned}$$

$$E, dt \models \text{Try } c1 \text{ Catch}(tn \text{ } vn) \text{ } c2 :: \checkmark$$

— cf. 14.18

$$\begin{aligned} | \text{Fin: } \llbracket E, dt \models c1 :: \checkmark; E, dt \models c2 :: \checkmark \rrbracket \implies \\ E, dt \models c1 \text{ Finally } c2 :: \checkmark \end{aligned}$$

$$| \text{Init: } \llbracket \text{is-class (prg } E) \text{ } C \rrbracket \implies$$

$$E, dt \models \text{Init } C :: \checkmark$$

— *Init* is created on the fly during evaluation (see Eval.thy). The class isn't necessarily accessible from the points *Init* is called. Therefore we only demand *is-class* and not *is-acc-class* here.

— well-typed expressions

— cf. 15.8

$$\begin{aligned} | \text{NewC: } \llbracket \text{is-acc-class (prg } E) \text{ (pkg } E) \text{ } C \rrbracket \implies \\ E, dt \models \text{NewC } C :: \text{--Class } C \end{aligned}$$

— cf. 15.9

$$\begin{aligned} | \text{NewA: } \llbracket \text{is-acc-type (prg } E) \text{ (pkg } E) \text{ } T; \\ E, dt \models i :: \text{--PrimT Integer} \rrbracket \implies \\ E, dt \models \text{New } T[i] :: \text{--T.} \end{aligned}$$

— cf. 15.15

$$\begin{aligned} | \text{Cast: } \llbracket E, dt \models e :: \text{--T}; \text{is-acc-type (prg } E) \text{ (pkg } E) \text{ } T'; \\ \text{prg } E \vdash T \preceq? T' \rrbracket \implies \\ E, dt \models \text{Cast } T' \text{ } e :: \text{--T}' \end{aligned}$$

— cf. 15.19.2

$$\begin{aligned} | \text{Inst: } \llbracket E, dt \models e :: \text{--RefT } T; \text{is-acc-type (prg } E) \text{ (pkg } E) \text{ (RefT } T'); \\ \text{prg } E \vdash \text{RefT } T \preceq? \text{RefT } T' \rrbracket \implies \\ E, dt \models e \text{ InstOf } T' :: \text{--PrimT Boolean} \end{aligned}$$

— cf. 15.7.1

$$\begin{aligned} | \text{Lit: } \llbracket \text{typeof } dt \text{ } x = \text{Some } T \rrbracket \implies \\ E, dt \models \text{Lit } x :: \text{--T} \end{aligned}$$

$$\begin{aligned} | \text{UnOp: } \llbracket E, dt \models e :: \text{--T}e; \text{wt-unop unop } Te; T = \text{PrimT (unop-type unop)} \rrbracket \\ \implies \\ E, dt \models \text{UnOp unop } e :: \text{--T} \end{aligned}$$

$$\begin{aligned} | \text{BinOp: } \llbracket E, dt \models e1 :: \text{--T}1; E, dt \models e2 :: \text{--T}2; \text{wt-binop (prg } E) \text{ binop } T1 \text{ } T2; \\ T = \text{PrimT (binop-type binop)} \rrbracket \\ \implies \\ E, dt \models \text{BinOp binop } e1 \text{ } e2 :: \text{--T} \end{aligned}$$

— cf. 15.10.2, 15.11.1

$$\begin{aligned} | \text{Super: } \llbracket \text{lcl } E \text{ This} = \text{Some (Class } C); C \neq \text{Object}; \\ \text{class (prg } E) \text{ } C = \text{Some } c \rrbracket \implies \\ E, dt \models \text{Super} :: \text{--Class (super } c) \end{aligned}$$

— cf. 15.13.1, 15.10.1, 15.12

$$\begin{aligned} | \text{Acc: } \llbracket E, dt \models va :: \text{--T} \rrbracket \implies \\ E, dt \models \text{Acc } va :: \text{--T} \end{aligned}$$

— cf. 15.25, 15.25.1

| *Ass*: $\llbracket E, dt \models va ::= T; va \neq LVar \ This; \\ E, dt \models v ::= T'; \\ prg \ E \vdash T' \preceq T \rrbracket \implies \\ E, dt \models va ::= v ::= T'$

— cf. 15.24

| *Cond*: $\llbracket E, dt \models e0 ::= PrimT \ Boolean; \\ E, dt \models e1 ::= T1; E, dt \models e2 ::= T2; \\ prg \ E \vdash T1 \preceq T2 \wedge T = T2 \vee prg \ E \vdash T2 \preceq T1 \wedge T = T1 \rrbracket \implies \\ E, dt \models e0 \ ? \ e1 : e2 ::= T$

— cf. 15.11.1, 15.11.2, 15.11.3

| *Call*: $\llbracket E, dt \models e ::= RefT \ statT; \\ E, dt \models ps ::= pTs; \\ max-spec \ (prg \ E) \ (cls \ E) \ statT \ (\{name=mn, parTs=pTs\}) \\ = \ \{(statDeclT, m), pTs'\} \\ \rrbracket \implies \\ E, dt \models \{cls \ E, statT, invmode \ m \ e\} \cdot mn(\{pTs'\}ps) ::= (resTy \ m)$

| *Method*: $\llbracket is-class \ (prg \ E) \ C; \\ methd \ (prg \ E) \ C \ sig = Some \ m; \\ E, dt \models Body \ (declclass \ m) \ (stmt \ (mbody \ (methd \ m))) ::= T \rrbracket \implies \\ E, dt \models Method \ C \ sig ::= T$

— The class C is the dynamic class of the method call (cf. Eval.thy). It hasn't got to be directly accessible from the current package $pkg \ E$. Only the static class must be accessible (enshured indirectly by *Call*). Note that l is just a dummy value. It is only used in the smallstep semantics. To proof typesafety directly for the smallstep semantics we would have to assume conformance of l here!

| *Body*: $\llbracket is-class \ (prg \ E) \ D; \\ E, dt \models blk ::= \surd; \\ (lcl \ E) \ Result = Some \ T; \\ is-type \ (prg \ E) \ T \rrbracket \implies \\ E, dt \models Body \ D \ blk ::= T$

— The class D implementing the method must not directly be accessible from the current package $pkg \ E$, but can also be indirectly accessible due to inheritance (enshured in *Call*) The result type hasn't got to be accessible in Java! (If it is not accessible you can only assign it to Object). For dummy value l see rule *Method*.

— well-typed variables

— cf. 15.13.1

| *LVar*: $\llbracket lcl \ E \ vn = Some \ T; is-acc-type \ (prg \ E) \ (pkg \ E) \ T \rrbracket \implies \\ E, dt \models LVar \ vn ::= T$

— cf. 15.10.1

| *FVar*: $\llbracket E, dt \models e ::= Class \ C; \\ accfield \ (prg \ E) \ (cls \ E) \ C \ fn = Some \ (statDeclC, f) \rrbracket \implies \\ E, dt \models \{cls \ E, statDeclC, is-static \ f\} \ e..fn ::= (type \ f)$

— cf. 15.12

| *AVar*: $\llbracket E, dt \models e ::= T.[]; \\ E, dt \models i ::= PrimT \ Integer \rrbracket \implies \\ E, dt \models e.[i] ::= T$

— well-typed expression lists

— cf. 15.11.???

| *Nil*: $E, dt \models [] ::= []$

— cf. 15.11.???

| Cons: $\llbracket E, dt \models e :: - T; E, dt \models es :: \doteq Ts \rrbracket \implies E, dt \models e \# es :: \doteq T \# Ts$

abbreviation

$wt\text{-syntax} :: env \Rightarrow [term, tys] \Rightarrow bool \ (-|-\doteq- [51,51,51] 50)$
where $E|-t::T == E, empty\text{-}dt \models t::T$

abbreviation

$wt\text{-stmt-syntax} :: env \Rightarrow stmt \Rightarrow bool \ (-|-\doteq\langle [51,51] \rangle 50)$
where $E|-s:\langle \rangle == E|-In1r s :: Inl (PrimT Void)$

abbreviation

$ty\text{-expr-syntax} :: env \Rightarrow [expr, ty] \Rightarrow bool \ (-|-\doteq- [51,51,51] 50)$
where $E|-e:-T == E|-In1l e :: Inl T$

abbreviation

$ty\text{-var-syntax} :: env \Rightarrow [var, ty] \Rightarrow bool \ (-|-\doteq= [51,51,51] 50)$
where $E|-e:=T == E|-In2 e :: Inl T$

abbreviation

$ty\text{-exprs-syntax} :: env \Rightarrow [expr\ list, ty\ list] \Rightarrow bool \ (-|-\doteq\# [51,51,51] 50)$
where $E|-e:\#T == E|-In3 e :: Inr T$

notation (*xsymbols*)

$wt\text{-syntax} \ (-|-\doteq- [51,51,51] 50)$ **and**
 $wt\text{-stmt-syntax} \ (-|-\doteq\sqrt [51,51] \rangle 50)$ **and**
 $ty\text{-expr-syntax} \ (-|-\doteq- [51,51,51] 50)$ **and**
 $ty\text{-var-syntax} \ (-|-\doteq= [51,51,51] 50)$ **and**
 $ty\text{-exprs-syntax} \ (-|-\doteq\# [51,51,51] 50)$

declare $not\text{-None-eq}$ [*simp del*]

declare $split\text{-if}$ [*split del*] $split\text{-if-asm}$ [*split del*]

declare $split\text{-paired-All}$ [*simp del*] $split\text{-paired-Ex}$ [*simp del*]

$\langle ML \rangle$

inductive-cases $wt\text{-elim-cases}$ [*cases set*]:

$E, dt \models In2 (LVar\ vn) :: T$
 $E, dt \models In2 (\{accC, statDeclC, s\}e..fn) :: T$
 $E, dt \models In2 (e.[i]) :: T$
 $E, dt \models In1l (NewC\ C) :: T$
 $E, dt \models In1l (New\ T'[i]) :: T$
 $E, dt \models In1l (Cast\ T'\ e) :: T$
 $E, dt \models In1l (e\ InstOf\ T') :: T$
 $E, dt \models In1l (Lit\ x) :: T$
 $E, dt \models In1l (UnOp\ unop\ e) :: T$
 $E, dt \models In1l (BinOp\ binop\ e1\ e2) :: T$
 $E, dt \models In1l (Super) :: T$
 $E, dt \models In1l (Acc\ va) :: T$
 $E, dt \models In1l (Ass\ va\ v) :: T$
 $E, dt \models In1l (e0\ ?\ e1\ :\ e2) :: T$
 $E, dt \models In1l (\{accC, statT, mode\}e.mn(\{pT'\}p)) :: T$
 $E, dt \models In1l (Methd\ C\ sig) :: T$
 $E, dt \models In1l (Body\ D\ blk) :: T$
 $E, dt \models In3 (\[]) :: Ts$
 $E, dt \models In3 (e\ \#es) :: Ts$
 $E, dt \models In1r\ Skip :: x$

$$\begin{array}{ll}
E, dt \models \text{In1r} (\text{Expr } e) & ::x \\
E, dt \models \text{In1r} (c1 ;; c2) & ::x \\
E, dt \models \text{In1r} (l \cdot c) & ::x \\
E, dt \models \text{In1r} (\text{If}(e) c1 \text{ Else } c2) & ::x \\
E, dt \models \text{In1r} (l \cdot \text{While}(e) c) & ::x \\
E, dt \models \text{In1r} (\text{Jmp } \text{jump}) & ::x \\
E, dt \models \text{In1r} (\text{Throw } e) & ::x \\
E, dt \models \text{In1r} (\text{Try } c1 \text{ Catch}(tn \text{ vn}) c2) & ::x \\
E, dt \models \text{In1r} (c1 \text{ Finally } c2) & ::x \\
E, dt \models \text{In1r} (\text{Init } C) & ::x
\end{array}$$

declare *not-None-eq* [*simp*]
declare *split-if* [*split*] *split-if-asm* [*split*]
declare *split-paired-All* [*simp*] *split-paired-Ex* [*simp*]
 $\langle ML \rangle$

lemma *is-acc-class-is-accessible*:
is-acc-class $G P C \implies G \vdash (\text{Class } C) \text{ accessible-in } P$
 $\langle \text{proof} \rangle$

lemma *is-acc-iface-is-iface*: *is-acc-iface* $G P I \implies \text{is-iface } G I$
 $\langle \text{proof} \rangle$

lemma *is-acc-iface-Iface-is-accessible*:
is-acc-iface $G P I \implies G \vdash (\text{Iface } I) \text{ accessible-in } P$
 $\langle \text{proof} \rangle$

lemma *is-acc-type-is-type*: *is-acc-type* $G P T \implies \text{is-type } G T$
 $\langle \text{proof} \rangle$

lemma *is-acc-iface-is-accessible*:
is-acc-type $G P T \implies G \vdash T \text{ accessible-in } P$
 $\langle \text{proof} \rangle$

lemma *wt-Methd-is-methd*:
 $E \vdash \text{In1l} (\text{Methd } C \text{ sig}) :: T \implies \text{is-methd} (\text{prg } E) C \text{ sig}$
 $\langle \text{proof} \rangle$

Special versions of some typing rules, better suited to pattern match the conclusion (no selectors in the conclusion)

lemma *wt-Call*:
 $\llbracket E, dt \models e :: - \text{RefT } \text{statT}; E, dt \models ps :: \doteq pTs;$
 $\text{max-spec } (\text{prg } E) (\text{cls } E) \text{ statT } (\text{name} = mn, \text{parTs} = pTs)$
 $= \{((\text{statDecl } C, m), pTs \wedge); rT = (\text{resTy } m); \text{accC} = \text{cls } E;$
 $\text{mode} = \text{invmode } m \ e\} \implies E, dt \models \{\text{accC}, \text{statT}, \text{mode}\} e \cdot mn (\{pTs \wedge\} ps) :: - rT$
 $\langle \text{proof} \rangle$

lemma *invocationTypeExpr-noClassD*:
 $\llbracket E \vdash e :: - \text{RefT } \text{statT} \rrbracket$
 $\implies (\forall \text{ statC}. \text{statT} \neq \text{ClassT } \text{statC}) \longrightarrow \text{invmode } m \ e \neq \text{SuperM}$
 $\langle \text{proof} \rangle$

lemma *wt-Super*:

$\llbracket \text{lcl } E \text{ This} = \text{Some } (\text{Class } C); C \neq \text{Object}; \text{class } (\text{prg } E) C = \text{Some } c; D = \text{super } c \rrbracket$
 $\implies E, dt \models \text{Super}::\text{Class } D$
 ⟨proof⟩

lemma *wt-FVar*:

$\llbracket E, dt \models e::\text{Class } C; \text{accfield } (\text{prg } E) (\text{cls } E) C \text{ fn} = \text{Some } (\text{statDecl } C, f);$
 $\text{sf} = \text{is-static } f; fT = (\text{type } f); \text{accC} = \text{cls } E \rrbracket$
 $\implies E, dt \models \{ \text{accC}, \text{statDecl } C, \text{sf} \} e.. \text{fn}::=fT$
 ⟨proof⟩

lemma *wt-init* [iff]: $E, dt \models \text{Init } C::\surd = \text{is-class } (\text{prg } E) C$

⟨proof⟩

declare *wt.Skip* [iff]

lemma *wt-StatRef*:

$\text{is-acc-type } (\text{prg } E) (\text{pkg } E) (\text{RefT } rt) \implies E \vdash \text{StatRef } rt::\text{RefT } rt$
 ⟨proof⟩

lemma *wt-Inj-elim*:

$\bigwedge E. E, dt \models t::U \implies \text{case } t \text{ of}$
 $\quad \text{In1 } ec \Rightarrow (\text{case } ec \text{ of}$
 $\quad \quad \text{Inl } e \Rightarrow \exists T. U = \text{Inl } T$
 $\quad \quad | \text{Inr } s \Rightarrow U = \text{Inl } (\text{PrimT } \text{Void}))$
 $\quad | \text{In2 } e \Rightarrow (\exists T. U = \text{Inl } T)$
 $\quad | \text{In3 } e \Rightarrow (\exists T. U = \text{Inr } T)$

⟨proof⟩

lemma *wt-expr-eq*: $E, dt \models \text{In1l } t::U = (\exists T. U = \text{Inl } T \wedge E, dt \models t::\neg T)$

⟨proof⟩

lemma *wt-var-eq*: $E, dt \models \text{In2 } t::U = (\exists T. U = \text{Inl } T \wedge E, dt \models t::=T)$

⟨proof⟩

lemma *wt-exprs-eq*: $E, dt \models \text{In3 } t::U = (\exists Ts. U = \text{Inr } Ts \wedge E, dt \models t::\doteq Ts)$

⟨proof⟩

lemma *wt-stmt-eq*: $E, dt \models \text{In1r } t::U = (U = \text{Inl } (\text{PrimT } \text{Void}) \wedge E, dt \models t::\surd)$

⟨proof⟩

⟨ML⟩

lemma *wt-elim-BinOp*:

$\llbracket E, dt \models \text{In1l } (\text{BinOp } \text{binop } e1 e2)::T;$

$\bigwedge T1 T2 T3.$

$\llbracket E, dt \models e1::\neg T1; E, dt \models e2::\neg T2; \text{wt-binop } (\text{prg } E) \text{ binop } T1 T2;$

$E, dt \models (\text{if } b \text{ then } \text{In1l } e2 \text{ else } \text{In1r } \text{Skip})::T3;$

$$\begin{aligned}
& T = \text{Inl } (\text{PrimT } (\text{binop-type binop})) \mathbb{I} \\
& \implies P \mathbb{I} \\
\implies P \\
\langle \text{proof} \rangle
\end{aligned}$$

lemma *Inj-eq-lemma* [*simp*]:
 $(\forall T. (\exists T'. T = \text{Inj } T' \wedge P T') \longrightarrow Q T) = (\forall T'. P T' \longrightarrow Q (\text{Inj } T'))$
 $\langle \text{proof} \rangle$

lemma *single-valued-tys-lemma* [*rule-format (no-asm)*]:
 $\forall S T. G \vdash S \preceq T \longrightarrow G \vdash T \preceq S \longrightarrow S = T \implies E, dt \models t :: T \implies$
 $G = \text{prg } E \longrightarrow (\forall T'. E, dt \models t :: T' \longrightarrow T = T')$
 $\langle \text{proof} \rangle$

lemma *single-valued-tys*:
 $\text{ws-prog } (\text{prg } E) \implies \text{single-valued } \{(t, T). E, dt \models t :: T\}$
 $\langle \text{proof} \rangle$

lemma *typeof-empty-is-type* [*rule-format (no-asm)*]:
 $\text{typeof } (\lambda a. \text{None}) v = \text{Some } T \longrightarrow \text{is-type } G T$
 $\langle \text{proof} \rangle$

lemma *typeof-is-type* [*rule-format (no-asm)*]:
 $(\forall a. v \neq \text{Addr } a) \longrightarrow (\exists T. \text{typeof } dt v = \text{Some } T \wedge \text{is-type } G T)$
 $\langle \text{proof} \rangle$

end

Chapter 12

DefiniteAssignment

29 Definite Assignment

theory *DefiniteAssignment* **imports** *WellType* **begin**

Definite Assignment Analysis (cf. 16)

The definite assignment analysis approximates the sets of local variables that will be assigned at a certain point of evaluation, and ensures that we will only read variables which previously were assigned. It should conform to the following idea: If the evaluation of a term completes normally (no abruption (exception, break, continue, return) appeared) , the set of local variables calculated by the analysis is a subset of the variables that were actually assigned during evaluation.

To get more precise information about the sets of assigned variables the analysis includes the following optimisations:

- Inside of a while loop we also take care of the variables assigned before break statements, since the break causes the while loop to continue normally.
- For conditional statements we take care of constant conditions to statically determine the path of evaluation.
- Inside a distinct path of a conditional statements we know to which boolean value the condition has evaluated to, and so can retrieve more information about the variables assigned during evaluation of the boolean condition.

Since in our model of Java the return values of methods are stored in a local variable we also ensure that every path of (normal) evaluation will assign the result variable, or in the sense of real Java every path ends up in and return instruction.

Not covered yet:

- analysis of definite unassigned
- special treatment of final fields

Correct nesting of jump statements

For definite assignment it becomes crucial, that jumps (break, continue, return) are nested correctly i.e. a continue jump is nested in a matching while statement, a break jump is nested in a proper label statement, a class initialiser does not terminate abruptly with a return. With this we can for example ensure that evaluation of an expression will never end up with a jump, since no breaks, continues or returns are allowed in an expression.

primrec *jumpNestingOkS* :: *jump set* \Rightarrow *stmt* \Rightarrow *bool*

where

- | *jumpNestingOkS* *jmps* (*Skip*) = *True*
- | *jumpNestingOkS* *jmps* (*Expr* *e*) = *True*
- | *jumpNestingOkS* *jmps* (*j* · *s*) = *jumpNestingOkS* ($\{j\} \cup$ *jmps*) *s*
- | *jumpNestingOkS* *jmps* (*c1* ;; *c2*) = (*jumpNestingOkS* *jmps* *c1* \wedge
jumpNestingOkS *jmps* *c2*)
- | *jumpNestingOkS* *jmps* (*If* (*e*) *c1* *Else* *c2*) = (*jumpNestingOkS* *jmps* *c1* \wedge
jumpNestingOkS *jmps* *c2*)
- | *jumpNestingOkS* *jmps* (*l* · *While*(*e*) *c*) = *jumpNestingOkS* ($\{Cont\ l\} \cup$ *jmps*) *c*
- The label of the while loop only handles continue jumps. Breaks are only handled by *Lab*
- | *jumpNestingOkS* *jmps* (*Jmp* *j*) = (*j* \in *jmps*)
- | *jumpNestingOkS* *jmps* (*Throw* *e*) = *True*
- | *jumpNestingOkS* *jmps* (*Try* *c1* *Catch*(*C vn*) *c2*) = (*jumpNestingOkS* *jmps* *c1* \wedge
jumpNestingOkS *jmps* *c2*)
- | *jumpNestingOkS* *jmps* (*c1* *Finally* *c2*) = (*jumpNestingOkS* *jmps* *c1* \wedge

$jumpNestingOkS\ jmps\ c2)$

| $jumpNestingOkS\ jmps\ (Init\ C) = True$
 — wellformedness of the program must ensure that for all initializers $jumpNestingOkS$ holds
 — Dummy analysis for intermediate smallest term $FinA$
 | $jumpNestingOkS\ jmps\ (FinA\ a\ c) = False$

definition $jumpNestingOk :: jump\ set \Rightarrow term \Rightarrow bool$ **where**
 $jumpNestingOk\ jmps\ t = (case\ t\ of$
 $In1\ se \Rightarrow (case\ se\ of$
 $Inl\ e \Rightarrow True$
 | $Inr\ s \Rightarrow jumpNestingOkS\ jmps\ s)$
 | $In2\ v \Rightarrow True$
 | $In3\ es \Rightarrow True)$

lemma $jumpNestingOk\ expr\ simp\ [simp]: jumpNestingOk\ jmps\ (In1l\ e) = True$
 <proof>

lemma $jumpNestingOk\ expr\ simp1\ [simp]: jumpNestingOk\ jmps\ \langle e::expr \rangle = True$
 <proof>

lemma $jumpNestingOk\ stmt\ simp\ [simp]:$
 $jumpNestingOk\ jmps\ (In1r\ s) = jumpNestingOkS\ jmps\ s$
 <proof>

lemma $jumpNestingOk\ stmt\ simp1\ [simp]:$
 $jumpNestingOk\ jmps\ \langle s::stmt \rangle = jumpNestingOkS\ jmps\ s$
 <proof>

lemma $jumpNestingOk\ var\ simp\ [simp]: jumpNestingOk\ jmps\ (In2\ v) = True$
 <proof>

lemma $jumpNestingOk\ var\ simp1\ [simp]: jumpNestingOk\ jmps\ \langle v::var \rangle = True$
 <proof>

lemma $jumpNestingOk\ expr\ list\ simp\ [simp]: jumpNestingOk\ jmps\ (In3\ es) = True$
 <proof>

lemma $jumpNestingOk\ expr\ list\ simp1\ [simp]:$
 $jumpNestingOk\ jmps\ \langle es::expr\ list \rangle = True$
 <proof>

Calculation of assigned variables for boolean expressions

30 Very restricted calculation fallback calculation

primrec $theLVarName :: var \Rightarrow lname$
where $theLVarName\ (LVar\ n) = n$

primrec $assignsE :: expr \Rightarrow lname\ set$
and $assignsV :: var \Rightarrow lname\ set$

and $assignsEs :: \text{expr list} \Rightarrow \text{lname set}$
where

$assignsE \text{ (NewC } c)$	$= \{\}$
$assignsE \text{ (NewA } t \ e)$	$= assignsE \ e$
$assignsE \text{ (Cast } t \ e)$	$= assignsE \ e$
$assignsE \text{ (e InstOf } r)$	$= assignsE \ e$
$assignsE \text{ (Lit } val)$	$= \{\}$
$assignsE \text{ (UnOp } unop \ e)$	$= assignsE \ e$
$assignsE \text{ (BinOp } binop \ e1 \ e2)$	$= (\text{if } binop = \text{CondAnd} \vee binop = \text{CondOr}$ $\text{then } (assignsE \ e1)$ $\text{else } (assignsE \ e1) \cup (assignsE \ e2))$
$assignsE \text{ (Super)}$	$= \{\}$
$assignsE \text{ (Acc } v)$	$= assignsV \ v$
$assignsE \text{ (v:=e)}$	$= (assignsV \ v) \cup (assignsE \ e) \cup$ $(\text{if } \exists n. v = (\text{LVar } n) \text{ then } \{\text{the-LVar-name } v\}$ $\text{else } \{\})$
$assignsE \text{ (b? e1 : e2)}$	$= (assignsE \ b) \cup ((assignsE \ e1) \cap (assignsE \ e2))$
$assignsE \text{ (\{accC,statT,mode\}objRef.mn(\{pTs\}args))}$	$= (assignsE \ \text{objRef}) \cup (assignsEs \ \text{args})$

— Only dummy analysis for intermediate expressions *Method*, *Body*, *InsInitE* and *Callee*

$assignsE \text{ (Method } C \ sig)$	$= \{\}$
$assignsE \text{ (Body } C \ s)$	$= \{\}$
$assignsE \text{ (InsInitE } s \ e)$	$= \{\}$
$assignsE \text{ (Callee } l \ e)$	$= \{\}$

$assignsV \text{ (LVar } n)$	$= \{\}$
$assignsV \text{ (\{accC,statDeclC,stat\}objRef..fn)}$	$= assignsE \ \text{objRef}$
$assignsV \text{ (e1.[e2])}$	$= assignsE \ e1 \cup assignsE \ e2$

$assignsEs \ \ []$	$= \{\}$
$assignsEs \text{ (e\#es)}$	$= assignsE \ e \cup assignsEs \ es$

definition $assigns :: \text{term} \Rightarrow \text{lname set}$ **where**

$assigns \ t = (\text{case } t \ \text{of}$
 $\quad \text{In1 } se \Rightarrow (\text{case } se \ \text{of}$
 $\quad \quad \text{Inl } e \Rightarrow assignsE \ e$
 $\quad \quad | \ \text{Inr } s \Rightarrow \{\})$
 $\quad | \ \text{In2 } v \Rightarrow assignsV \ v$
 $\quad | \ \text{In3 } es \Rightarrow assignsEs \ es)$

lemma $assigns\text{-expr}\text{-simp}$ [simp]: $assigns \ (\text{In1l } e) = assignsE \ e$
 $\langle \text{proof} \rangle$

lemma $assigns\text{-expr}\text{-simp1}$ [simp]: $assigns \ (\langle e \rangle) = assignsE \ e$
 $\langle \text{proof} \rangle$

lemma $assigns\text{-stmt}\text{-simp}$ [simp]: $assigns \ (\text{In1r } s) = \{\}$
 $\langle \text{proof} \rangle$

lemma $assigns\text{-stmt}\text{-simp1}$ [simp]: $assigns \ (\langle s :: \text{stmt} \rangle) = \{\}$
 $\langle \text{proof} \rangle$

lemma $assigns\text{-var}\text{-simp}$ [simp]: $assigns \ (\text{In2 } v) = assignsV \ v$
 $\langle \text{proof} \rangle$

lemma *assigns-var-simp1* [*simp*]: *assigns* ($\langle v \rangle$) = *assignsV* *v*
 ⟨*proof*⟩

lemma *assigns-expr-list-simp* [*simp*]: *assigns* (*In3* *es*) = *assignsEs* *es*
 ⟨*proof*⟩

lemma *assigns-expr-list-simp1* [*simp*]: *assigns* ($\langle es \rangle$) = *assignsEs* *es*
 ⟨*proof*⟩

31 Analysis of constant expressions

primrec *constVal* :: *expr* \Rightarrow *val option*

where

constVal (*NewC* *c*) = *None*
 | *constVal* (*NewA* *t e*) = *None*
 | *constVal* (*Cast* *t e*) = *None*
 | *constVal* (*Inst* *e r*) = *None*
 | *constVal* (*Lit* *val*) = *Some val*
 | *constVal* (*UnOp* *unop e*) = (case (*constVal* *e*) of
 None \Rightarrow *None*
 | *Some v* \Rightarrow *Some* (*eval-unop* *unop v*))
 | *constVal* (*BinOp* *binop e1 e2*) = (case (*constVal* *e1*) of
 None \Rightarrow *None*
 | *Some v1* \Rightarrow (case (*constVal* *e2*) of
 None \Rightarrow *None*
 | *Some v2* \Rightarrow *Some* (*eval-binop*
 binop v1 v2)))
 | *constVal* (*Super*) = *None*
 | *constVal* (*Acc* *v*) = *None*
 | *constVal* (*Ass* *v e*) = *None*
 | *constVal* (*Cond* *b e1 e2*) = (case (*constVal* *b*) of
 None \Rightarrow *None*
 | *Some bv* \Rightarrow (case *the-Bool* *bv* of
 True \Rightarrow (case (*constVal* *e2*) of
 None \Rightarrow *None*
 | *Some v* \Rightarrow *constVal* *e1*)
 | *False* \Rightarrow (case (*constVal* *e1*) of
 None \Rightarrow *None*
 | *Some v* \Rightarrow *constVal* *e2*)))

— Note that *constVal* (*Cond* *b e1 e2*) is stricter as it could be. It requires that all tree expressions are constant even if we can decide which branch to choose, provided the constant value of *b*

| *constVal* (*Call* *accC statT mode objRef mn pTs args*) = *None*
 | *constVal* (*Methd* *C sig*) = *None*
 | *constVal* (*Body* *C s*) = *None*
 | *constVal* (*InsInitE* *s e*) = *None*
 | *constVal* (*Callee* *l e*) = *None*

lemma *constVal-Some-induct* [*consumes* 1, *case-names* *Lit UnOp BinOp CondL CondR*]:

assumes *const*: *constVal* *e* = *Some v* **and**

hyp-Lit: $\bigwedge v. P$ (*Lit* *v*) **and**

hyp-UnOp: $\bigwedge unop e'. P e' \Longrightarrow P$ (*UnOp* *unop e'*) **and**

hyp-BinOp: $\bigwedge binop e1 e2. [P e1; P e2] \Longrightarrow P$ (*BinOp* *binop e1 e2*) **and**

hyp-CondL: $\bigwedge b bv e1 e2. [constVal b = Some bv; the-Bool bv; P b; P e1]$
 $\Longrightarrow P$ (*b? e1 : e2*) **and**

$$\text{hyp-CondR: } \bigwedge b \text{ bv } e1 \ e2. \llbracket \text{constVal } b = \text{Some } bv; \neg \text{the-Bool } bv; P \ b; P \ e2 \rrbracket \\ \implies P \ (b? \ e1 : e2)$$

shows $P \ e$
(proof)

lemma *assignsE-const-simp*: $\text{constVal } e = \text{Some } v \implies \text{assignsE } e = \{\}$
(proof)

32 Main analysis for boolean expressions

Assigned local variables after evaluating the expression if it evaluates to a specific boolean value. If the expression cannot evaluate to a *Boolean* value UNIV is returned. If we expect true/false the opposite constant false/true will also lead to UNIV.

primrec *assigns-if* :: $\text{bool} \Rightarrow \text{expr} \Rightarrow \text{lname set}$

where

<i>assigns-if</i> b (<i>NewC</i> c)	= UNIV — can never evaluate to Boolean
<i>assigns-if</i> b (<i>NewA</i> $t \ e$)	= UNIV — can never evaluate to Boolean
<i>assigns-if</i> b (<i>Cast</i> $t \ e$)	= <i>assigns-if</i> $b \ e$
<i>assigns-if</i> b (<i>Inst</i> $e \ r$)	= <i>assignsE</i> e — Inst has type Boolean but e is a reference type
<i>assigns-if</i> b (<i>Lit</i> val)	= (if $val = \text{Bool } b$ then $\{\}$ else UNIV)
<i>assigns-if</i> b (<i>UnOp</i> $unop \ e$)	= (case $\text{constVal } (\text{UnOp } unop \ e)$ of <div style="margin-left: 20px;">None \Rightarrow (if $unop = \text{UNot}$ <div style="margin-left: 20px;">then <i>assigns-if</i> $(\neg b) \ e$ <div style="margin-left: 20px;">else UNIV)</div> </div> </div> <div style="margin-left: 20px;"> $\text{Some } v \Rightarrow$ (if $v = \text{Bool } b$ <div style="margin-left: 20px;">then $\{\}$ <div style="margin-left: 20px;">else UNIV))</div> </div> </div>
<i>assigns-if</i> b (<i>BinOp</i> $binop \ e1 \ e2$)	= (case $\text{constVal } (\text{BinOp } binop \ e1 \ e2)$ of <div style="margin-left: 20px;">None \Rightarrow (if $binop = \text{CondAnd}$ then <div style="margin-left: 20px;">(case b of <div style="margin-left: 20px;">True \Rightarrow <i>assigns-if</i> True $e1 \cup$ <i>assigns-if</i> True $e2$ <div style="margin-left: 20px;"> False \Rightarrow <i>assigns-if</i> False $e1 \cap$ <div style="margin-left: 20px;">(<i>assigns-if</i> True $e1 \cup$ <i>assigns-if</i> False $e2$))</div> </div> </div> </div> </div> <div style="margin-left: 20px;">else <div style="margin-left: 20px;">(if $binop = \text{CondOr}$ then <div style="margin-left: 20px;">(case b of <div style="margin-left: 20px;">True \Rightarrow <i>assigns-if</i> True $e1 \cap$ <div style="margin-left: 20px;">(<i>assigns-if</i> False $e1 \cup$ <i>assigns-if</i> True $e2$)</div> </div> </div> </div> </div>

| $\text{Some } v \Rightarrow$ (if $v = \text{Bool } b$ then $\{\}$ else UNIV))

	assigns-if b (*Super*)	= UNIV — can never evaluate to Boolean		
	assigns-if b (*Acc* v)	= (*assignsV* v)		
	assigns-if b ($v := e$)	= (*assignsE* (*Ass* $v \ e$))		
	assigns-if b ($c? \ e1 : e2$)	= (*assignsE* c) \cup (case ($\text{constVal } c$) of None \Rightarrow (*assigns-if* $b \ e1$) \cap (*assigns-if* $b \ e2$)	$\text{Some } bv \Rightarrow$ (case $\text{the-Bool } bv$ of True \Rightarrow *assigns-if* $b \ e1$	False \Rightarrow *assigns-if* $b \ e2$))
	assigns-if b ($\{\text{accC, statT, mode}\} \text{objRef} \cdot \text{mn}(\{\text{pTs}\} \text{args})$)	= *assignsE* ($\{\text{accC, statT, mode}\} \text{objRef} \cdot \text{mn}(\{\text{pTs}\} \text{args})$)		
— Only dummy analysis for intermediate expressions *Method*, *Body*, *InsInitE* and *Callee*				
	assigns-if b (*Method* $C \ sig$)	= $\{\}$		

| *assigns-if* *b* (*Body C s*) = {}
 | *assigns-if* *b* (*InsInitE s e*) = {}
 | *assigns-if* *b* (*Callee l e*) = {}

lemma *assigns-if-const-b-simp*:

assumes *boolConst*: *constVal e = Some (Bool b) (is ?Const b e)*
shows *assigns-if b e = {} (is ?Ass b e)*
 ⟨*proof*⟩

lemma *assigns-if-const-not-b-simp*:

assumes *boolConst*: *constVal e = Some (Bool b) (is ?Const b e)*
shows *assigns-if (¬b) e = UNIV (is ?Ass b e)*
 ⟨*proof*⟩

33 Lifting set operations to range of tables (map to a set)

definition

union-ts :: ('a,'b) tables ⇒ ('a,'b) tables ⇒ ('a,'b) tables (- ⇒_U - [67,67] 65)
where *A ⇒_U B* = (λ *k*. *A k* ∪ *B k*)

definition

intersect-ts :: ('a,'b) tables ⇒ ('a,'b) tables ⇒ ('a,'b) tables (- ⇒_∩ - [72,72] 71)
where *A ⇒_∩ B* = (λ *k*. *A k* ∩ *B k*)

definition

all-union-ts :: ('a,'b) tables ⇒ 'b set ⇒ ('a,'b) tables (**infixl** ⇒_{U_∨} 40)
where (*A ⇒_{U_∨} B*) = (λ *k*. *A k* ∪ *B*)

Binary union of tables

lemma *union-ts-iff [simp]*: (*c* ∈ (*A ⇒_U B*) *k*) = (*c* ∈ *A k* ∨ *c* ∈ *B k*)
 ⟨*proof*⟩

lemma *union-tsI1 [elim?]*: *c* ∈ *A k* ⇒ *c* ∈ (*A ⇒_U B*) *k*
 ⟨*proof*⟩

lemma *union-tsI2 [elim?]*: *c* ∈ *B k* ⇒ *c* ∈ (*A ⇒_U B*) *k*
 ⟨*proof*⟩

lemma *union-tsCI [intro!]*: (*c* ∉ *B k* ⇒ *c* ∈ *A k*) ⇒ *c* ∈ (*A ⇒_U B*) *k*
 ⟨*proof*⟩

lemma *union-tsE [elim!]*:

[[*c* ∈ (*A ⇒_U B*) *k*; (*c* ∈ *A k* ⇒ *P*); (*c* ∈ *B k* ⇒ *P*)] ⇒ *P*
 ⟨*proof*⟩

Binary intersection of tables

lemma *intersect-ts-iff [simp]*: *c* ∈ (*A ⇒_∩ B*) *k* = (*c* ∈ *A k* ∧ *c* ∈ *B k*)
 ⟨*proof*⟩

lemma *intersect-tsI [intro!]*: [[*c* ∈ *A k*; *c* ∈ *B k*] ⇒ *c* ∈ (*A ⇒_∩ B*) *k*

(proof)

lemma *intersect-tsD1*: $c \in (A \Rightarrow \cap B) k \Longrightarrow c \in A k$
(proof)

lemma *intersect-tsD2*: $c \in (A \Rightarrow \cap B) k \Longrightarrow c \in B k$
(proof)

lemma *intersect-tsE* [*elim!*]:
 $\llbracket c \in (A \Rightarrow \cap B) k; \llbracket c \in A k; c \in B k \rrbracket \Longrightarrow P \rrbracket \Longrightarrow P$
(proof)

All-Union of tables and set

lemma *all-union-ts-iff* [*simp*]: $(c \in (A \Rightarrow \cup B) k) = (c \in A k \vee c \in B)$
(proof)

lemma *all-union-tsI1* [*elim?*]: $c \in A k \Longrightarrow c \in (A \Rightarrow \cup B) k$
(proof)

lemma *all-union-tsI2* [*elim?*]: $c \in B \Longrightarrow c \in (A \Rightarrow \cup B) k$
(proof)

lemma *all-union-tsCI* [*intro!*]: $(c \notin B \Longrightarrow c \in A k) \Longrightarrow c \in (A \Rightarrow \cup B) k$
(proof)

lemma *all-union-tsE* [*elim!*]:
 $\llbracket c \in (A \Rightarrow \cup B) k; (c \in A k \Longrightarrow P); (c \in B \Longrightarrow P) \rrbracket \Longrightarrow P$
(proof)

The rules of definite assignment

type-synonym *breakass* = (*label*, *lname*) *tables*

— Mapping from a break label, to the set of variables that will be assigned if the evaluation terminates with this break

record *assigned* =

nrm :: *lname set* — Definetly assigned variables for normal completion

brk :: *breakass* — Definetly assigned variables for abrupt completion with a break

definition

rmlab :: '*a* \Rightarrow ('*a*, '*b*) *tables* \Rightarrow ('*a*, '*b*) *tables*

where *rmlab* *k A* = ($\lambda x. \text{if } x=k \text{ then UNIV else } A \ x$)

definition

range-inter-ts :: ('*a*, '*b*) *tables* \Rightarrow '*b set* ($\Rightarrow \cap$ - 80)

where $\Rightarrow \cap A = \{x \mid x. \forall k. x \in A \ k\}$

In $E \vdash B \gg t \gg A$, *B* denotes the "assigned" variables before evaluating term *t*, whereas *A* denotes the "assigned" variables after evaluating term *t*. The environment *E* is only needed for the conditional -

? - : -. The definite assignment rules refer to the typing rules here to distinguish boolean and other expressions.

inductive

$da :: env \Rightarrow lname\ set \Rightarrow term \Rightarrow assigned \Rightarrow bool$ (-+ - >>-> - [65,65,65,65] 71)

where

$Skip: Env \vdash B \gg \langle Skip \rangle \gg (\{nrm=B, brk=\lambda l. UNIV\})$

| $Expr: Env \vdash B \gg \langle e \rangle \gg A$

\implies

$Env \vdash B \gg \langle Expr\ e \rangle \gg A$

| $Lab: \llbracket Env \vdash B \gg \langle c \rangle \gg C; nrm\ A = nrm\ C \cap (brk\ C)\ l; brk\ A = rmlab\ l\ (brk\ C) \rrbracket$

\implies

$Env \vdash B \gg \langle Break\ l.\ c \rangle \gg A$

| $Comp: \llbracket Env \vdash B \gg \langle c1 \rangle \gg C1; Env \vdash nrm\ C1 \gg \langle c2 \rangle \gg C2;$

$nrm\ A = nrm\ C2; brk\ A = (brk\ C1) \Rightarrow \cap (brk\ C2) \rrbracket$

\implies

$Env \vdash B \gg \langle c1;; c2 \rangle \gg A$

| $If: \llbracket Env \vdash B \gg \langle e \rangle \gg E;$

$Env \vdash (B \cup assigns\ if\ True\ e) \gg \langle c1 \rangle \gg C1;$

$Env \vdash (B \cup assigns\ if\ False\ e) \gg \langle c2 \rangle \gg C2;$

$nrm\ A = nrm\ C1 \cap nrm\ C2;$

$brk\ A = brk\ C1 \Rightarrow \cap brk\ C2 \rrbracket$

\implies

$Env \vdash B \gg \langle If(e)\ c1\ Else\ c2 \rangle \gg A$

— Note that E is not further used, because we take the specialized sets that also consider if the expression evaluates to true or false. Inside of e there is no **break** or **finally**, so the break map of E will be the trivial one. So $Env \vdash B \gg \langle e \rangle \gg E$ is just used to ensure the definite assignment in expression e . Notice the implicit analysis of a constant boolean expression e in this rule. For example, if e is constantly *True* then *assigns-if False e* = *UNIV* and therefor $nrm\ C2 = UNIV$. So finally $nrm\ A = nrm\ C1$. For the break maps this trick workd too, because the trival break map will map all labels to *UNIV*. In the example, if no break occurs in $c2$ the break maps will trivially map to *UNIV* and if a break occurs it will map to *UNIV* too, because *assigns-if False e* = *UNIV*. So in the intersection of the break maps the path $c2$ will have no contribution.

| $Loop: \llbracket Env \vdash B \gg \langle e \rangle \gg E;$

$Env \vdash (B \cup assigns\ if\ True\ e) \gg \langle c \rangle \gg C;$

$nrm\ A = nrm\ C \cap (B \cup assigns\ if\ False\ e);$

$brk\ A = brk\ C \rrbracket$

\implies

$Env \vdash B \gg \langle l.\ While(e)\ c \rangle \gg A$

— The *Loop* rule resembles some of the ideas of the *If* rule. For the $nrm\ A$ the set $B \cup assigns\ if\ False\ e$ will be *UNIV* if the condition is constantly true. To normally exit the while loop, we must consider the body c to be completed normally ($nrm\ C$) or with a break. But in this model, the label l of the loop only handles continue labels, not break labels. The break label will be handled by an enclosing *Lab* statement. So we don't have to handle the breaks specially.

| $Jmp: \llbracket jump=Ret \longrightarrow Result \in B;$

$nrm\ A = UNIV;$

$brk\ A = (case\ jump\ of$

$Break\ l \Rightarrow \lambda k. if\ k=l\ then\ B\ else\ UNIV$

| $Cont\ l \Rightarrow \lambda k. UNIV$

| $Ret \Rightarrow \lambda k. UNIV) \rrbracket$

\implies

$Env \vdash B \gg \langle Jmp\ jump \rangle \gg A$

— In case of a break to label l the corresponding break set is all variables assigned before the break. The assigned variables for normal completion of the *Jmp* is *UNIV*, because the statement will never complete

normally. For continue and return the break map is the trivial one. In case of a return we ensure that the result value is assigned.

| *Throw*: $\llbracket Env \vdash B \gg \langle e \rangle \gg E; nrm A = UNIV; brk A = (\lambda l. UNIV) \rrbracket$
 $\implies Env \vdash B \gg \langle Throw e \rangle \gg A$

| *Try*: $\llbracket Env \vdash B \gg \langle c1 \rangle \gg C1;$
 $Env(\{lcl := lcl\ Env(VName\ vn \mapsto Class\ C)}) \vdash (B \cup \{VName\ vn\}) \gg \langle c2 \rangle \gg C2;$
 $nrm A = nrm C1 \cap nrm C2;$
 $brk A = brk C1 \Rightarrow \cap brk C2 \rrbracket$
 $\implies Env \vdash B \gg \langle Try\ c1\ Catch(C\ vn)\ c2 \rangle \gg A$

| *Fin*: $\llbracket Env \vdash B \gg \langle c1 \rangle \gg C1;$
 $Env \vdash B \gg \langle c2 \rangle \gg C2;$
 $nrm A = nrm C1 \cup nrm C2;$
 $brk A = ((brk C1) \Rightarrow \cup_{\vee} (nrm C2)) \Rightarrow \cap (brk C2) \rrbracket$
 \implies
 $Env \vdash B \gg \langle c1\ Finally\ c2 \rangle \gg A$

— The set of assigned variables before execution $c2$ are the same as before execution $c1$, because $c1$ could throw an exception and so we can't guarantee that any variable will be assigned in $c1$. The *Finally* statement completes normally if both $c1$ and $c2$ complete normally. If $c1$ completes abruptly with a break, then $c2$ also will be executed and may terminate normally or with a break. The overall break map then is the intersection of the maps of both paths. If $c2$ terminates normally we have to extend all break sets in $brk C1$ with $nrm C2$ ($\Rightarrow \cup_{\vee}$). If $c2$ exits with a break this break will appear in the overall result state. We don't know if $c1$ completed normally or abruptly (maybe with an exception not only a break) so $c1$ has no contribution to the break map following this path.

— Evaluation of expressions and the break sets of definite assignment: Thinking of a Java expression we assume that we can never have a break statement inside of an expression. So for all expressions the break sets could be set to the trivial one: $\lambda l. UNIV$. But we can't trivially prove, that evaluating an expression will never result in a break, although Java expressions already syntactically don't allow nested statements in them. The reason are the nested class initialization statements which are inserted by the evaluation rules. So to prove the absence of a break we need to ensure, that the initialization statements will never end up in a break. In a wellformed initialization statement, of course, where breaks are nested correctly inside of *Lab* or *Loop* statements evaluation of the whole initialization statement will never result in a break, because this break will be handled inside of the statement. But for simplicity we haven't added the analysis of the correct nesting of breaks in the typing judgments right now. So we have decided to adjust the rules of definite assignment to fit to these circumstances. If an initialization is involved during evaluation of the expression (evaluation rules *FVar*, *NewC* and *NewA*

| *Init*: $Env \vdash B \gg \langle Init\ C \rangle \gg (\{nrm=B, brk=\lambda l. UNIV\})$

— Wellformedness of a program will ensure, that every static initialiser is definitely assigned and the jumps are nested correctly. The case here for *Init* is just for convenience, to get a proper precondition for the induction hypothesis in various proofs, so that we don't have to expand the initialisation on every point where it is triggered by the evaluation rules.

| *NewC*: $Env \vdash B \gg \langle NewC\ C \rangle \gg (\{nrm=B, brk=\lambda l. UNIV\})$

| *NewA*: $Env \vdash B \gg \langle e \rangle \gg A$
 \implies
 $Env \vdash B \gg \langle New\ T[e] \rangle \gg A$

| *Cast*: $Env \vdash B \gg \langle e \rangle \gg A$
 \implies
 $Env \vdash B \gg \langle Cast\ T\ e \rangle \gg A$

| *Inst*: $Env \vdash B \gg \langle e \rangle \gg A$
 \implies
 $Env \vdash B \gg \langle e\ InstOf\ T \rangle \gg A$

| *Lit*: $Env \vdash B \gg \langle Lit\ v \rangle \gg (\text{nrm}=B, \text{brk}=\lambda l. UNIV)$

| *UnOp*: $Env \vdash B \gg \langle e \rangle \gg A$

\implies

$Env \vdash B \gg \langle UnOp\ unop\ e \rangle \gg A$

| *CondAnd*: $\llbracket Env \vdash B \gg \langle e1 \rangle \gg E1; Env \vdash (B \cup \text{assigns-if True } e1) \gg \langle e2 \rangle \gg E2;$

$\text{nrm } A = B \cup (\text{assigns-if True } (BinOp\ CondAnd\ e1\ e2) \cap$

$\text{assigns-if False } (BinOp\ CondAnd\ e1\ e2));$

$\text{brk } A = (\lambda l. UNIV) \rrbracket$

\implies

$Env \vdash B \gg \langle BinOp\ CondAnd\ e1\ e2 \rangle \gg A$

| *CondOr*: $\llbracket Env \vdash B \gg \langle e1 \rangle \gg E1; Env \vdash (B \cup \text{assigns-if False } e1) \gg \langle e2 \rangle \gg E2;$

$\text{nrm } A = B \cup (\text{assigns-if True } (BinOp\ CondOr\ e1\ e2) \cap$

$\text{assigns-if False } (BinOp\ CondOr\ e1\ e2));$

$\text{brk } A = (\lambda l. UNIV) \rrbracket$

\implies

$Env \vdash B \gg \langle BinOp\ CondOr\ e1\ e2 \rangle \gg A$

| *BinOp*: $\llbracket Env \vdash B \gg \langle e1 \rangle \gg E1; Env \vdash \text{nrm } E1 \gg \langle e2 \rangle \gg A;$

$\text{binop} \neq \text{CondAnd}; \text{binop} \neq \text{CondOr} \rrbracket$

\implies

$Env \vdash B \gg \langle BinOp\ binop\ e1\ e2 \rangle \gg A$

| *Super*: $This \in B$

\implies

$Env \vdash B \gg \langle Super \rangle \gg (\text{nrm}=B, \text{brk}=\lambda l. UNIV)$

| *AccLVar*: $\llbracket vn \in B;$

$\text{nrm } A = B; \text{brk } A = (\lambda k. UNIV) \rrbracket$

\implies

$Env \vdash B \gg \langle Acc\ (LVar\ vn) \rangle \gg A$

— To properly access a local variable we have to test the definite assignment here. The variable must occur in the set B

| *Acc*: $\llbracket \forall vn. v \neq LVar\ vn;$

$Env \vdash B \gg \langle v \rangle \gg A \rrbracket$

\implies

$Env \vdash B \gg \langle Acc\ v \rangle \gg A$

| *AssLVar*: $\llbracket Env \vdash B \gg \langle e \rangle \gg E; \text{nrm } A = \text{nrm } E \cup \{vn\}; \text{brk } A = \text{brk } E \rrbracket$

\implies

$Env \vdash B \gg \langle (LVar\ vn) := e \rangle \gg A$

| *Ass*: $\llbracket \forall vn. v \neq LVar\ vn; Env \vdash B \gg \langle v \rangle \gg V; Env \vdash \text{nrm } V \gg \langle e \rangle \gg A \rrbracket$

\implies

$Env \vdash B \gg \langle v := e \rangle \gg A$

| *CondBool*: $\llbracket Env \vdash (c ? e1 : e2) :: \neg (PrimT\ Boolean);$

$Env \vdash B \gg \langle c \rangle \gg C;$

$Env \vdash (B \cup \text{assigns-if True } c) \gg \langle e1 \rangle \gg E1;$

$Env \vdash (B \cup \text{assigns-if False } c) \gg \langle e2 \rangle \gg E2;$

$\text{nrm } A = B \cup (\text{assigns-if True } (c ? e1 : e2) \cap$

$\text{assigns-if False } (c ? e1 : e2));$

$\text{brk } A = (\lambda l. UNIV) \rrbracket$

\implies

$Env \vdash B \gg \langle c ? e1 : e2 \rangle \gg A$

$$\begin{array}{l}
| \text{Cond: } \llbracket \neg \text{Env} \vdash (c \ ? \ e1 : e2) :: \neg (\text{PrimT Boolean}); \\
\text{Env} \vdash B \gg \langle c \rangle \gg C; \\
\text{Env} \vdash (B \cup \text{assigns-if True } c) \gg \langle e1 \rangle \gg E1; \\
\text{Env} \vdash (B \cup \text{assigns-if False } c) \gg \langle e2 \rangle \gg E2; \\
\text{nrm } A = \text{nrm } E1 \cap \text{nrm } E2; \text{brk } A = (\lambda l. \text{UNIV}) \rrbracket \\
\implies \\
\text{Env} \vdash B \gg \langle c \ ? \ e1 : e2 \rangle \gg A
\end{array}$$

$$\begin{array}{l}
| \text{Call: } \llbracket \text{Env} \vdash B \gg \langle e \rangle \gg E; \text{Env} \vdash \text{nrm } E \gg \langle \text{args} \rangle \gg A \rrbracket \\
\implies \\
\text{Env} \vdash B \gg \langle \{\text{accC}, \text{statT}, \text{mode}\} e \cdot \text{mn}(\{\text{pTs}\} \text{args}) \rangle \gg A
\end{array}$$

— The interplay of *Call*, *Method* and *Body*: Why rules for *Method* and *Body* at all? Note that a Java source program will not include bare *Method* or *Body* terms. These terms are just introduced during evaluation. So definite assignment of *Call* does not consider *Method* or *Body* at all. So for definite assignment alone we could omit the rules for *Method* and *Body*. But since evaluation of the method invocation is split up into three rules we must ensure that we have enough information about the call even in the *Body* term to make sure that we can proof type safety. Also we must be able transport this information from *Call* to *Method* and then further to *Body* during evaluation to establish the definite assignment of *Method* during evaluation of *Call*, and of *Body* during evaluation of *Method*. This is necessary since definite assignment will be a precondition for each induction hypothesis coming out of the evaluation rules, and therefor we have to establish the definite assignment of the sub-evaluation during the type-safety proof. Note that well-typedness is also a precondition for type-safety and so we can omit some assertion that are already ensured by well-typedness.

$$\begin{array}{l}
| \text{Method: } \llbracket \text{method } (\text{prg } \text{Env}) \ D \ \text{sig} = \text{Some } m; \\
\text{Env} \vdash B \gg \langle \text{Body } (\text{declclass } m) \ (\text{stmt } (\text{mbody } (\text{mthd } m))) \rangle \gg A \\
\rrbracket \\
\implies \\
\text{Env} \vdash B \gg \langle \text{Method } D \ \text{sig} \rangle \gg A
\end{array}$$

$$\begin{array}{l}
| \text{Body: } \llbracket \text{Env} \vdash B \gg \langle c \rangle \gg C; \text{jumpNestingOkS } \{\text{Ret}\} \ c; \text{Result} \in \text{nrm } C; \\
\text{nrm } A = B; \text{brk } A = (\lambda l. \text{UNIV}) \rrbracket \\
\implies \\
\text{Env} \vdash B \gg \langle \text{Body } D \ c \rangle \gg A
\end{array}$$

— Note that A is not correlated to C . If the body statement returns abruptly with return, evaluation of *Body* will absorb this return and complete normally. So we cannot trivially get the assigned variables of the body statement since it has not completed normally or with a break. If the body completes normally we guarantee that the result variable is set with this rule. But if the body completes abruptly with a return we can't guarantee that the result variable is set here, since definite assignment only talks about normal completion and breaks. So for a return the *Jump* rule ensures that the result variable is set and then this information must be carried over to the *Body* rule by the conformance predicate of the state.

$$| \text{LVar: } \text{Env} \vdash B \gg \langle \text{LVar } vn \rangle \gg (\text{nrm} = B, \text{brk} = \lambda l. \text{UNIV})$$

$$\begin{array}{l}
| \text{FVar: } \text{Env} \vdash B \gg \langle e \rangle \gg A \\
\implies \\
\text{Env} \vdash B \gg \langle \{\text{accC}, \text{statDeclC}, \text{stat}\} e \cdot \text{fn} \rangle \gg A
\end{array}$$

$$\begin{array}{l}
| \text{AVar: } \llbracket \text{Env} \vdash B \gg \langle e1 \rangle \gg E1; \text{Env} \vdash \text{nrm } E1 \gg \langle e2 \rangle \gg A \rrbracket \\
\implies \\
\text{Env} \vdash B \gg \langle e1.[e2] \rangle \gg A
\end{array}$$

$$| \text{Nil: } \text{Env} \vdash B \gg \langle [] :: \text{expr list} \rangle \gg (\text{nrm} = B, \text{brk} = \lambda l. \text{UNIV})$$

$$\begin{array}{l}
| \text{Cons: } \llbracket \text{Env} \vdash B \gg \langle e :: \text{expr} \rangle \gg E; \text{Env} \vdash \text{nrm } E \gg \langle es \rangle \gg A \rrbracket \\
\implies \\
\text{Env} \vdash B \gg \langle e \# es \rangle \gg A
\end{array}$$

declare *inj-term-sym-simps* [simp]
declare *assigns-if.simps* [simp del]

declare *split-paired-All* [*simp del*] *split-paired-Ex* [*simp del*]
 ⟨*ML*⟩

inductive-cases *da-elim-cases* [*cases set*]:

$Env \vdash B \gg \langle \text{Skip} \rangle \gg A$
 $Env \vdash B \gg \text{In1r Skip} \gg A$
 $Env \vdash B \gg \langle \text{Expr } e \rangle \gg A$
 $Env \vdash B \gg \text{In1r (Expr } e) \gg A$
 $Env \vdash B \gg \langle l \cdot c \rangle \gg A$
 $Env \vdash B \gg \text{In1r (} l \cdot c) \gg A$
 $Env \vdash B \gg \langle c1 ;; c2 \rangle \gg A$
 $Env \vdash B \gg \text{In1r (} c1 ;; c2) \gg A$
 $Env \vdash B \gg \langle \text{If } (e) \ c1 \ \text{Else } c2 \rangle \gg A$
 $Env \vdash B \gg \text{In1r (If } (e) \ c1 \ \text{Else } c2) \gg A$
 $Env \vdash B \gg \langle l \cdot \text{While}(e) \ c \rangle \gg A$
 $Env \vdash B \gg \text{In1r (} l \cdot \text{While}(e) \ c) \gg A$
 $Env \vdash B \gg \langle \text{Jmp } \text{jump} \rangle \gg A$
 $Env \vdash B \gg \text{In1r (Jmp } \text{jump}) \gg A$
 $Env \vdash B \gg \langle \text{Throw } e \rangle \gg A$
 $Env \vdash B \gg \text{In1r (Throw } e) \gg A$
 $Env \vdash B \gg \langle \text{Try } c1 \ \text{Catch}(C \ vn) \ c2 \rangle \gg A$
 $Env \vdash B \gg \text{In1r (Try } c1 \ \text{Catch}(C \ vn) \ c2) \gg A$
 $Env \vdash B \gg \langle c1 \ \text{Finally } c2 \rangle \gg A$
 $Env \vdash B \gg \text{In1r (} c1 \ \text{Finally } c2) \gg A$
 $Env \vdash B \gg \langle \text{Init } C \rangle \gg A$
 $Env \vdash B \gg \text{In1r (Init } C) \gg A$
 $Env \vdash B \gg \langle \text{NewC } C \rangle \gg A$
 $Env \vdash B \gg \text{In1l (NewC } C) \gg A$
 $Env \vdash B \gg \langle \text{New } T[e] \rangle \gg A$
 $Env \vdash B \gg \text{In1l (New } T[e]) \gg A$
 $Env \vdash B \gg \langle \text{Cast } T \ e \rangle \gg A$
 $Env \vdash B \gg \text{In1l (Cast } T \ e) \gg A$
 $Env \vdash B \gg \langle e \ \text{InstOf } T \rangle \gg A$
 $Env \vdash B \gg \text{In1l (} e \ \text{InstOf } T) \gg A$
 $Env \vdash B \gg \langle \text{Lit } v \rangle \gg A$
 $Env \vdash B \gg \text{In1l (Lit } v) \gg A$
 $Env \vdash B \gg \langle \text{UnOp } \text{unop } e \rangle \gg A$
 $Env \vdash B \gg \text{In1l (UnOp } \text{unop } e) \gg A$
 $Env \vdash B \gg \langle \text{BinOp } \text{binop } e1 \ e2 \rangle \gg A$
 $Env \vdash B \gg \text{In1l (BinOp } \text{binop } e1 \ e2) \gg A$
 $Env \vdash B \gg \langle \text{Super} \rangle \gg A$
 $Env \vdash B \gg \text{In1l (Super)} \gg A$
 $Env \vdash B \gg \langle \text{Acc } v \rangle \gg A$
 $Env \vdash B \gg \text{In1l (Acc } v) \gg A$
 $Env \vdash B \gg \langle v := e \rangle \gg A$
 $Env \vdash B \gg \text{In1l (} v := e) \gg A$
 $Env \vdash B \gg \langle c \ ? \ e1 : e2 \rangle \gg A$
 $Env \vdash B \gg \text{In1l (} c \ ? \ e1 : e2) \gg A$
 $Env \vdash B \gg \langle \{ \text{accC}, \text{statT}, \text{mode} \} e \cdot \text{mn}(\{ pTs \} \text{args}) \rangle \gg A$
 $Env \vdash B \gg \text{In1l (} \{ \text{accC}, \text{statT}, \text{mode} \} e \cdot \text{mn}(\{ pTs \} \text{args})) \gg A$
 $Env \vdash B \gg \langle \text{Methd } C \ \text{sig} \rangle \gg A$
 $Env \vdash B \gg \text{In1l (Methd } C \ \text{sig}) \gg A$
 $Env \vdash B \gg \langle \text{Body } D \ c \rangle \gg A$
 $Env \vdash B \gg \text{In1l (Body } D \ c) \gg A$
 $Env \vdash B \gg \langle \text{LVar } vn \rangle \gg A$
 $Env \vdash B \gg \text{In2 (LVar } vn) \gg A$
 $Env \vdash B \gg \langle \{ \text{accC}, \text{statDeclC}, \text{stat} \} e \cdot \text{fn} \rangle \gg A$
 $Env \vdash B \gg \text{In2 (} \{ \text{accC}, \text{statDeclC}, \text{stat} \} e \cdot \text{fn}) \gg A$
 $Env \vdash B \gg \langle e1.[e2] \rangle \gg A$

$Env \vdash B \gg In2 (e1.[e2]) \gg A$
 $Env \vdash B \gg \langle [] :: expr\ list \rangle \gg A$
 $Env \vdash B \gg In3 ([] :: expr\ list) \gg A$
 $Env \vdash B \gg \langle e \# es \rangle \gg A$
 $Env \vdash B \gg In3 (e \# es) \gg A$

declare *inj-term-sym-simps* [*simp del*]

declare *assigns-if.simps* [*simp*]

declare *split-paired-All* [*simp*] *split-paired-Ex* [*simp*]

$\langle ML \rangle$

lemma *da-Skip*: $A = \langle nrm=B, brk=\lambda l. UNIV \rangle \implies Env \vdash B \gg \langle Skip \rangle \gg A$
 $\langle proof \rangle$

lemma *da-NewC*: $A = \langle nrm=B, brk=\lambda l. UNIV \rangle \implies Env \vdash B \gg \langle NewC\ C \rangle \gg A$
 $\langle proof \rangle$

lemma *da-Lit*: $A = \langle nrm=B, brk=\lambda l. UNIV \rangle \implies Env \vdash B \gg \langle Lit\ v \rangle \gg A$
 $\langle proof \rangle$

lemma *da-Super*: $\llbracket This \in B; A = \langle nrm=B, brk=\lambda l. UNIV \rangle \rrbracket \implies Env \vdash B \gg \langle Super \rangle \gg A$
 $\langle proof \rangle$

lemma *da-Init*: $A = \langle nrm=B, brk=\lambda l. UNIV \rangle \implies Env \vdash B \gg \langle Init\ C \rangle \gg A$
 $\langle proof \rangle$

lemma *assignsE-subseteq-assigns-ifs*:

assumes *boolEx*: $E \vdash e :: \text{--PrimT Boolean (is ?Boolean e)}$

shows $assignsE\ e \subseteq assigns\text{-if}\ True\ e \cap assigns\text{-if}\ False\ e$ (**is** *?Incl e*)
 $\langle proof \rangle$

lemma *rmlab-same-label* [*simp*]: $(rmlab\ l\ A)\ l = UNIV$
 $\langle proof \rangle$

lemma *rmlab-same-label1* [*simp*]: $l=l' \implies (rmlab\ l\ A)\ l' = UNIV$
 $\langle proof \rangle$

lemma *rmlab-other-label* [*simp*]: $l \neq l' \implies (rmlab\ l\ A)\ l' = A\ l'$
 $\langle proof \rangle$

lemma *range-inter-ts-subseteq* [*intro*]: $\forall k. A\ k \subseteq B\ k \implies \bigcap A \subseteq \bigcap B$
 $\langle proof \rangle$

lemma *range-inter-ts-subseteq'*: $\forall k. A \ k \subseteq B \ k \implies x \in \Rightarrow \bigcap A \implies x \in \Rightarrow \bigcap B$
 ⟨proof⟩

lemma *da-monotone*:

assumes *da*: $Env \vdash B \gg t \gg A$ **and**

$B \subseteq B'$ **and**

da': $Env \vdash B' \gg t \gg A'$

shows $(nrm \ A \subseteq nrm \ A') \wedge (\forall l. (brk \ A \ l \subseteq brk \ A' \ l))$

⟨proof⟩

lemma *da-weaken*:

assumes *da*: $Env \vdash B \gg t \gg A$ **and** $B \subseteq B'$

shows $\exists A'. Env \vdash B' \gg t \gg A'$

⟨proof⟩

corollary *da-weakenE* [*consumes 2*]:

assumes $da: Env \vdash B \gg t \gg A$ **and**

$B': B \subseteq B'$ **and**

ex-mono: $\bigwedge A'. \llbracket Env \vdash B' \gg t \gg A'; nrm \ A \subseteq nrm \ A';$
 $\bigwedge l. brk \ A \ l \subseteq brk \ A' \ l \rrbracket \implies P$

shows P

⟨proof⟩

end

Chapter 13

WellForm

34 Well-formedness of Java programs

theory *WellForm* **imports** *DefiniteAssignment* **begin**

For static checks on expressions and statements, see *WellType.thy* improvements over Java Specification 1.0 (cf. 8.4.6.3, 8.4.6.4, 9.4.1):

- a method implementing or overwriting another method may have a result type that widens to the result type of the other method (instead of identical type)
- if a method hides another method (both methods have to be static!) there are no restrictions to the result type since the methods have to be static and there is no dynamic binding of static methods
- if an interface inherits more than one method with the same signature, the methods need not have identical return types

simplifications:

- Object and standard exceptions are assumed to be declared like normal classes

well-formed field declarations

well-formed field declaration (common part for classes and interfaces), cf. 8.3 and (9.3)

definition

$wf_fdecl :: prog \Rightarrow pname \Rightarrow fdecl \Rightarrow bool$
where $wf_fdecl\ G\ P = (\lambda(fn,f). is_acc_type\ G\ P\ (type\ f))$

lemma $wf_fdecl_def2: \bigwedge fd. wf_fdecl\ G\ P\ fd = is_acc_type\ G\ P\ (type\ (snd\ fd))$
 $\langle proof \rangle$

well-formed method declarations

A method head is wellformed if:

- the signature and the method head agree in the number of parameters
- all types of the parameters are visible
- the result type is visible
- the parameter names are unique

definition

$wf_mhead :: prog \Rightarrow pname \Rightarrow sig \Rightarrow mhead \Rightarrow bool$ **where**
 $wf_mhead\ G\ P = (\lambda\ sig\ mh. length\ (parTs\ sig) = length\ (pars\ mh) \wedge$
 $(\forall T \in set\ (parTs\ sig). is_acc_type\ G\ P\ T) \wedge$
 $is_acc_type\ G\ P\ (resTy\ mh) \wedge$
 $distinct\ (pars\ mh))$

A method declaration is wellformed if:

- the method head is wellformed
- the names of the local variables are unique
- the types of the local variables must be accessible

- the local variables don't shadow the parameters
- the class of the method is defined
- the body statement is welltyped with respect to the modified environment of local names, were the local variables, the parameters the special result variable (Res) and This are assoziated with there types.

definition

callee-lcl :: *qname* \Rightarrow *sig* \Rightarrow *methd* \Rightarrow *lenv* **where**
callee-lcl *C sig m* =
 $(\lambda k. (\text{case } k \text{ of}$
 EName *e*
 $\Rightarrow (\text{case } e \text{ of}$
 VNam *v*
 $\Rightarrow (\text{table-of } (lcls \ (mbody \ m)) ((pars \ m)[\mapsto](parTs \ sig))) \ v$
 | *Res* \Rightarrow *Some* (*resTy* *m*))
 | *This* \Rightarrow *if is-static* *m* *then None* *else Some* (*Class* *C*)))

definition

parameters :: *methd* \Rightarrow *lname* *set* **where**
parameters *m* = *set* (*map* (*EName* \circ *VNam*) (*pars* *m*)) \cup (*if* (*static* *m*) *then* {} *else* {*This*})

definition

wf-mdecl :: *prog* \Rightarrow *qname* \Rightarrow *mdecl* \Rightarrow *bool* **where**
wf-mdecl *G C* =
 $(\lambda (sig, m).$
 wf-mhead *G* (*pid* *C*) *sig* (*mhead* *m*) \wedge
 unique (*lcls* (*mbody* *m*)) \wedge
 $(\forall (vn, T) \in \text{set } (lcls \ (mbody \ m)). \text{is-acc-type } G \ (pid \ C) \ T) \wedge$
 $(\forall pn \in \text{set } (pars \ m). \text{table-of } (lcls \ (mbody \ m)) \ pn = \text{None}) \wedge$
 jumpNestingOkS {*Ret*} (*stmt* (*mbody* *m*)) \wedge
 is-class *G C* \wedge
 $(\langle prg = G, cls = C, lcl = \text{callee-lcl } C \ sig \ m \rangle \vdash (\text{stmt } (mbody \ m))) :: \checkmark \wedge$
 $(\exists A. (\langle prg = G, cls = C, lcl = \text{callee-lcl } C \ sig \ m \rangle$
 $\vdash \text{parameters } m \gg \langle \text{stmt } (mbody \ m) \rangle \gg A$
 $\wedge \text{Result} \in \text{nrm } A))$

lemma *callee-lcl-VNam-simp* [*simp*]:

callee-lcl *C sig m* (*EName* (*VNam* *v*))
 = (*table-of* (*lcls* (*mbody* *m*)) ((*pars* *m*) $[\mapsto]$ (*parTs* *sig*))) *v*
 $\langle \text{proof} \rangle$

lemma *callee-lcl-Res-simp* [*simp*]:

callee-lcl *C sig m* (*EName* *Res*) = *Some* (*resTy* *m*)
 $\langle \text{proof} \rangle$

lemma *callee-lcl-This-simp* [*simp*]:

callee-lcl *C sig m* (*This*) = (*if is-static* *m* *then None* *else Some* (*Class* *C*))
 $\langle \text{proof} \rangle$

lemma *callee-lcl-This-static-simp*:

is-static *m* \implies *callee-lcl* *C sig m* (*This*) = *None*
 $\langle \text{proof} \rangle$

lemma *callee-lcl-This-not-static-simp*:

\neg *is-static* $m \implies$ *callee-lcl* C *sig* m (*This*) = *Some* (*Class* C)
 <proof>

lemma *wf-mheadI*:

\llbracket *length* (*parTs* *sig*) = *length* (*pars* m); $\forall T \in \text{set}$ (*parTs* *sig*). *is-acc-type* G P T ;
is-acc-type G P (*resTy* m); *distinct* (*pars* m) $\rrbracket \implies$
wf-mhead G P *sig* m
 <proof>

lemma *wf-mdeclI*: \llbracket

wf-mhead G (*pid* C) *sig* (*mhead* m); *unique* (*lcls* (*mbody* m));
 $\forall pn \in \text{set}$ (*pars* m). *table-of* (*lcls* (*mbody* m)) pn = *None*;
 $\forall (vn, T) \in \text{set}$ (*lcls* (*mbody* m)). *is-acc-type* G (*pid* C) T ;
jumpNestingOkS {*Ret*} (*stmt* (*mbody* m));
is-class G C ;
 $(\text{prg} = G, \text{cls} = C, \text{lcl} = \text{callee-lcl } C \text{ sig } m) \vdash (\text{stmt } (\text{mbody } m)) :: \surd$;
 $(\exists A. (\text{prg} = G, \text{cls} = C, \text{lcl} = \text{callee-lcl } C \text{ sig } m) \vdash \text{parameters } m \gg (\text{stmt } (\text{mbody } m)) \gg A$
 $\wedge \text{Result} \in \text{nrm } A)$
 $\rrbracket \implies$
wf-mdecl G C (*sig*, m)
 <proof>

lemma *wf-mdeclE* [*consumes 1*]:

\llbracket *wf-mdecl* G C (*sig*, m);
 \llbracket *wf-mhead* G (*pid* C) *sig* (*mhead* m); *unique* (*lcls* (*mbody* m));
 $\forall pn \in \text{set}$ (*pars* m). *table-of* (*lcls* (*mbody* m)) pn = *None*;
 $\forall (vn, T) \in \text{set}$ (*lcls* (*mbody* m)). *is-acc-type* G (*pid* C) T ;
jumpNestingOkS {*Ret*} (*stmt* (*mbody* m));
is-class G C ;
 $(\text{prg} = G, \text{cls} = C, \text{lcl} = \text{callee-lcl } C \text{ sig } m) \vdash (\text{stmt } (\text{mbody } m)) :: \surd$;
 $(\exists A. (\text{prg} = G, \text{cls} = C, \text{lcl} = \text{callee-lcl } C \text{ sig } m) \vdash \text{parameters } m \gg (\text{stmt } (\text{mbody } m)) \gg A$
 $\wedge \text{Result} \in \text{nrm } A)$
 $\rrbracket \implies P$
 $\rrbracket \implies P$
 <proof>

lemma *wf-mdeclD1*:

wf-mdecl G C (*sig*, m) \implies
wf-mhead G (*pid* C) *sig* (*mhead* m) \wedge *unique* (*lcls* (*mbody* m)) \wedge
 $(\forall pn \in \text{set}$ (*pars* m). *table-of* (*lcls* (*mbody* m)) pn = *None*) \wedge
 $(\forall (vn, T) \in \text{set}$ (*lcls* (*mbody* m)). *is-acc-type* G (*pid* C) T)
 <proof>

lemma *wf-mdecl-bodyD*:

wf-mdecl G C (*sig*, m) \implies
 $(\exists T. (\text{prg} = G, \text{cls} = C, \text{lcl} = \text{callee-lcl } C \text{ sig } m) \vdash \text{Body } C (\text{stmt } (\text{mbody } m)) :: -T \wedge$
 $G \vdash T \preceq (\text{resTy } m))$
 <proof>

lemma *rT-is-acc-type*:

$wf\text{-mhead } G \ P \ sig \ m \implies is\text{-acc-type } G \ P \ (resTy \ m)$
 ⟨proof⟩

well-formed interface declarations

A interface declaration is wellformed if:

- the interface hierarchy is wellstructured
- there is no class with the same name
- the method heads are wellformed and not static and have Public access
- the methods are uniquely named
- all superinterfaces are accessible
- the result type of a method overriding a method of Object widens to the result type of the overridden method. Shadowing static methods is forbidden.
- the result type of a method overriding a set of methods defined in the superinterfaces widens to each of the corresponding result types

definition

$wf\text{-idecl} :: prog \implies idecl \implies bool$ **where**
 $wf\text{-idecl } G =$
 $(\lambda(I,i).$
 $\quad ws\text{-idecl } G \ I \ (isuperIfs \ i) \wedge$
 $\quad \neg is\text{-class } G \ I \wedge$
 $\quad (\forall (sig,mh) \in set \ (imethods \ i). wf\text{-mhead } G \ (pid \ I) \ sig \ mh \wedge$
 $\quad \quad \neg is\text{-static } mh \wedge$
 $\quad \quad accmodi \ mh = Public) \wedge$
 $\quad unique \ (imethods \ i) \wedge$
 $\quad (\forall J \in set \ (isuperIfs \ i). is\text{-acc-iface } G \ (pid \ I) \ J) \wedge$
 $\quad (table\text{-of } (imethods \ i)$
 $\quad \quad hiding \ (methd \ G \ Object)$
 $\quad \quad under \ (\lambda new \ old. accmodi \ old \neq Private)$
 $\quad \quad entails \ (\lambda new \ old. G \vdash resTy \ new \preceq resTy \ old \wedge$
 $\quad \quad \quad is\text{-static } new = is\text{-static } old)) \wedge$
 $\quad (Option.set \circ table\text{-of } (imethods \ i)$
 $\quad \quad hidings \ Un\text{-tables}((\lambda J.(imethds \ G \ J))'set \ (isuperIfs \ i))$
 $\quad \quad entails \ (\lambda new \ old. G \vdash resTy \ new \preceq resTy \ old)))$

lemma *wf-idecl-mhead*: $\llbracket wf\text{-idecl } G \ (I,i); (sig,mh) \in set \ (imethods \ i) \rrbracket \implies$
 $wf\text{-mhead } G \ (pid \ I) \ sig \ mh \wedge \neg is\text{-static } mh \wedge accmodi \ mh = Public$
 ⟨proof⟩

lemma *wf-idecl-hidings*:

$wf\text{-idecl } G \ (I, i) \implies$
 $(\lambda s. Option.set \ (table\text{-of } (imethods \ i) \ s))$
 $\quad hidings \ Un\text{-tables} \ ((\lambda J. imethds \ G \ J) \ 'set \ (isuperIfs \ i))$
 $\quad entails \ \lambda new \ old. G \vdash resTy \ new \preceq resTy \ old$
 ⟨proof⟩

lemma *wf-idecl-hiding*:

$wf\text{-idecl } G (I, i) \implies$
 $(\text{table-of } (i\text{methods } i)$
 $\quad \text{hiding } (\text{methd } G \text{ Object})$
 $\quad \text{under } (\lambda \text{ new old. } \text{accmodi } \text{old} \neq \text{Private})$
 $\quad \text{entails } (\lambda \text{ new old. } G \vdash \text{resTy } \text{new} \leq \text{resTy } \text{old} \wedge$
 $\quad \quad \text{is-static } \text{new} = \text{is-static } \text{old}))$
 $\langle \text{proof} \rangle$

lemma *wf-idecl-supD*:

$\llbracket wf\text{-idecl } G (I, i); J \in \text{set } (i\text{superIfs } i) \rrbracket$
 $\implies \text{is-acc-iface } G (\text{pid } I) J \wedge (J, I) \notin (\text{subint1 } G) \hat{+}$
 $\langle \text{proof} \rangle$

well-formed class declarations

A class declaration is wellformed if:

- there is no interface with the same name
- all superinterfaces are accessible and for all methods implementing an interface method the result type widens to the result type of the interface method, the method is not static and offers at least as much access (this actually means that the method has Public access, since all interface methods have public access)
- all field declarations are wellformed and the field names are unique
- all method declarations are wellformed and the method names are unique
- the initialization statement is welltyped
- the classhierarchy is wellstructured
- Unless the class is Object:
 - the superclass is accessible
 - for all methods overriding another method (of a superclass) the result type widens to the result type of the overridden method, the access modifier of the new method provides at least as much access as the overwritten one.
 - for all methods hiding a method (of a superclass) the hidden method must be static and offer at least as much access rights. Remark: In contrast to the Java Language Specification we don't restrict the result types of the method (as in case of overriding), because there seems to be no reason, since there is no dynamic binding of static methods. (cf. 8.4.6.3 vs. 15.12.1). Stricly speaking the restrictions on the access rights aren't necessary to, since the static type and the access rights together determine which method is to be called statically. But if a class gains more then one static method with the same signature due to inheritance, it is confusing when the method selection depends on the access rights only: e.g. Class C declares static public method foo(). Class D is subclass of C and declares static method foo() with default package access. D.foo() ? if this call is in the same package as D then foo of class D is called, otherwise foo of class C.

definition

$\text{entails} :: ('a, 'b) \text{table} \Rightarrow ('b \Rightarrow \text{bool}) \Rightarrow \text{bool} \text{ (- entails - 20)}$
 $\text{where } (t \text{ entails } P) = (\forall k. \forall x \in t k: P x)$

lemma *entailsD*:

$\llbracket t \text{ entails } P; t k = \text{Some } x \rrbracket \implies P x$
 ⟨proof⟩

lemma *empty-entails[simp]*: *empty entails P*

⟨proof⟩

definition

wf-cdecl :: *prog* \Rightarrow *cdecl* \Rightarrow *bool* **where**

wf-cdecl *G* =

($\lambda(C,c).$
 $\neg \text{is-iface } G \ C \wedge$
 $(\forall I \in \text{set } (\text{superIfs } c). \text{is-acc-iface } G \ (\text{pid } C) \ I \wedge$
 $(\forall s. \forall im \in \text{imethds } G \ I \ s.$
 $(\exists cm \in \text{methd } G \ C \ s: G \vdash \text{resTy } cm \preceq \text{resTy } im \wedge$
 $\neg \text{is-static } cm \wedge$
 $\text{accmodi } im \leq \text{accmodi } cm))) \wedge$
 $(\forall f \in \text{set } (\text{cfields } c). \text{wf-fdecl } G \ (\text{pid } C) \ f) \wedge \text{unique } (\text{cfields } c) \wedge$
 $(\forall m \in \text{set } (\text{methods } c). \text{wf-mdecl } G \ C \ m) \wedge \text{unique } (\text{methods } c) \wedge$
 $\text{jumpNestingOkS } \{\} \ (\text{init } c) \wedge$
 $(\exists A. (\text{prg}=G, \text{cls}=C, \text{lcl}=\text{empty}) \vdash \{\} \gg \langle \text{init } c \rangle \gg A) \wedge$
 $(\text{prg}=G, \text{cls}=C, \text{lcl}=\text{empty}) \vdash (\text{init } c) :: \checkmark \wedge \text{ws-cdecl } G \ C \ (\text{super } c) \wedge$
 $(C \neq \text{Object} \longrightarrow$
 $(\text{is-acc-class } G \ (\text{pid } C) \ (\text{super } c) \wedge$
 $(\text{table-of } (\text{map } (\lambda (s,m). (s,C,m)) \ (\text{methods } c))$
 $\text{entails } (\lambda \text{ new. } \forall \text{ old sig.}$
 $(G, \text{sig} \vdash \text{new overrides}_S \text{ old}$
 $\longrightarrow (G \vdash \text{resTy } \text{new} \preceq \text{resTy } \text{old} \wedge$
 $\text{accmodi } \text{old} \leq \text{accmodi } \text{new} \wedge$
 $\neg \text{is-static } \text{old})) \wedge$
 $(G, \text{sig} \vdash \text{new hides old}$
 $\longrightarrow (\text{accmodi } \text{old} \leq \text{accmodi } \text{new} \wedge$
 $\text{is-static } \text{old}))))$
 $)))$

lemma *wf-cdeclE* [*consumes 1*]:

$\llbracket \text{wf-cdecl } G \ (C,c);$
 $\llbracket \neg \text{is-iface } G \ C;$
 $(\forall I \in \text{set } (\text{superIfs } c). \text{is-acc-iface } G \ (\text{pid } C) \ I \wedge$
 $(\forall s. \forall im \in \text{imethds } G \ I \ s.$
 $(\exists cm \in \text{methd } G \ C \ s: G \vdash \text{resTy } cm \preceq \text{resTy } im \wedge$
 $\neg \text{is-static } cm \wedge$
 $\text{accmodi } im \leq \text{accmodi } cm)))$;
 $\forall f \in \text{set } (\text{cfields } c). \text{wf-fdecl } G \ (\text{pid } C) \ f; \text{unique } (\text{cfields } c);$
 $\forall m \in \text{set } (\text{methods } c). \text{wf-mdecl } G \ C \ m; \text{unique } (\text{methods } c);$
 $\text{jumpNestingOkS } \{\} \ (\text{init } c);$
 $\exists A. (\text{prg}=G, \text{cls}=C, \text{lcl}=\text{empty}) \vdash \{\} \gg \langle \text{init } c \rangle \gg A;$
 $(\text{prg}=G, \text{cls}=C, \text{lcl}=\text{empty}) \vdash (\text{init } c) :: \checkmark;$
 $\text{ws-cdecl } G \ C \ (\text{super } c);$
 $(C \neq \text{Object} \longrightarrow$
 $(\text{is-acc-class } G \ (\text{pid } C) \ (\text{super } c) \wedge$
 $(\text{table-of } (\text{map } (\lambda (s,m). (s,C,m)) \ (\text{methods } c))$
 $\text{entails } (\lambda \text{ new. } \forall \text{ old sig.}$
 $(G, \text{sig} \vdash \text{new overrides}_S \text{ old}$

lemma *wf-cdecl-hides-SomeD*:

$\llbracket wf\text{-}cdecl\ G\ (C, c); C \neq Object; \text{table-of (methods } c) \text{ sig} = \text{Some newM};$
 $G, sig \vdash (C, newM) \text{ hides old}$
 $\rrbracket \implies \text{accmodi old} \leq \text{access newM} \wedge$
 is-static old
 <proof>

lemma *wf-cdecl-wt-init*:

$wf\text{-}cdecl\ G\ (C, c) \implies (\text{prg} = G, \text{cls} = C, \text{lcl} = \text{empty}) \vdash \text{init } c :: \checkmark$
 <proof>

well-formed programs

A program declaration is wellformed if:

- the class ObjectC of Object is defined
- every method of Object has an access modifier distinct from Package. This is necessary since every interface automatically inherits from Object. We must know, that every time a Object method is "overridden" by an interface method this is also overridden by the class implementing the the interface (see *implement-dynmethod* and *class-mheadsD*)
- all standard Exceptions are defined
- all defined interfaces are wellformed
- all defined classes are wellformed

definition

$wf\text{-}prog :: prog \Rightarrow bool$ **where**
 $wf\text{-}prog\ G = (\text{let } is = \text{ifaces } G; cs = \text{classes } G \text{ in}$
 $\text{ObjectC} \in \text{set } cs \wedge$
 $(\forall m \in \text{set } Object\text{-}mdecls. \text{accmodi } m \neq \text{Package}) \wedge$
 $(\forall xn. SXcptC\ xn \in \text{set } cs) \wedge$
 $(\forall i \in \text{set } is. wf\text{-}idecl\ G\ i) \wedge \text{unique } is \wedge$
 $(\forall c \in \text{set } cs. wf\text{-}cdecl\ G\ c) \wedge \text{unique } cs)$

lemma *wf-prog-idecl*: $\llbracket \text{iface } G\ I = \text{Some } i; wf\text{-}prog\ G \rrbracket \implies wf\text{-}idecl\ G\ (I, i)$
 <proof>

lemma *wf-prog-cdecl*: $\llbracket \text{class } G\ C = \text{Some } c; wf\text{-}prog\ G \rrbracket \implies wf\text{-}cdecl\ G\ (C, c)$
 <proof>

lemma *wf-prog-Object-mdecls*:

$wf\text{-}prog\ G \implies (\forall m \in \text{set } Object\text{-}mdecls. \text{accmodi } m \neq \text{Package})$
 <proof>

lemma *wf-prog-acc-superD*:

$\llbracket wf\text{-}prog\ G; \text{class } G\ C = \text{Some } c; C \neq Object \rrbracket$
 $\implies \text{is-acc-class } G\ (\text{pid } C)\ (\text{super } c)$
 <proof>

lemma *wf-ws-prog* [*elim!*,*simp*]: $wf\text{-prog } G \implies ws\text{-prog } G$
 ⟨*proof*⟩

lemma *class-Object* [*simp*]:
 $wf\text{-prog } G \implies$
 $class\ G\ Object = Some (\{access=Public,cfields=[],methods=Object\text{-mdecls},$
 $init=Skip,super=undefined,superIfs=[]\})$
 ⟨*proof*⟩

lemma *methd-Object*[*simp*]: $wf\text{-prog } G \implies methd\ G\ Object =$
 $table\ of\ (\lambda(s,m). (s, Object, m))\ Object\text{-mdecls}$
 ⟨*proof*⟩

lemma *wf-prog-Object-methd*:
 $\llbracket wf\text{-prog } G; methd\ G\ Object\ sig = Some\ m \rrbracket \implies accmodi\ m \neq Package$
 ⟨*proof*⟩

lemma *wf-prog-Object-is-public*[*intro*]:
 $wf\text{-prog } G \implies is\text{-public } G\ Object$
 ⟨*proof*⟩

lemma *class-SXcpt* [*simp*]:
 $wf\text{-prog } G \implies$
 $class\ G\ (SXcpt\ xn) = Some (\{access=Public,cfields=[],methods=SXcpt\text{-mdecls},$
 $init=Skip,$
 $super=if\ xn = Throwable\ then\ Object$
 $else\ SXcpt\ Throwable,$
 $superIfs=[]\})$
 ⟨*proof*⟩

lemma *wf-ObjectC* [*simp*]:
 $wf\text{-cdecl } G\ ObjectC = (\neg is\text{-iface } G\ Object \wedge Ball\ (set\ Object\text{-mdecls})$
 $(wf\text{-mdecl } G\ Object) \wedge unique\ Object\text{-mdecls})$
 ⟨*proof*⟩

lemma *Object-is-class* [*simp,elim!*]: $wf\text{-prog } G \implies is\text{-class } G\ Object$
 ⟨*proof*⟩

lemma *Object-is-acc-class* [*simp,elim!*]: $wf\text{-prog } G \implies is\text{-acc-class } G\ S\ Object$
 ⟨*proof*⟩

lemma *SXcpt-is-class* [*simp,elim!*]: $wf\text{-prog } G \implies is\text{-class } G\ (SXcpt\ xn)$
 ⟨*proof*⟩

lemma *SXcpt-is-acc-class* [*simp,elim!*]:
 $wf\text{-prog } G \implies is\text{-acc-class } G\ S\ (SXcpt\ xn)$
 ⟨*proof*⟩

lemma *fields-Object* [simp]: $wf\text{-prog } G \implies DeclConcepts.fields\ G\ Object = []$
 ⟨proof⟩

lemma *accfield-Object* [simp]:
 $wf\text{-prog } G \implies accfield\ G\ S\ Object = empty$
 ⟨proof⟩

lemma *fields-Throwable* [simp]:
 $wf\text{-prog } G \implies DeclConcepts.fields\ G\ (SXcpt\ Throwable) = []$
 ⟨proof⟩

lemma *fields-SXcpt* [simp]: $wf\text{-prog } G \implies DeclConcepts.fields\ G\ (SXcpt\ xn) = []$
 ⟨proof⟩

lemmas *widen-trans* = *ws-widen-trans* [OF - - *wf-ws-prog*, *elim*]

lemma *widen-trans2* [elim]: $\llbracket G \vdash U \preceq T; G \vdash S \preceq U; wf\text{-prog } G \rrbracket \implies G \vdash S \preceq T$
 ⟨proof⟩

lemma *Xcpt-subcls-Throwable* [simp]:
 $wf\text{-prog } G \implies G \vdash SXcpt\ xn \preceq_C\ SXcpt\ Throwable$
 ⟨proof⟩

lemma *unique-fields*:
 $\llbracket is\text{-class } G\ C; wf\text{-prog } G \rrbracket \implies unique\ (DeclConcepts.fields\ G\ C)$
 ⟨proof⟩

lemma *fields-mono*:
 $\llbracket table\text{-of } (DeclConcepts.fields\ G\ C)\ fn = Some\ f; G \vdash D \preceq_C\ C; is\text{-class } G\ D; wf\text{-prog } G \rrbracket$
 $\implies table\text{-of } (DeclConcepts.fields\ G\ D)\ fn = Some\ f$
 ⟨proof⟩

lemma *fields-is-type* [elim]:
 $\llbracket table\text{-of } (DeclConcepts.fields\ G\ C)\ m = Some\ f; wf\text{-prog } G; is\text{-class } G\ C \rrbracket \implies$
 $is\text{-type } G\ (type\ f)$
 ⟨proof⟩

lemma *imethds-wf-mhead* [rule-format (no-asm)]:
 $\llbracket m \in imethds\ G\ I\ sig; wf\text{-prog } G; is\text{-iface } G\ I \rrbracket \implies$
 $wf\text{-mhead } G\ (pid\ (decliface\ m))\ sig\ (mthd\ m) \wedge$
 $\neg is\text{-static } m \wedge accmodi\ m = Public$
 ⟨proof⟩

lemma *methd-wf-mdecl*:
 $\llbracket methd\ G\ C\ sig = Some\ m; wf\text{-prog } G; class\ G\ C = Some\ y \rrbracket \implies$
 $G \vdash C \preceq_C\ (declclass\ m) \wedge is\text{-class } G\ (declclass\ m) \wedge$
 $wf\text{-mdecl } G\ (declclass\ m)\ (sig,(mthd\ m))$
 ⟨proof⟩

lemma *methd-rT-is-type*:
 $\llbracket wf\text{-prog } G; methd\ G\ C\ sig = Some\ m;$
 $\quad class\ G\ C = Some\ y \rrbracket$
 $\implies is\text{-type } G\ (resTy\ m)$
 $\langle proof \rangle$

lemma *accmethd-rT-is-type*:
 $\llbracket wf\text{-prog } G; accmethd\ G\ S\ C\ sig = Some\ m;$
 $\quad class\ G\ C = Some\ y \rrbracket$
 $\implies is\text{-type } G\ (resTy\ m)$
 $\langle proof \rangle$

lemma *methd-Object-SomeD*:
 $\llbracket wf\text{-prog } G; methd\ G\ Object\ sig = Some\ m \rrbracket$
 $\implies declclass\ m = Object$
 $\langle proof \rangle$

lemmas *iface-rec-induct'* = *iface-rec.induct* [of $\%x\ y\ z.\ P\ x\ y$] **for** P

lemma *wf-imethdsD*:
 $\llbracket im \in imethds\ G\ I\ sig; wf\text{-prog } G; is\text{-iface } G\ I \rrbracket$
 $\implies \neg is\text{-static } im \wedge accmodi\ im = Public$
 $\langle proof \rangle$

lemma *wf-prog-hidesD*:
assumes *hides*: $G \vdash new\ hides\ old$ **and** $wf : wf\text{-prog } G$
shows
 $accmodi\ old \leq accmodi\ new \wedge$
 $is\text{-static } old$
 $\langle proof \rangle$

Compare this lemma about static overriding $G \vdash new\ overrides_S\ old$ with the definition of dynamic overriding $G \vdash new\ overrides\ old$. Conforming result types and restrictions on the access modifiers of the old and the new method are not part of the predicate for static overriding. But they are enshured in a wellformed program. Dynamic overriding has no restrictions on the access modifiers but enforces conform result types as precondition. But with some effort we can guarantee the access modifier restriction for dynamic overriding, too. See lemma *wf-prog-dyn-override-prop*.

lemma *wf-prog-stat-overridesD*:
assumes *stat-override*: $G \vdash new\ overrides_S\ old$ **and** $wf : wf\text{-prog } G$
shows
 $G \vdash resTy\ new \preceq resTy\ old \wedge$
 $accmodi\ old \leq accmodi\ new \wedge$
 $\neg is\text{-static } old$
 $\langle proof \rangle$

lemma *static-to-dynamic-overriding*:
assumes *stat-override*: $G \vdash new\ overrides_S\ old$ **and** $wf : wf\text{-prog } G$
shows $G \vdash new\ overrides\ old$

$\langle proof \rangle$

lemma *non-Package-instance-method-inheritance:*

assumes *old-inheritable*: $G \vdash \text{Method } old \text{ inheritable-in } (pid \ C)$ **and**
accmodi-old: $accmodi \ old \neq \text{Package}$ **and**
instance-method: $\neg \text{is-static } old$ **and**
subcls: $G \vdash C \prec_C \text{declclass } old$ **and**
old-declared: $G \vdash \text{Method } old \text{ declared-in } (\text{declclass } old)$ **and**
wf: $wf\text{-prog } G$

shows $G \vdash \text{Method } old \text{ member-of } C \vee$

$(\exists \text{ new. } G \vdash \text{new overrides}_S \ old \wedge G \vdash \text{Method } new \text{ member-of } C)$

$\langle proof \rangle$

lemma *non-Package-instance-method-inheritance-cases:*

assumes *old-inheritable*: $G \vdash \text{Method } old \text{ inheritable-in } (pid \ C)$ **and**
accmodi-old: $accmodi \ old \neq \text{Package}$ **and**
instance-method: $\neg \text{is-static } old$ **and**
subcls: $G \vdash C \prec_C \text{declclass } old$ **and**
old-declared: $G \vdash \text{Method } old \text{ declared-in } (\text{declclass } old)$ **and**
wf: $wf\text{-prog } G$

obtains (*Inheritance*) $G \vdash \text{Method } old \text{ member-of } C$

| (*Overriding*) *new* **where** $G \vdash \text{new overrides}_S \ old$ **and** $G \vdash \text{Method } new \text{ member-of } C$

$\langle proof \rangle$

lemma *dynamic-to-static-overriding:*

assumes *dyn-override*: $G \vdash \text{new overrides } old$ **and**
accmodi-old: $accmodi \ old \neq \text{Package}$ **and**
wf: $wf\text{-prog } G$

shows $G \vdash \text{new overrides}_S \ old$

$\langle proof \rangle$

lemma *wf-prog-dyn-override-prop:*

assumes *dyn-override*: $G \vdash \text{new overrides } old$ **and**
wf: $wf\text{-prog } G$

shows $accmodi \ old \leq accmodi \ new$

$\langle proof \rangle$

lemma *overrides-Package-old:*

assumes *dyn-override*: $G \vdash \text{new overrides } old$ **and**
accmodi-new: $accmodi \ new = \text{Package}$ **and**
wf: $wf\text{-prog } G$

shows $accmodi \ old = \text{Package}$

$\langle proof \rangle$

lemma *dyn-override-Package:*

assumes *dyn-override*: $G \vdash \text{new overrides } old$ **and**
accmodi-old: $accmodi \ old = \text{Package}$ **and**
accmodi-new: $accmodi \ new = \text{Package}$ **and**
wf: $wf\text{-prog } G$

shows $pid \ (\text{declclass } old) = pid \ (\text{declclass } new)$

$\langle proof \rangle$

lemma *dyn-override-Package-escape*:

assumes *dyn-override*: $G \vdash \text{new overrides old}$ **and**
accomodi-old: $\text{accomodi old} = \text{Package}$ **and**
outside-pack: $\text{pid}(\text{declclass old}) \neq \text{pid}(\text{declclass new})$ **and**
wf: *wf-prog* G

shows $\exists \text{inter}. G \vdash \text{new overrides inter} \wedge G \vdash \text{inter overrides old} \wedge$
 $\text{pid}(\text{declclass old}) = \text{pid}(\text{declclass inter}) \wedge$
 $\text{Protected} \leq \text{accomodi inter}$

<proof>

lemmas *class-rec-induct'* = *class-rec.induct* [of $\%x y z w. P x y$] **for** P

lemma *declclass-widen*[*rule-format*]:

wf-prog G
 $\longrightarrow (\forall c m. \text{class } G C = \text{Some } c \longrightarrow \text{methd } G C \text{ sig} = \text{Some } m$
 $\longrightarrow G \vdash C \preceq_C \text{declclass } m) \text{ (is ?P } G C)$

<proof>

lemma *declclass-methd-Object*:

$\llbracket \text{wf-prog } G; \text{methd } G \text{ Object sig} = \text{Some } m \rrbracket \Longrightarrow \text{declclass } m = \text{Object}$

<proof>

lemma *methd-declaredD*:

$\llbracket \text{wf-prog } G; \text{is-class } G C; \text{methd } G C \text{ sig} = \text{Some } m \rrbracket$
 $\Longrightarrow G \vdash (\text{mdecl}(\text{sig}, \text{methd } m)) \text{ declared-in}(\text{declclass } m)$

<proof>

lemma *methd-rec-Some-cases*:

assumes *methd-C*: $\text{methd } G C \text{ sig} = \text{Some } m$ **and**
ws: *ws-prog* G **and**
clsC: $\text{class } G C = \text{Some } c$ **and**
neq-C-Obj: $C \neq \text{Object}$

obtains (*NewMethod*) *table-of* ($\text{map}(\lambda(s, m). (s, C, m))(\text{methods } c)$) $\text{sig} = \text{Some } m$
 $| (\text{InheritedMethod}) G \vdash C \text{ inherits}(\text{method } \text{sig } m)$ **and** $\text{methd } G(\text{super } c) \text{ sig} = \text{Some } m$

<proof>

lemma *methd-member-of*:

assumes *wf*: *wf-prog* G

shows

$\llbracket \text{is-class } G C; \text{methd } G C \text{ sig} = \text{Some } m \rrbracket \Longrightarrow G \vdash \text{Methd sig } m \text{ member-of } C$
 $(\text{is } ?\text{Class } C \Longrightarrow ?\text{Method } C \Longrightarrow ?\text{MemberOf } C)$

<proof>

lemma *current-methd*:

$\llbracket \text{table-of}(\text{methods } c) \text{ sig} = \text{Some } \text{new};$
 $\text{ws-prog } G; \text{class } G C = \text{Some } c; C \neq \text{Object};$
 $\text{methd } G(\text{super } c) \text{ sig} = \text{Some } \text{old} \rrbracket$
 $\Longrightarrow \text{methd } G C \text{ sig} = \text{Some}(C, \text{new})$

<proof>

lemma *wf-prog-staticD*:

assumes $wf: wf\text{-prog } G$ **and**
 $clsC: class\ G\ C = Some\ c$ **and**
 $neq\text{-}C\text{-}Obj: C \neq Object$ **and**
 $old: methd\ G\ (super\ c)\ sig = Some\ old$ **and**
 $accommodi\text{-}old: Protected \leq accmodi\ old$ **and**
 $new: table\text{-}of\ (methods\ c)\ sig = Some\ new$
shows $is\text{-}static\ new = is\text{-}static\ old$
 $\langle proof \rangle$

lemma *inheritable-instance-methd*:
assumes $subclseq\text{-}C\text{-}D: G \vdash C \preceq_C D$ **and**
 $is\text{-}cls\text{-}D: is\text{-}class\ G\ D$ **and**
 $wf: wf\text{-prog } G$ **and**
 $old: methd\ G\ D\ sig = Some\ old$ **and**
 $accommodi\text{-}old: Protected \leq accmodi\ old$ **and**
 $not\text{-}static\text{-}old: \neg is\text{-}static\ old$
shows
 $\exists new. methd\ G\ C\ sig = Some\ new \wedge$
 $(new = old \vee G, sig \vdash new\ overrides_S\ old)$
(is $(\exists new. (?Constraint\ C\ new\ old)))$
 $\langle proof \rangle$

lemma *inheritable-instance-methd-cases*:
assumes $subclseq\text{-}C\text{-}D: G \vdash C \preceq_C D$ **and**
 $is\text{-}cls\text{-}D: is\text{-}class\ G\ D$ **and**
 $wf: wf\text{-prog } G$ **and**
 $old: methd\ G\ D\ sig = Some\ old$ **and**
 $accommodi\text{-}old: Protected \leq accmodi\ old$ **and**
 $not\text{-}static\text{-}old: \neg is\text{-}static\ old$
obtains $(Inheritance)\ methd\ G\ C\ sig = Some\ old$
 $| (Overriding)\ new$ **where** $methd\ G\ C\ sig = Some\ new$ **and** $G, sig \vdash new\ overrides_S\ old$
 $\langle proof \rangle$

lemma *inheritable-instance-methd-props*:
assumes $subclseq\text{-}C\text{-}D: G \vdash C \preceq_C D$ **and**
 $is\text{-}cls\text{-}D: is\text{-}class\ G\ D$ **and**
 $wf: wf\text{-prog } G$ **and**
 $old: methd\ G\ D\ sig = Some\ old$ **and**
 $accommodi\text{-}old: Protected \leq accmodi\ old$ **and**
 $not\text{-}static\text{-}old: \neg is\text{-}static\ old$
shows
 $\exists new. methd\ G\ C\ sig = Some\ new \wedge$
 $\neg is\text{-}static\ new \wedge G \vdash resTy\ new \preceq_{resTy}\ old \wedge accmodi\ old \leq accmodi\ new$
(is $(\exists new. (?Constraint\ C\ new\ old)))$
 $\langle proof \rangle$

lemma $beXI'$: $x \in A \implies P\ x \implies \exists x \in A. P\ x$ $\langle proof \rangle$

lemma $ballE'$: $\forall x \in A. P\ x \implies (x \notin A \implies Q) \implies (P\ x \implies Q) \implies Q$ $\langle proof \rangle$

lemma *subint-widen-imethds*:
assumes $irel: G \vdash I \preceq I\ J$
and $wf: wf\text{-prog } G$

and *is-iface*: *is-iface* G J
and *jm*: $jm \in \text{imethds } G$ J *sig*
shows $\exists im \in \text{imethds } G$ I *sig*. *is-static* $im = \text{is-static } jm \wedge$
 $\text{accmodi } im = \text{accmodi } jm \wedge$
 $G \vdash \text{resTy } im \preceq \text{resTy } jm$
 ⟨*proof*⟩

lemma *implmt1-methd*:
 $\wedge \text{sig. } \llbracket G \vdash C \rightsquigarrow I; \text{wf-prog } G; im \in \text{imethds } G$ I *sig* $\rrbracket \implies$
 $\exists cm \in \text{methd } G$ C *sig*: $\neg \text{is-static } cm \wedge \neg \text{is-static } im \wedge$
 $G \vdash \text{resTy } cm \preceq \text{resTy } im \wedge$
 $\text{accmodi } im = \text{Public} \wedge \text{accmodi } cm = \text{Public}$
 ⟨*proof*⟩

lemma *implmt-methd* [*rule-format* (*no-asm*)]:
 $\llbracket \text{wf-prog } G; G \vdash C \rightsquigarrow I \rrbracket \implies \text{is-iface } G$ $I \longrightarrow$
 $(\forall im \in \text{imethds } G$ I *sig*.
 $\exists cm \in \text{methd } G$ C *sig*: $\neg \text{is-static } cm \wedge \neg \text{is-static } im \wedge$
 $G \vdash \text{resTy } cm \preceq \text{resTy } im \wedge$
 $\text{accmodi } im = \text{Public} \wedge \text{accmodi } cm = \text{Public})$
 ⟨*proof*⟩

lemma *mheadsD* [*rule-format* (*no-asm*)]:
 $emh \in \text{mheads } G$ S t *sig* $\longrightarrow \text{wf-prog } G \longrightarrow$
 $(\exists C$ D m . $t = \text{ClassT } C \wedge \text{declrefT } emh = \text{ClassT } D \wedge$
 $\text{accmethd } G$ S C *sig* $= \text{Some } m \wedge$
 $(\text{declclass } m = D) \wedge \text{mhead } (\text{mthd } m) = (\text{mhd } emh)) \vee$
 $(\exists I$. $t = \text{IfaceT } I \wedge ((\exists im$. $im \in \text{accimethds } G$ $(\text{pid } S)$ I *sig* \wedge
 $\text{mthd } im = \text{mhd } emh) \vee$
 $(\exists m$. $G \vdash \text{Iface } I$ *accessible-in* $(\text{pid } S) \wedge \text{accmethd } G$ S *Object sig* $= \text{Some } m \wedge$
 $\text{accmodi } m \neq \text{Private} \wedge$
 $\text{declrefT } emh = \text{ClassT } \text{Object} \wedge \text{mhead } (\text{mthd } m) = \text{mhd } emh))) \vee$
 $(\exists T$ m . $t = \text{ArrayT } T \wedge G \vdash \text{Array } T$ *accessible-in* $(\text{pid } S) \wedge$
 $\text{accmethd } G$ S *Object sig* $= \text{Some } m \wedge \text{accmodi } m \neq \text{Private} \wedge$
 $\text{declrefT } emh = \text{ClassT } \text{Object} \wedge \text{mhead } (\text{mthd } m) = \text{mhd } emh)$
 ⟨*proof*⟩

lemma *mheads-cases*:
assumes $emh \in \text{mheads } G$ S t *sig* **and** *wf-prog* G
obtains (*Class-methd*) C D m **where**
 $t = \text{ClassT } C$ $\text{declrefT } emh = \text{ClassT } D$ $\text{accmethd } G$ S C *sig* $= \text{Some } m$
 $\text{declclass } m = D$ $\text{mhead } (\text{mthd } m) = \text{mhd } emh$
 | (*Iface-methd*) I im **where** $t = \text{IfaceT } I$
 $im \in \text{accimethds } G$ $(\text{pid } S)$ I *sig* $\text{mthd } im = \text{mhd } emh$
 | (*Iface-Object-methd*) I m **where**
 $t = \text{IfaceT } I$ $G \vdash \text{Iface } I$ *accessible-in* $(\text{pid } S)$
 $\text{accmethd } G$ S *Object sig* $= \text{Some } m$ $\text{accmodi } m \neq \text{Private}$
 $\text{declrefT } emh = \text{ClassT } \text{Object}$ $\text{mhead } (\text{mthd } m) = \text{mhd } emh$

| (*Array-Object-method*) $T\ m$ **where**
 $t = \text{Array}T\ T\ G \vdash \text{Array}\ T\ \text{accessible-in}\ (pid\ S)$
 $\text{accmethd}\ G\ S\ \text{Object}\ sig = \text{Some}\ m\ \text{accmodi}\ m \neq \text{Private}$
 $\text{declref}T\ emh = \text{Class}T\ \text{Object}\ mhead\ (mthd\ m) = mhd\ emh$
 ⟨proof⟩

lemma *declclassD*[*rule-format*]:
 $\llbracket wf\text{-prog}\ G; \text{class}\ G\ C = \text{Some}\ c; \text{methd}\ G\ C\ sig = \text{Some}\ m;$
 $\text{class}\ G\ (\text{declclass}\ m) = \text{Some}\ d \rrbracket$
 $\implies \text{table-of}\ (\text{methods}\ d)\ sig = \text{Some}\ (mthd\ m)$
 ⟨proof⟩

lemma *dynmethd-Object*:
assumes $\text{stat}M: \text{methd}\ G\ \text{Object}\ sig = \text{Some}\ \text{stat}M$ **and**
 $\text{private}: \text{accmodi}\ \text{stat}M = \text{Private}$ **and**
 $\text{is-cls-}C: \text{is-class}\ G\ C$ **and**
 $wf: wf\text{-prog}\ G$
shows $\text{dynmethd}\ G\ \text{Object}\ C\ sig = \text{Some}\ \text{stat}M$
 ⟨proof⟩

lemma *wf-imethds-hiding-objmethdsD*:
assumes $\text{old}: \text{methd}\ G\ \text{Object}\ sig = \text{Some}\ \text{old}$ **and**
 $\text{is-if-}I: \text{is-iface}\ G\ I$ **and**
 $wf: wf\text{-prog}\ G$ **and**
 $\text{not-private}: \text{accmodi}\ \text{old} \neq \text{Private}$ **and**
 $\text{new}: \text{new} \in \text{imethds}\ G\ I\ sig$
shows $G \vdash \text{resTy}\ \text{new} \preceq \text{resTy}\ \text{old} \wedge \text{is-static}\ \text{new} = \text{is-static}\ \text{old}$ (**is** ? P new)
 ⟨proof⟩

Which dynamic classes are valid to look up a member of a distinct static type? We have to distinct class members (named static members in Java) from instance members. Class members are global to all Objects of a class, instance members are local to a single Object instance. If a member is equipped with the static modifier it is a class member, else it is an instance member. The following table gives an overview of the current framework. We assume to have a reference with static type $\text{stat}T$ and a dynamic class $\text{dyn}C$. Between both of these types the widening relation holds $G \vdash \text{Class}\ \text{dyn}C \preceq \text{stat}T$. Unfortunately this ordinary widening relation isn't enough to describe the valid lookup classes, since we must cope the special cases of arrays and interfaces, too. If we statically expect an array or interface we may lookup a field or a method in Object which isn't covered in the widening relation.

statT	field	instance	method	static	(class)	method
NullT	/	/	/	Iface	/	dynC
Object	Class	dynC	dynC	dynC	dynC	Array
Object	Object					Object

In most cases we can lookup the member in the dynamic class. But as an interface can't declare new static methods, nor an array can define new methods at all, we have to lookup methods in the base class Object.

The limitation to classes in the field column is artificial and comes out of the typing rule for the field access (see rule *FVar* in the welltyping relation *wt* in theory WellType). It stems out of the fact, that Object indeed has no non private fields. So interfaces and arrays can actually have no fields at all and a field access would be senseless. (In Java interfaces are allowed to declare new fields but in current Bali not!). So there is no principal reason why we should not allow Objects to declare non private fields. Then we would get the following column:

statT	field	NullT	/	Iface	Object	Class	dynC	Array	Object

primrec *valid-lookup-cls*:: $\text{prog} \Rightarrow \text{ref-ty} \Rightarrow \text{qname} \Rightarrow \text{bool} \Rightarrow \text{bool}$

(-, - ⊢ - *valid'-lookup'-cls'-for* - [61,61,61,61] 60)

where

$G, \text{Null}T \vdash \text{dyn}C \text{ valid-lookup-cls-for static-membr} = \text{False}$
 $| G, \text{Iface}T I \vdash \text{dyn}C \text{ valid-lookup-cls-for static-membr}$
 $\quad = (\text{if } \text{static-membr}$
 $\quad \quad \text{then } \text{dyn}C = \text{Object}$
 $\quad \quad \text{else } G \vdash \text{Class } \text{dyn}C \preceq \text{Iface } I)$
 $| G, \text{Class}T C \vdash \text{dyn}C \text{ valid-lookup-cls-for static-membr} = G \vdash \text{Class } \text{dyn}C \preceq \text{Class } C$
 $| G, \text{Array}T T \vdash \text{dyn}C \text{ valid-lookup-cls-for static-membr} = (\text{dyn}C = \text{Object})$

lemma *valid-lookup-cls-is-class*:

assumes $\text{dyn}C: G, \text{stat}T \vdash \text{dyn}C \text{ valid-lookup-cls-for static-membr}$ **and**
 $\text{ty-stat}T: \text{isrtype } G \text{ stat}T$ **and**
 $\text{wf}: \text{wf-prog } G$

shows $\text{is-class } G \text{ dyn}C$

$\langle \text{proof} \rangle$

declare *split-paired-All* [simp del] *split-paired-Ex* [simp del]

$\langle \text{ML} \rangle$

lemma *dynamic-mheadsD*:

$\llbracket \text{emh} \in \text{mheads } G \text{ S stat}T \text{ sig};$

$G, \text{stat}T \vdash \text{dyn}C \text{ valid-lookup-cls-for } (\text{is-static } \text{emh});$

$\text{isrtype } G \text{ stat}T; \text{wf-prog } G$

$\rrbracket \implies \exists m \in \text{dynlookup } G \text{ stat}T \text{ dyn}C \text{ sig}:$

$\text{is-static } m = \text{is-static } \text{emh} \wedge G \vdash \text{resTy } m \preceq \text{resTy } \text{emh}$

$\langle \text{proof} \rangle$

declare *split-paired-All* [simp] *split-paired-Ex* [simp]

$\langle \text{ML} \rangle$

lemma *methd-declclass*:

$\llbracket \text{class } G \text{ C} = \text{Some } c; \text{wf-prog } G; \text{methd } G \text{ C sig} = \text{Some } m \rrbracket$

$\implies \text{methd } G (\text{declclass } m) \text{ sig} = \text{Some } m$

$\langle \text{proof} \rangle$

lemma *dynmethd-declclass*:

$\llbracket \text{dynmethd } G \text{ stat}C \text{ dyn}C \text{ sig} = \text{Some } m;$

$\text{wf-prog } G; \text{is-class } G \text{ stat}C$

$\rrbracket \implies \text{methd } G (\text{declclass } m) \text{ sig} = \text{Some } m$

$\langle \text{proof} \rangle$

lemma *dynlookup-declC*:

$\llbracket \text{dynlookup } G \text{ stat}T \text{ dyn}C \text{ sig} = \text{Some } m; \text{wf-prog } G;$

$\text{is-class } G \text{ dyn}C; \text{isrtype } G \text{ stat}T$

$\rrbracket \implies G \vdash \text{dyn}C \preceq_C (\text{declclass } m) \wedge \text{is-class } G (\text{declclass } m)$

$\langle \text{proof} \rangle$

lemma *dynlookup-Array-declclassD* [simp]:

$\llbracket \text{dynlookup } G (\text{Array}T T) \text{ Object sig} = \text{Some } dm; \text{wf-prog } G \rrbracket$

$\implies \text{declclass } dm = \text{Object}$
 ⟨proof⟩

declare *split-paired-All* [simp del] *split-paired-Ex* [simp del]
 ⟨ML⟩

lemma *wt-is-type*: $E, dt \models v :: T \implies \text{wf-prog } (\text{prg } E) \longrightarrow$
 $dt = \text{empty-dt} \longrightarrow (\text{case } T \text{ of}$
 $\quad \text{Inl } T \Rightarrow \text{is-type } (\text{prg } E) T$
 $\quad | \text{Inr } Ts \Rightarrow \text{Ball } (\text{set } Ts) (\text{is-type } (\text{prg } E)))$

⟨proof⟩

declare *split-paired-All* [simp] *split-paired-Ex* [simp]
 ⟨ML⟩

lemma *ty-expr-is-type*:
 $\llbracket E \vdash e :: - T; \text{wf-prog } (\text{prg } E) \rrbracket \implies \text{is-type } (\text{prg } E) T$
 ⟨proof⟩

lemma *ty-var-is-type*:
 $\llbracket E \vdash v :: T; \text{wf-prog } (\text{prg } E) \rrbracket \implies \text{is-type } (\text{prg } E) T$
 ⟨proof⟩

lemma *ty-exprs-is-type*:
 $\llbracket E \vdash es :: Ts; \text{wf-prog } (\text{prg } E) \rrbracket \implies \text{Ball } (\text{set } Ts) (\text{is-type } (\text{prg } E))$
 ⟨proof⟩

lemma *static-mheadsD*:
 $\llbracket emh \in \text{mheads } G S t \text{ sig}; \text{wf-prog } G; E \vdash e :: - \text{RefT } t; \text{prg } E = G ;$
 $\quad \text{invmode } (\text{mhd } emh) e \neq \text{IntVir}$
 $\rrbracket \implies \exists m. ((\exists C. t = \text{ClassT } C \wedge \text{accmethd } G S C \text{ sig} = \text{Some } m)$
 $\quad \vee (\forall C. t \neq \text{ClassT } C \wedge \text{accmethd } G S \text{ Object } \text{ sig} = \text{Some } m)) \wedge$
 $\quad \text{declrefT } emh = \text{ClassT } (\text{declclass } m) \wedge \text{mhead } (\text{mthd } m) = (\text{mhd } emh)$
 ⟨proof⟩

lemma *wt-MethdI*:
 $\llbracket \text{methd } G C \text{ sig} = \text{Some } m; \text{wf-prog } G;$
 $\quad \text{class } G C = \text{Some } c \rrbracket \implies$
 $\exists T. (\llbracket \text{prg} = G, \text{cls} = (\text{declclass } m),$
 $\quad \text{lcl} = \text{callee-lcl } (\text{declclass } m) \text{ sig } (\text{mthd } m) \rrbracket \vdash \text{Methd } C \text{ sig} :: - T \wedge G \vdash T \preceq_{\text{resTy}} m$
 ⟨proof⟩

35 accessibility concerns

lemma *mheads-type-accessible*:
 $\llbracket emh \in \text{mheads } G S T \text{ sig}; \text{wf-prog } G \rrbracket$
 $\implies G \vdash \text{RefT } T \text{ accessible-in } (\text{pid } S)$
 ⟨proof⟩

lemma *static-to-dynamic-accessible-from-aux*:
 $\llbracket G \vdash m \text{ of } C \text{ accessible-from } \text{accC}; \text{wf-prog } G \rrbracket$
 $\implies G \vdash m \text{ in } C \text{ dyn-accessible-from } \text{accC}$
 ⟨proof⟩

lemma *static-to-dynamic-accessible-from*:

assumes *stat-acc*: $G \vdash m$ of *statC* *accessible-from* *accC* **and**
subclseq: $G \vdash \text{dyn}C \preceq_C \text{stat}C$ **and**
wf: *wf-prog* *G*

shows $G \vdash m$ in *dynC* *dyn-accessible-from* *accC*

<proof>

lemma *static-to-dynamic-accessible-from-static*:

assumes *stat-acc*: $G \vdash m$ of *statC* *accessible-from* *accC* **and**
static: *is-static* *m* **and**
wf: *wf-prog* *G*

shows $G \vdash m$ in (*declclass* *m*) *dyn-accessible-from* *accC*

<proof>

lemma *dynmethd-member-in*:

assumes *m*: *dynmethd* *G* *statC* *dynC* *sig* = *Some m* **and**
iscls-statC: *is-class* *G* *statC* **and**
wf: *wf-prog* *G*

shows $G \vdash \text{Methd } \text{sig } m$ *member-in* *dynC*

<proof>

lemma *dynmethd-access-prop*:

assumes *statM*: *methd* *G* *statC* *sig* = *Some statM* **and**
stat-acc: $G \vdash \text{Methd } \text{sig } \text{stat}M$ of *statC* *accessible-from* *accC* **and**
dynM: *dynmethd* *G* *statC* *dynC* *sig* = *Some dynM* **and**
wf: *wf-prog* *G*

shows $G \vdash \text{Methd } \text{sig } \text{dyn}M$ in *dynC* *dyn-accessible-from* *accC*

<proof>

lemma *implmt-methd-access*:

fixes *accC*::*qname*
assumes *iface-methd*: *imethds* *G* *I* *sig* $\neq \{\}$ **and**
implements: $G \vdash \text{dyn}C \rightsquigarrow I$ **and**
isif-I: *is-iface* *G* *I* **and**
wf: *wf-prog* *G*

shows $\exists \text{dyn}M. \text{methd } G \text{ dyn}C \text{ sig} = \text{Some } \text{dyn}M \wedge$
 $G \vdash \text{Methd } \text{sig } \text{dyn}M$ in *dynC* *dyn-accessible-from* *accC*

<proof>

corollary *implmt-dynimethd-access*:

fixes *accC*::*qname*
assumes *iface-methd*: *imethds* *G* *I* *sig* $\neq \{\}$ **and**
implements: $G \vdash \text{dyn}C \rightsquigarrow I$ **and**
isif-I: *is-iface* *G* *I* **and**
wf: *wf-prog* *G*

shows $\exists \text{dyn}M. \text{dynimethd } G \text{ I } \text{dyn}C \text{ sig} = \text{Some } \text{dyn}M \wedge$
 $G \vdash \text{Methd } \text{sig } \text{dyn}M$ in *dynC* *dyn-accessible-from* *accC*

<proof>

lemma *dynlookup-access-prop*:

assumes *emh*: *emh* \in *mheads* *G* *accC* *statT* *sig* **and**
dynM: *dynlookup* *G* *statT* *dynC* *sig* = *Some dynM* **and**

$\text{dynC-prop: } G, \text{statT} \vdash \text{dynC valid-lookup-cls-for is-static emh}$ **and**
 $\text{isT-statT: isrtype } G \text{ statT}$ **and**
 $\text{wf: wf-prog } G$
shows $G \vdash \text{Methd sig dynM in dynC dyn-accessible-from accC}$
 ⟨proof⟩

lemma *dynlookup-access:*

assumes $\text{emh: emh} \in \text{mheads } G \text{ accC statT sig}$ **and**
 $\text{dynC-prop: } G, \text{statT} \vdash \text{dynC valid-lookup-cls-for (is-static emh)}$ **and**
 $\text{isT-statT: isrtype } G \text{ statT}$ **and**
 $\text{wf: wf-prog } G$
shows $\exists \text{ dynM. dynlookup } G \text{ statT dynC sig} = \text{Some dynM} \wedge$
 $G \vdash \text{Methd sig dynM in dynC dyn-accessible-from accC}$
 ⟨proof⟩

lemma *stat-overrides-Package-old:*

assumes $\text{stat-override: } G \vdash \text{new overrides}_S \text{ old}$ **and**
 $\text{accmodi-new: accmodi new} = \text{Package}$ **and**
 $\text{wf: wf-prog } G$
shows $\text{accmodi old} = \text{Package}$
 ⟨proof⟩

Properties of dynamic accessibility

lemma *dyn-accessible-Private:*

assumes $\text{dyn-acc: } G \vdash m \text{ in } C \text{ dyn-accessible-from accC}$ **and**
 $\text{priv: accmodi } m = \text{Private}$
shows $\text{accC} = \text{declclass } m$
 ⟨proof⟩

dyn-accessible-Package only works with the *wf-prog* assumption. Without it, it is easy to leaf the Package!

lemma *dyn-accessible-Package:*

$\llbracket G \vdash m \text{ in } C \text{ dyn-accessible-from accC; accmodi } m = \text{Package};$
 $\text{wf-prog } G \rrbracket$
 $\implies \text{pid accC} = \text{pid (declclass } m)$
 ⟨proof⟩

For fields we don't need the wellformedness of the program, since there is no overriding

lemma *dyn-accessible-field-Package:*

assumes $\text{dyn-acc: } G \vdash f \text{ in } C \text{ dyn-accessible-from accC}$ **and**
 $\text{pack: accmodi } f = \text{Package}$ **and**
 $\text{field: is-field } f$
shows $\text{pid accC} = \text{pid (declclass } f)$
 ⟨proof⟩

dyn-accessible-instance-field-Protected only works for fields since methods can break the package bounds due to overriding

lemma *dyn-accessible-instance-field-Protected:*

assumes $\text{dyn-acc: } G \vdash f \text{ in } C \text{ dyn-accessible-from accC}$ **and**
 $\text{prot: accmodi } f = \text{Protected}$ **and**
 $\text{field: is-field } f$ **and**
 $\text{instance-field: } \neg \text{is-static } f$ **and**
 $\text{outside: pid (declclass } f) \neq \text{pid accC}$
shows $G \vdash C \preceq_C \text{accC}$
 ⟨proof⟩

lemma *dyn-accessible-static-field-Protected*:
assumes *dyn-acc*: $G \vdash f$ in C *dyn-accessible-from* *accC* **and**
prot: *accmodi* $f = Protected$ **and**
field: *is-field* f **and**
static-field: *is-static* f **and**
outside: *pid* (*declclass* f) \neq *pid* *accC*
shows $G \vdash accC \preceq_C declclass f \wedge G \vdash C \preceq_C declclass f$
<proof>

end

Chapter 14

State

36 State for evaluation of Java expressions and statements

theory *State*
imports *DeclConcepts*
begin

design issues:

- all kinds of objects (class instances, arrays, and class objects) are handled via a general object abstraction
- the heap and the map for class objects are combined into a single table (*recall* (*loc*, *obj*) *table* \times (*qname*, *obj*) *table* $\sim =$ (*loc* + *qname*, *obj*) *table*)

objects

datatype *obj-tag* = — tag for generic object
 CInst qname — class instance
 | *Arr ty int* — array with component type and length
 — CStat *qname* the tag is irrelevant for a class object, i.e. the static fields of a class, since its type is given already by the reference to it (see below)

type-synonym *vn* = *fspec* + *int* — variable name

record *obj* = — generalized object
 tag :: *obj-tag*
 values :: (*vn*, *val*) *table*

translations

(*type*) *fspec* <= (*type*) *vname* \times *qname*
 (*type*) *vn* <= (*type*) *fspec* + *int*
 (*type*) *obj* <= (*type*) (\downarrow *tag*::*obj-tag*, *values*::*vn* \Rightarrow *val option*)
 (*type*) *obj* <= (*type*) (\downarrow *tag*::*obj-tag*, *values*::*vn* \Rightarrow *val option*,...::'*a*)

definition

the-Arr :: *obj option* \Rightarrow *ty* \times *int* \times (*vn*, *val*) *table*
where *the-Arr obj* = (*SOME* (*T,k,t*). *obj* = *Some* (\downarrow *tag=Arr T k,values=t))*

lemma *the-Arr-Arr [simp]*: *the-Arr* (*Some* (\downarrow *tag=Arr T k,values=cs)) = (*T,k,cs*)
 <proof>*

lemma *the-Arr-Arr1 [simp,intro,dest]*:

\llbracket *tag obj* = *Arr T k $\rrbracket \Longrightarrow$ *the-Arr* (*Some obj*) = (*T,k,values obj*)
 <proof>*

definition

upd-obj :: *vn* \Rightarrow *val* \Rightarrow *obj* \Rightarrow *obj*
where *upd-obj n v* = (λ *obj. obj* (\downarrow *values:=*(*values obj*)(*n* \mapsto *v)))*

lemma *upd-obj-def2 [simp]*:

upd-obj n v obj = *obj* (\downarrow *values:=*(*values obj*)(*n* \mapsto *v))
 <proof>*

definition

obj-ty :: *obj* \Rightarrow *ty* **where**
obj-ty obj = (*case tag obj of*

$$\begin{array}{l} CInst\ C \Rightarrow Class\ C \\ | Arr\ T\ k \Rightarrow T.[] \end{array}$$

lemma *obj-ty-eq* [intro!]: $obj\text{-}ty\ (\!|tag=oi,values=x\!) = obj\text{-}ty\ (\!|tag=oi,values=y\!)$
 ⟨proof⟩

lemma *obj-ty-eq1* [intro!,dest]:
 $tag\ obj = tag\ obj' \implies obj\text{-}ty\ obj = obj\text{-}ty\ obj'$
 ⟨proof⟩

lemma *obj-ty-cong* [simp]:
 $obj\text{-}ty\ (obj\ (\!|values:=vs\!)) = obj\text{-}ty\ obj$
 ⟨proof⟩

lemma *obj-ty-CInst* [simp]:
 $obj\text{-}ty\ (\!|tag=CInst\ C,values=vs\!) = Class\ C$
 ⟨proof⟩

lemma *obj-ty-CInst1* [simp,intro!,dest]:
 $\llbracket tag\ obj = CInst\ C \rrbracket \implies obj\text{-}ty\ obj = Class\ C$
 ⟨proof⟩

lemma *obj-ty-Arr* [simp]:
 $obj\text{-}ty\ (\!|tag=Arr\ T\ i,values=vs\!) = T.[]$
 ⟨proof⟩

lemma *obj-ty-Arr1* [simp,intro!,dest]:
 $\llbracket tag\ obj = Arr\ T\ i \rrbracket \implies obj\text{-}ty\ obj = T.[]$
 ⟨proof⟩

lemma *obj-ty-widenD*:
 $G \vdash obj\text{-}ty\ obj \preceq_{RefT}\ t \implies (\exists C. tag\ obj = CInst\ C) \vee (\exists T\ k. tag\ obj = Arr\ T\ k)$
 ⟨proof⟩

definition

obj-class :: $obj \Rightarrow qname$ **where**
 $obj\text{-}class\ obj = (case\ tag\ obj\ of$
 $\quad CInst\ C \Rightarrow C$
 $\quad | Arr\ T\ k \Rightarrow Object)$

lemma *obj-class-CInst* [simp]: $obj\text{-}class\ (\!|tag=CInst\ C,values=vs\!) = C$
 ⟨proof⟩

lemma *obj-class-CInst1* [simp,intro!,dest]:
 $tag\ obj = CInst\ C \implies obj\text{-}class\ obj = C$
 ⟨proof⟩

lemma *obj-class-Arr* [simp]: *obj-class* (*tag=Arr T k, values=vs*) = *Object*
 ⟨*proof*⟩

lemma *obj-class-Arr1* [simp,intro!,dest]:
tag obj = Arr T k \implies *obj-class obj = Object*
 ⟨*proof*⟩

lemma *obj-ty-obj-class*: $G \vdash \text{obj-ty } obj \preceq \text{Class } statC = G \vdash \text{obj-class } obj \preceq_C \text{statC}$
 ⟨*proof*⟩

object references

type-synonym *oref* = *loc* + *qname* — generalized object reference

syntax

Heap :: *loc* \Rightarrow *oref*
Stat :: *qname* \Rightarrow *oref*

translations

Heap \Rightarrow *CONST Inl*
Stat \Rightarrow *CONST Inr*
 (*type*) *oref* \leq (*type*) *loc* + *qname*

definition

fields-table :: *prog* \Rightarrow *qname* \Rightarrow (*fspec* \Rightarrow *field* \Rightarrow *bool*) \Rightarrow (*fspec, ty*) *table* **where**
fields-table *G C P* =
Option.map type \circ *table-of* (*filter* (*split P*) (*DeclConcepts.fields G C*))

lemma *fields-table-SomeI*:
 $\llbracket \text{table-of } (DeclConcepts.fields G C) n = \text{Some } f; P n f \rrbracket$
 $\implies \text{fields-table } G C P n = \text{Some } (type f)$
 ⟨*proof*⟩

lemma *fields-table-SomeD'*: *fields-table G C P fn = Some T* \implies
 $\exists f. (fn, f) \in \text{set}(DeclConcepts.fields G C) \wedge \text{type } f = T$
 ⟨*proof*⟩

lemma *fields-table-SomeD*:
 $\llbracket \text{fields-table } G C P fn = \text{Some } T; \text{unique } (DeclConcepts.fields G C) \rrbracket \implies$
 $\exists f. \text{table-of } (DeclConcepts.fields G C) fn = \text{Some } f \wedge \text{type } f = T$
 ⟨*proof*⟩

definition

in-bounds :: *int* \Rightarrow *int* \Rightarrow *bool* (*(-/ in'-bounds -)* [50, 51] 50)
where *i in-bounds k* = ($0 \leq i \wedge i < k$)

definition

arr-comps :: '*a*' \Rightarrow *int* \Rightarrow *int* \Rightarrow '*a*' *option*
where *arr-comps T k* = ($\lambda i. \text{if } i \text{ in-bounds } k \text{ then } \text{Some } T \text{ else } \text{None}$)

definition

var-tys :: *prog* \Rightarrow *obj-tag* \Rightarrow *oref* \Rightarrow (*vn, ty*) *table* **where**
var-tys G oi r =

$$\begin{aligned}
& (\text{case } r \text{ of} \\
& \quad \text{Heap } a \Rightarrow (\text{case } oi \text{ of} \\
& \quad \quad \text{CInst } C \Rightarrow \text{fields-table } G \ C \ (\lambda n \ f. \neg \text{static } f) \ (+) \ \text{empty} \\
& \quad \quad | \text{Arr } T \ k \Rightarrow \text{empty } (+) \ \text{arr-comps } T \ k) \\
& \quad | \text{Stat } C \Rightarrow \text{fields-table } G \ C \ (\lambda fn \ f. \text{declclassf } fn = C \wedge \text{static } f) \\
& \quad \quad (+) \ \text{empty})
\end{aligned}$$

lemma *var-tys-Some-eq*:

$$\begin{aligned}
& \text{var-tys } G \ oi \ r \ n = \text{Some } T \\
& = (\text{case } r \text{ of} \\
& \quad \text{Inl } a \Rightarrow (\text{case } oi \text{ of} \\
& \quad \quad \text{CInst } C \Rightarrow (\exists nt. n = \text{Inl } nt \wedge \text{fields-table } G \ C \ (\lambda n \ f. \\
& \quad \quad \quad \neg \text{static } f) \ nt = \text{Some } T) \\
& \quad \quad | \text{Arr } t \ k \Rightarrow (\exists i. n = \text{Inr } i \wedge i \text{ in-bounds } k \wedge t = T)) \\
& \quad | \text{Inr } C \Rightarrow (\exists nt. n = \text{Inl } nt \wedge \\
& \quad \quad \text{fields-table } G \ C \ (\lambda fn \ f. \text{declclassf } fn = C \wedge \text{static } f) \ nt \\
& \quad \quad = \text{Some } T))
\end{aligned}$$

<proof>

stores

type-synonym *globals* — global variables: heap and static variables

$$= (\text{oref } , \text{obj}) \ \text{table}$$

type-synonym *heap*

$$= (\text{loc } , \text{obj}) \ \text{table}$$

translations

$$(\text{type}) \ \text{globals} \leq (\text{type}) \ (\text{oref } , \text{obj}) \ \text{table}$$

$$(\text{type}) \ \text{heap} \leq (\text{type}) \ (\text{loc } , \text{obj}) \ \text{table}$$

datatype *st* =

$$\text{st } \text{globals } \ \text{locals}$$

37 access

definition

$$\text{globals} :: \text{st} \Rightarrow \text{globals}$$

where $\text{globals} = \text{st-case } (\lambda g \ l. \ g)$

definition

$$\text{locals} :: \text{st} \Rightarrow \text{locals}$$

where $\text{locals} = \text{st-case } (\lambda g \ l. \ l)$

definition *heap* :: *st* \Rightarrow *heap* **where**

$$\text{heap } s = \text{globals } s \circ \text{Heap}$$

lemma *globals-def2* [*simp*]: $\text{globals } (\text{st } g \ l) = g$

<proof>

lemma *locals-def2* [*simp*]: $\text{locals } (\text{st } g \ l) = l$

<proof>

lemma *heap-def2* [*simp*]: $\text{heap } s \text{ a} = \text{globs } s \text{ (Heap } a)$
 ⟨*proof*⟩

abbreviation *val-this* :: $st \Rightarrow val$
where *val-this* $s == \text{the (locals } s \text{ This)}$

abbreviation *lookup-obj* :: $st \Rightarrow val \Rightarrow obj$
where *lookup-obj* $s \text{ a}' == \text{the (heap } s \text{ (the-Addr } a'))$

38 memory allocation

definition

new-Addr :: $\text{heap} \Rightarrow \text{loc option}$ **where**
new-Addr $h = (\text{if } (\forall a. h \text{ a} \neq \text{None}) \text{ then None else Some (SOME } a. h \text{ a} = \text{None}))$

lemma *new-AddrD*: $\text{new-Addr } h = \text{Some } a \implies h \text{ a} = \text{None}$
 ⟨*proof*⟩

lemma *new-AddrD2*: $\text{new-Addr } h = \text{Some } a \implies \forall b. h \text{ b} \neq \text{None} \longrightarrow b \neq a$
 ⟨*proof*⟩

lemma *new-Addr-SomeI*: $h \text{ a} = \text{None} \implies \exists b. \text{new-Addr } h = \text{Some } b \wedge h \text{ b} = \text{None}$
 ⟨*proof*⟩

39 initialization

abbreviation *init-vals* :: $('a, ty) \text{ table} \Rightarrow ('a, val) \text{ table}$
where *init-vals* $vs == \text{Option.map default-val } \circ vs$

lemma *init-arr-comps-base* [*simp*]: $\text{init-vals (arr-comps } T \ 0) = \text{empty}$
 ⟨*proof*⟩

lemma *init-arr-comps-step* [*simp*]:
 $0 < j \implies \text{init-vals (arr-comps } T \ j) =$
 $\text{init-vals (arr-comps } T \ (j - 1))(j - 1 \mapsto \text{default-val } T)$
 ⟨*proof*⟩

40 update

definition

gupd :: $\text{oref} \Rightarrow \text{obj} \Rightarrow \text{st} \Rightarrow \text{st} \text{ (gupd}'(-\mapsto-)' [10, 10] 1000)$
where *gupd* $r \text{ obj} = \text{st-case } (\lambda g \text{ l. st } (g(r \mapsto \text{obj})) \text{ l})$

definition

lupd :: $\text{lname} \Rightarrow \text{val} \Rightarrow \text{st} \Rightarrow \text{st} \text{ (lupd}'(-\mapsto-)' [10, 10] 1000)$
where *lupd* $vn \text{ v} = \text{st-case } (\lambda g \text{ l. st } g \text{ (l(vn} \mapsto \text{v}))$

definition

upd-gobj :: $\text{oref} \Rightarrow \text{vn} \Rightarrow \text{val} \Rightarrow \text{st} \Rightarrow \text{st}$
where *upd-gobj* $r \text{ n } v = \text{st-case } (\lambda g \text{ l. st } (\text{chg-map (upd-obj } n \text{ v) } r \text{ g) } l)$

definition

set-locals :: $\text{locals} \Rightarrow \text{st} \Rightarrow \text{st}$

where *set-locals* $l = st\text{-case } (\lambda g l'. st\ g\ l)$

definition

init-obj $:: prog \Rightarrow obj\text{-tag} \Rightarrow oref \Rightarrow st \Rightarrow st$

where *init-obj* $G\ oi\ r = gupd(r \mapsto (\!|tag=oi, values=init\text{-vals } (var\text{-tys } G\ oi\ r)\!|))$

abbreviation

init-class-obj $:: prog \Rightarrow qname \Rightarrow st \Rightarrow st$

where *init-class-obj* $G\ C == init\text{-obj } G\ undefined\ (Inr\ C)$

lemma *gupd-def2* [*simp*]: $gupd(r \mapsto obj)\ (st\ g\ l) = st\ (g(r \mapsto obj))\ l$
 ⟨*proof*⟩

lemma *lupd-def2* [*simp*]: $lupd(vn \mapsto v)\ (st\ g\ l) = st\ g\ (l(vn \mapsto v))$
 ⟨*proof*⟩

lemma *globs-gupd* [*simp*]: $globs\ (gupd(r \mapsto obj)\ s) = globs\ s(r \mapsto obj)$
 ⟨*proof*⟩

lemma *globs-lupd* [*simp*]: $globs\ (lupd(vn \mapsto v)\ s) = globs\ s$
 ⟨*proof*⟩

lemma *locals-gupd* [*simp*]: $locals\ (gupd(r \mapsto obj)\ s) = locals\ s$
 ⟨*proof*⟩

lemma *locals-lupd* [*simp*]: $locals\ (lupd(vn \mapsto v)\ s) = locals\ s(vn \mapsto v)$
 ⟨*proof*⟩

lemma *globs-upd-gobj-new* [*rule-format* (*no-asm*), *simp*]:
 $globs\ s\ r = None \longrightarrow globs\ (upd\text{-gobj } r\ n\ v\ s) = globs\ s$
 ⟨*proof*⟩

lemma *globs-upd-gobj-upd* [*rule-format* (*no-asm*), *simp*]:
 $globs\ s\ r = Some\ obj \longrightarrow globs\ (upd\text{-gobj } r\ n\ v\ s) = globs\ s(r \mapsto upd\text{-obj } n\ v\ obj)$
 ⟨*proof*⟩

lemma *locals-upd-gobj* [*simp*]: $locals\ (upd\text{-gobj } r\ n\ v\ s) = locals\ s$
 ⟨*proof*⟩

lemma *globs-init-obj* [*simp*]: $globs\ (init\text{-obj } G\ oi\ r\ s)\ t =$
 (if $t=r$ then $Some\ (\!|tag=oi, values=init\text{-vals } (var\text{-tys } G\ oi\ r)\!|)$ else $globs\ s\ t$)
 ⟨*proof*⟩

lemma *locals-init-obj* [*simp*]: $locals\ (init\text{-obj } G\ oi\ r\ s) = locals\ s$
 ⟨*proof*⟩

lemma *surjective-st* [simp]: $st (globs\ s) (locals\ s) = s$
 ⟨proof⟩

lemma *surjective-st-init-obj*:
 $st (globs (init-obj\ G\ oi\ r\ s)) (locals\ s) = init-obj\ G\ oi\ r\ s$
 ⟨proof⟩

lemma *heap-heap-upd* [simp]:
 $heap (st (g(Inl\ a\mapsto\ obj)))\ l = heap (st\ g\ l)(a\mapsto\ obj)$
 ⟨proof⟩

lemma *heap-stat-upd* [simp]: $heap (st (g(Inr\ C\mapsto\ obj)))\ l = heap (st\ g\ l)$
 ⟨proof⟩

lemma *heap-local-upd* [simp]: $heap (st\ g (l(vn\mapsto\ v))) = heap (st\ g\ l)$
 ⟨proof⟩

lemma *heap-gupd-Heap* [simp]: $heap (gupd(Heap\ a\mapsto\ obj)\ s) = heap\ s(a\mapsto\ obj)$
 ⟨proof⟩

lemma *heap-gupd-Stat* [simp]: $heap (gupd(Stat\ C\mapsto\ obj)\ s) = heap\ s$
 ⟨proof⟩

lemma *heap-lupd* [simp]: $heap (lupd(vn\mapsto\ v)\ s) = heap\ s$
 ⟨proof⟩

lemma *heap-upd-gobj-Stat* [simp]: $heap (upd-gobj (Stat\ C)\ n\ v\ s) = heap\ s$
 ⟨proof⟩

lemma *set-locals-def2* [simp]: $set-locals\ l (st\ g\ l') = st\ g\ l$
 ⟨proof⟩

lemma *set-locals-id* [simp]: $set-locals (locals\ s)\ s = s$
 ⟨proof⟩

lemma *set-set-locals* [simp]: $set-locals\ l (set-locals\ l'\ s) = set-locals\ l\ s$
 ⟨proof⟩

lemma *locals-set-locals* [simp]: $locals (set-locals\ l\ s) = l$
 ⟨proof⟩

lemma *globs-set-locals* [simp]: $globs (set-locals\ l\ s) = globs\ s$
 ⟨proof⟩

lemma *heap-set-locals* [simp]: $heap (set-locals\ l\ s) = heap\ s$
 ⟨proof⟩

abrupt completion

primrec *the-Xcpt* :: *abrupt* \Rightarrow *xcpt*
where *the-Xcpt* (*Xcpt* *x*) = *x*

primrec *the-Jump* :: *abrupt* \Rightarrow *jump*
where *the-Jump* (*Jump* *j*) = *j*

primrec *the-Loc* :: *xcpt* \Rightarrow *loc*
where *the-Loc* (*Loc* *a*) = *a*

primrec *the-Std* :: *xcpt* \Rightarrow *xname*
where *the-Std* (*Std* *x*) = *x*

definition

abrupt-if :: *bool* \Rightarrow *abopt* \Rightarrow *abopt* \Rightarrow *abopt*
where *abrupt-if* *c* *x'* *x* = (*if* *c* \wedge (*x* = *None*) *then* *x'* *else* *x*)

lemma *abrupt-if-True-None* [*simp*]: *abrupt-if* *True* *x* *None* = *x*
 \langle *proof* \rangle

lemma *abrupt-if-True-not-None* [*simp*]: *x* \neq *None* \implies *abrupt-if* *True* *x* *y* \neq *None*
 \langle *proof* \rangle

lemma *abrupt-if-False* [*simp*]: *abrupt-if* *False* *x* *y* = *y*
 \langle *proof* \rangle

lemma *abrupt-if-Some* [*simp*]: *abrupt-if* *c* *x* (*Some* *y*) = *Some* *y*
 \langle *proof* \rangle

lemma *abrupt-if-not-None* [*simp*]: *y* \neq *None* \implies *abrupt-if* *c* *x* *y* = *y*
 \langle *proof* \rangle

lemma *split-abrupt-if*:
P (*abrupt-if* *c* *x'* *x*) =
 ((*c* \wedge *x* = *None* \longrightarrow *P* *x'*) \wedge (\neg (*c* \wedge *x* = *None*) \longrightarrow *P* *x*))
 \langle *proof* \rangle

abbreviation *raise-if* :: *bool* \Rightarrow *xname* \Rightarrow *abopt* \Rightarrow *abopt*
where *raise-if* *c* *xn* == *abrupt-if* *c* (*Some* (*Xcpt* (*Std* *xn*)))

abbreviation *np* :: *val* \Rightarrow *abopt* \Rightarrow *abopt*
where *np* *v* == *raise-if* (*v* = *Null*) *NullPointer*

abbreviation *check-neg* :: *val* \Rightarrow *abopt* \Rightarrow *abopt*
where *check-neg* *i'* == *raise-if* (*the-Intg* *i'* < 0) *NegArrSize*

abbreviation *error-if* :: *bool* \Rightarrow *error* \Rightarrow *abopt* \Rightarrow *abopt*
where *error-if* *c* *e* == *abrupt-if* *c* (*Some* (*Error* *e*))

lemma *raise-if-None* [*simp*]: $(\text{raise-if } c \ x \ y = \text{None}) = (\neg c \wedge y = \text{None})$
 ⟨*proof*⟩
declare *raise-if-None* [*THEN iffD1, dest!*]

lemma *if-raise-if-None* [*simp*]:
 $((\text{if } b \ \text{then } y \ \text{else } \text{raise-if } c \ x \ y) = \text{None}) = ((c \longrightarrow b) \wedge y = \text{None})$
 ⟨*proof*⟩

lemma *raise-if-SomeD* [*dest!*]:
 $\text{raise-if } c \ x \ y = \text{Some } z \implies c \wedge z = (\text{Xcpt } (\text{Std } x)) \wedge y = \text{None} \vee (y = \text{Some } z)$
 ⟨*proof*⟩

lemma *error-if-None* [*simp*]: $(\text{error-if } c \ e \ y = \text{None}) = (\neg c \wedge y = \text{None})$
 ⟨*proof*⟩
declare *error-if-None* [*THEN iffD1, dest!*]

lemma *if-error-if-None* [*simp*]:
 $((\text{if } b \ \text{then } y \ \text{else } \text{error-if } c \ e \ y) = \text{None}) = ((c \longrightarrow b) \wedge y = \text{None})$
 ⟨*proof*⟩

lemma *error-if-SomeD* [*dest!*]:
 $\text{error-if } c \ e \ y = \text{Some } z \implies c \wedge z = (\text{Error } e) \wedge y = \text{None} \vee (y = \text{Some } z)$
 ⟨*proof*⟩

definition

absorb :: *jump* \Rightarrow *abopt* \Rightarrow *abopt*
where *absorb* *j* *a* = (*if* *a*=*Some* (*Jump* *j*) *then* *None* *else* *a*)

lemma *absorb-SomeD* [*dest!*]: *absorb* *j* *a* = *Some* *x* \implies *a* = *Some* *x*
 ⟨*proof*⟩

lemma *absorb-same* [*simp*]: *absorb* *j* (*Some* (*Jump* *j*)) = *None*
 ⟨*proof*⟩

lemma *absorb-other* [*simp*]: *a* \neq *Some* (*Jump* *j*) \implies *absorb* *j* *a* = *a*
 ⟨*proof*⟩

lemma *absorb-Some-NoneD*: *absorb* *j* (*Some* *abr*) = *None* \implies *abr* = *Jump* *j*
 ⟨*proof*⟩

lemma *absorb-Some-JumpD*: *absorb* *j* *s* = *Some* (*Jump* *j'*) \implies *j'* \neq *j*
 ⟨*proof*⟩

full program state

type-synonym

state = *abopt* \times *st* — state including abruption information

translations

(*type*) *abopt* <= (*type*) *abrupt option*
 (*type*) *state* <= (*type*) *abopt* × *st*

abbreviation

Norm :: *st* ⇒ *state*
where *Norm* *s* == (*None*, *s*)

abbreviation (*input*)

abrupt :: *state* ⇒ *abopt*
where *abrupt* == *fst*

abbreviation (*input*)

store :: *state* ⇒ *st*
where *store* == *snd*

lemma *single-stateE*: ∀ *Z*. *Z* = (*s*::*state*) ⇒ *False*
 ⟨*proof*⟩

lemma *state-not-single*: All (*op* = (*x*::*state*)) ⇒ *R*
 ⟨*proof*⟩

definition

normal :: *state* ⇒ *bool*
where *normal* = (λ*s*. *abrupt* *s* = *None*)

lemma *normal-def2* [*simp*]: *normal* *s* = (*abrupt* *s* = *None*)
 ⟨*proof*⟩

definition

heap-free :: *nat* ⇒ *state* ⇒ *bool*
where *heap-free* *n* = (λ*s*. *atleast-free* (*heap* (*store* *s*)) *n*)

lemma *heap-free-def2* [*simp*]: *heap-free* *n* *s* = *atleast-free* (*heap* (*store* *s*)) *n*
 ⟨*proof*⟩

41 update**definition**

abupd :: (*abopt* ⇒ *abopt*) ⇒ *state* ⇒ *state*
where *abupd* *f* = *map-pair* *f* *id*

definition

supd :: (*st* ⇒ *st*) ⇒ *state* ⇒ *state*
where *supd* = *map-pair* *id*

lemma *abupd-def2* [*simp*]: *abupd* *f* (*x*,*s*) = (*f* *x*,*s*)
 ⟨*proof*⟩

lemma *abupd-abrupt-if-False* [*simp*]: ∧ *s*. *abupd* (*abrupt-if* *False* *xo*) *s* = *s*
 ⟨*proof*⟩

lemma *supd-def2* [*simp*]: *supd* *f* (*x*,*s*) = (*x*,*f* *s*)

$\langle proof \rangle$

lemma *supd-lupd* [simp]:

$\bigwedge s. \text{supd} (\text{lupd } vn \ v) \ s = (\text{abrupt } s, \text{lupd } vn \ v \ (\text{store } s))$
 $\langle proof \rangle$

lemma *supd-gupd* [simp]:

$\bigwedge s. \text{supd} (\text{gupd } r \ \text{obj}) \ s = (\text{abrupt } s, \text{gupd } r \ \text{obj} \ (\text{store } s))$
 $\langle proof \rangle$

lemma *supd-init-obj* [simp]:

$\text{supd} (\text{init-obj } G \ \text{oi } r) \ s = (\text{abrupt } s, \text{init-obj } G \ \text{oi } r \ (\text{store } s))$
 $\langle proof \rangle$

lemma *abupd-store-invariant* [simp]: $\text{store} (\text{abupd } f \ s) = \text{store } s$

$\langle proof \rangle$

lemma *supd-abrupt-invariant* [simp]: $\text{abrupt} (\text{supd } f \ s) = \text{abrupt } s$

$\langle proof \rangle$

abbreviation *set-lvars* :: $\text{locals} \Rightarrow \text{state} \Rightarrow \text{state}$

where *set-lvars* $l == \text{supd} (\text{set-locals } l)$

abbreviation *restore-lvars* :: $\text{state} \Rightarrow \text{state} \Rightarrow \text{state}$

where *restore-lvars* $s' \ s == \text{set-lvars} (\text{locals} (\text{store } s')) \ s$

lemma *set-set-lvars* [simp]: $\bigwedge s. \text{set-lvars } l (\text{set-lvars } l' \ s) = \text{set-lvars } l \ s$

$\langle proof \rangle$

lemma *set-lvars-id* [simp]: $\bigwedge s. \text{set-lvars} (\text{locals} (\text{store } s)) \ s = s$

$\langle proof \rangle$

initialisation test

definition

initd :: $qname \Rightarrow \text{globs} \Rightarrow \text{bool}$

where *initd* $C \ g = (g \ (\text{Stat } C) \neq \text{None})$

definition

initd :: $qname \Rightarrow \text{state} \Rightarrow \text{bool}$

where *initd* $C = \text{initd } C \circ \text{globs} \circ \text{store}$

lemma *not-initd-empty* [simp]: $\neg \text{initd } C \ \text{empty}$

$\langle proof \rangle$

lemma *initd-gupdate* [simp]: $\text{initd } C \ (g(r \mapsto \text{obj})) = (\text{initd } C \ g \ \vee \ r = \text{Stat } C)$

$\langle proof \rangle$

lemma *inited-init-class-obj* [intro!]: *inited C (globs (init-class-obj G C s))*
 ⟨proof⟩

lemma *not-initedD*: $\neg \textit{inited C g} \implies g (\textit{Stat C}) = \textit{None}$
 ⟨proof⟩

lemma *initedD*: *inited C g* $\implies \exists \textit{obj. g (Stat C) = Some obj}$
 ⟨proof⟩

lemma *initd-def2* [simp]: *initd C s = inited C (globs (store s))*
 ⟨proof⟩

error-free

definition

error-free :: *state* \Rightarrow *bool*

where *error-free s* = $(\neg (\exists \textit{err. abrupt s = Some (Error err)}))$

lemma *error-free-Norm* [simp,intro]: *error-free (Norm s)*
 ⟨proof⟩

lemma *error-free-normal* [simp,intro]: *normal s* \implies *error-free s*
 ⟨proof⟩

lemma *error-free-Xcpt* [simp]: *error-free (Some (Xcpt x),s)*
 ⟨proof⟩

lemma *error-free-Jump* [simp,intro]: *error-free (Some (Jump j),s)*
 ⟨proof⟩

lemma *error-free-Error* [simp]: *error-free (Some (Error e),s) = False*
 ⟨proof⟩

lemma *error-free-Some* [simp,intro]:
 $\neg (\exists \textit{err. x=Error err}) \implies \textit{error-free ((Some x),s)}$
 ⟨proof⟩

lemma *error-free-abupd-absorb* [simp,intro]:
error-free s \implies *error-free (abupd (absorb j) s)*
 ⟨proof⟩

lemma *error-free-absorb* [simp,intro]:
error-free (a,s) \implies *error-free (absorb j a, s)*
 ⟨proof⟩

lemma *error-free-abrupt-if* [simp,intro]:
 $\llbracket \textit{error-free s; } \neg (\exists \textit{err. x=Error err}) \rrbracket$

$\implies \text{error-free } (\text{abupd } (\text{abrupt-if } p \text{ (Some } x)) \text{ } s)$
 $\langle \text{proof} \rangle$

lemma *error-free-abrupt-if1* [simp,intro]:
 $\llbracket \text{error-free } (a,s); \neg (\exists \text{ err. } x = \text{Error } \text{err}) \rrbracket$
 $\implies \text{error-free } (\text{abrupt-if } p \text{ (Some } x) \text{ } a, s)$
 $\langle \text{proof} \rangle$

lemma *error-free-abrupt-if-Xcpt* [simp,intro]:
 $\text{error-free } s$
 $\implies \text{error-free } (\text{abupd } (\text{abrupt-if } p \text{ (Some } (\text{Xcpt } x))) \text{ } s)$
 $\langle \text{proof} \rangle$

lemma *error-free-abrupt-if-Xcpt1* [simp,intro]:
 $\text{error-free } (a,s)$
 $\implies \text{error-free } (\text{abrupt-if } p \text{ (Some } (\text{Xcpt } x)) \text{ } a, s)$
 $\langle \text{proof} \rangle$

lemma *error-free-abrupt-if-Jump* [simp,intro]:
 $\text{error-free } s$
 $\implies \text{error-free } (\text{abupd } (\text{abrupt-if } p \text{ (Some } (\text{Jump } j))) \text{ } s)$
 $\langle \text{proof} \rangle$

lemma *error-free-abrupt-if-Jump1* [simp,intro]:
 $\text{error-free } (a,s)$
 $\implies \text{error-free } (\text{abrupt-if } p \text{ (Some } (\text{Jump } j)) \text{ } a, s)$
 $\langle \text{proof} \rangle$

lemma *error-free-raise-if* [simp,intro]:
 $\text{error-free } s \implies \text{error-free } (\text{abupd } (\text{raise-if } p \text{ } x) \text{ } s)$
 $\langle \text{proof} \rangle$

lemma *error-free-raise-if1* [simp,intro]:
 $\text{error-free } (a,s) \implies \text{error-free } ((\text{raise-if } p \text{ } x) \text{ } a, s)$
 $\langle \text{proof} \rangle$

lemma *error-free-supd* [simp,intro]:
 $\text{error-free } s \implies \text{error-free } (\text{supd } f \text{ } s)$
 $\langle \text{proof} \rangle$

lemma *error-free-supd1* [simp,intro]:
 $\text{error-free } (a,s) \implies \text{error-free } (a, f \text{ } s)$
 $\langle \text{proof} \rangle$

lemma *error-free-set-lvars* [simp,intro]:
 $\text{error-free } s \implies \text{error-free } ((\text{set-lvars } l) \text{ } s)$
 $\langle \text{proof} \rangle$

lemma *error-free-set-locals* [*simp,intro*]:
error-free (*x*, *s*)
 \implies *error-free* (*x*, *set-locals l s'*)
<proof>

end

Chapter 15

Eval

42 Operational evaluation (big-step) semantics of Java expressions and statements

theory *Eval* imports *State DeclConcepts* begin

improvements over Java Specification 1.0:

- dynamic method lookup does not need to consider the return type (cf.15.11.4.4)
- throw raises a NullPointerException if a null reference is given, and each throw of a standard exception yield a fresh exception object (was not specified)
- if there is not enough memory even to allocate an OutOfMemory exception, evaluation/execution fails, i.e. simply stops (was not specified)
- array assignment checks lhs (and may throw exceptions) before evaluating rhs
- fixed exact positions of class initializations (immediate at first active use)

design issues:

- evaluation vs. (single-step) transition semantics evaluation semantics chosen, because:
 - ++ less verbose and therefore easier to read (and to handle in proofs)
 - + more abstract
 - + intermediate values (appearing in recursive rules) need not be stored explicitly, e.g. no call body construct or stack of invocation frames containing local variables and return addresses for method calls needed
 - + convenient rule induction for subject reduction theorem
 - no interleaving (for parallelism) can be described
 - stating a property of infinite executions requires the meta-level argument that this property holds for any finite prefixes of it (e.g. stopped using a counter that is decremented to zero and then throwing an exception)
- unified evaluation for variables, expressions, expression lists, statements
- the value entry in statement rules is redundant
- the value entry in rules is irrelevant in case of exceptions, but its full inclusion helps to make the rule structure independent of exception occurrence.
- as irrelevant value entries are ignored, it does not matter if they are unique. For simplicity, (fixed) arbitrary values are preferred over "free" values.
- the rule format is such that the start state may contain an exception.
 - ++ facilitates exception handling
 - + symmetry
- the rules are defined carefully in order to be applicable even in not type-correct situations (yielding undefined values), e.g. $the-Addr (Val (Bool b)) = undefined$.
 - ++ fewer rules
 - less readable because of auxiliary functions like *the-Addr*

Alternative: "defensive" evaluation throwing some `InternalError` exception in case of (impossible, for correct programs) type mismatches

- there is exactly one rule per syntactic construct
 - + no redundancy in case distinctions
- `halloc` fails iff there is no free heap address. When there is only one free heap address left, it returns an `OutOfMemory` exception. In this way it is guaranteed that when an `OutOfMemory` exception is thrown for the first time, there is a free location on the heap to allocate it.
- the allocation of objects that represent standard exceptions is deferred until execution of any enclosing catch clause, which is transparent to the program.
 - requires an auxiliary execution relation
 - ++ avoids copies of allocation code and awkward case distinctions (whether there is enough memory to allocate the exception) in evaluation rules
- unfortunately `new-Addr` is not directly executable because of Hilbert operator.

simplifications:

- local variables are initialized with default values (no definite assignment)
- garbage collection not considered, therefore also no finalizers
- stack overflow and memory overflow during class initialization not modelled
- exceptions in initializations not replaced by `ExceptionInInitializerError`

type-synonym $vvar = val \times (val \Rightarrow state \Rightarrow state)$

type-synonym $vals = (val, vvar, val\ list) \text{ sum}3$

translations

$(type) vvar \leq (type) val \times (val \Rightarrow state \Rightarrow state)$

$(type) vals \leq (type) (val, vvar, val\ list) \text{ sum}3$

To avoid redundancy and to reduce the number of rules, there is only one evaluation rule for each syntactic term. This is also true for variables (e.g. see the rules below for `LVar`, `FVar` and `AVar`). So evaluation of a variable must capture both possible further uses: read (rule `Acc`) or write (rule `Ass`) to the variable. Therefore a variable evaluates to a special value `vvar`, which is a pair, consisting of the current value (for later read access) and an update function (for later write access). Because during assignment to an array variable an exception may occur if the types don't match, the update function is very generic: it transforms the full state. This generic update function causes some technical trouble during some proofs (e.g. type safety, correctness of definite assignment). There we need to prove some additional invariant on this update function to prove the assignment correct, since the update function could potentially alter the whole state in an arbitrary manner. This invariant must be carried around through the whole induction. So for future approaches it may be better not to take such a generic update function, but only to store the address and the kind of variable (array (+ element type), local variable or field) for later assignment.

abbreviation (*xsymbols*)

$dummy-res :: vals \ (\diamond)$

where $\diamond == In1\ Unit$

abbreviation (*input*)

$val-inj-vals \ ([_]_e \ 1000)$

where $[e]_e == In1\ e$

abbreviation (*input*)

$var-inj-vals \ ([_]_v \ 1000)$

where $[v]_v == In2\ v$

abbreviation (*input*)
lst-inj-vals ($\lfloor _ \rfloor_l$ 1000)
where $\lfloor es \rfloor_l == In3\ es$

definition *undefined3* :: (*'al + 'ar, 'b, 'c*) *sum3* \Rightarrow *vals* **where**
undefined3 = *sum3-case* (*In1* \circ *sum-case* ($\lambda x.$ *undefined*) ($\lambda x.$ *Unit*))
($\lambda x.$ *In2* *undefined*) ($\lambda x.$ *In3* *undefined*)

lemma [*simp*]: *undefined3* (*In1l* *x*) = *In1* *undefined*
 \langle *proof* \rangle

lemma [*simp*]: *undefined3* (*In1r* *x*) = \diamond
 \langle *proof* \rangle

lemma [*simp*]: *undefined3* (*In2* *x*) = *In2* *undefined*
 \langle *proof* \rangle

lemma [*simp*]: *undefined3* (*In3* *x*) = *In3* *undefined*
 \langle *proof* \rangle

exception throwing and catching

definition
throw :: *val* \Rightarrow *abopt* \Rightarrow *abopt* **where**
throw *a' x* = *abrupt-if* *True* (*Some* (*Xcpt* (*Loc* (*the-Addr* *a'*)))) (*np* *a' x*)

lemma *throw-def2*:
throw *a' x* = *abrupt-if* *True* (*Some* (*Xcpt* (*Loc* (*the-Addr* *a'*)))) (*np* *a' x*)
 \langle *proof* \rangle

definition
fits :: *prog* \Rightarrow *st* \Rightarrow *val* \Rightarrow *ty* \Rightarrow *bool* ($_ , _ \vdash _$ *fits* $\lfloor 61, 61, 61, 61 \rfloor 60$)
where $G, s \vdash a' \text{ fits } T = ((\exists rt. T = \text{RefT } rt) \longrightarrow a' = \text{Null} \vee G \vdash \text{obj-ty}(\text{lookup-obj } s \ a') \preceq T)$

lemma *fits-Null* [*simp*]: $G, s \vdash \text{Null} \text{ fits } T$
 \langle *proof* \rangle

lemma *fits-Addr-RefT* [*simp*]:
 $G, s \vdash \text{Addr } a \text{ fits } \text{RefT } t = G \vdash \text{obj-ty}(\text{the } (\text{heap } s \ a)) \preceq \text{RefT } t$
 \langle *proof* \rangle

lemma *fitsD*: $\bigwedge X. G, s \vdash a' \text{ fits } T \Longrightarrow (\exists pt. T = \text{PrimT } pt) \vee$
 $(\exists t. T = \text{RefT } t) \wedge a' = \text{Null} \vee$
 $(\exists t. T = \text{RefT } t) \wedge a' \neq \text{Null} \wedge G \vdash \text{obj-ty}(\text{lookup-obj } s \ a') \preceq T$
 \langle *proof* \rangle

definition
catch :: *prog* \Rightarrow *state* \Rightarrow *qname* \Rightarrow *bool* ($_ , _ \vdash _$ *catch* $\lfloor 61, 61, 61 \rfloor 60$) **where**
 $G, s \vdash \text{catch } C = (\exists xc. \text{abrupt } s = \text{Some } (\text{Xcpt } xc)) \wedge$

$G, \text{store } s \vdash \text{Addr } (\text{the-Loc } xc) \text{ fits Class } C$

lemma *catch-Norm* [simp]: $\neg G, \text{Norm } s \vdash \text{catch } tn$
 ⟨proof⟩

lemma *catch-XcptLoc* [simp]:
 $G, (\text{Some } (\text{Xcpt } (\text{Loc } a)), s) \vdash \text{catch } C = G, s \vdash \text{Addr } a \text{ fits Class } C$
 ⟨proof⟩

lemma *catch-Jump* [simp]: $\neg G, (\text{Some } (\text{Jump } j), s) \vdash \text{catch } tn$
 ⟨proof⟩

lemma *catch-Error* [simp]: $\neg G, (\text{Some } (\text{Error } e), s) \vdash \text{catch } tn$
 ⟨proof⟩

definition

new-xcpt-var :: $vname \Rightarrow state \Rightarrow state$ **where**
new-xcpt-var $vn = (\lambda(x,s). \text{Norm } (\text{lupd}(\text{VName } vn \mapsto \text{Addr } (\text{the-Loc } (\text{the-Xcpt } (\text{the } x)))) s))$

lemma *new-xcpt-var-def2* [simp]:
new-xcpt-var $vn (x,s) =$
 $\text{Norm } (\text{lupd}(\text{VName } vn \mapsto \text{Addr } (\text{the-Loc } (\text{the-Xcpt } (\text{the } x)))) s)$
 ⟨proof⟩

misc

definition

assign :: $('a \Rightarrow state \Rightarrow state) \Rightarrow 'a \Rightarrow state \Rightarrow state$ **where**
assign $f v = (\lambda(x,s). \text{let } (x',s') = (\text{if } x = \text{None} \text{ then } f v \text{ else } id) (x,s)$
 $\text{in } (x', \text{if } x' = \text{None} \text{ then } s' \text{ else } s))$

lemma *assign-Norm-Norm* [simp]:
 $f v (\text{Norm } s) = \text{Norm } s' \Longrightarrow \text{assign } f v (\text{Norm } s) = \text{Norm } s'$
 ⟨proof⟩

lemma *assign-Norm-Some* [simp]:
 $\llbracket \text{abrupt } (f v (\text{Norm } s)) = \text{Some } y \rrbracket$
 $\Longrightarrow \text{assign } f v (\text{Norm } s) = (\text{Some } y, s)$
 ⟨proof⟩

lemma *assign-Some* [simp]:
 $\text{assign } f v (\text{Some } x, s) = (\text{Some } x, s)$
 ⟨proof⟩

lemma *assign-Some1* [simp]: $\neg \text{normal } s \Longrightarrow \text{assign } f v s = s$

$\langle proof \rangle$

lemma *assign-supd* [simp]:
assign ($\lambda v. \text{supd } (f v)$) $v (x, s)$
 = ($x, \text{if } x = \text{None} \text{ then } f v s \text{ else } s$)
 $\langle proof \rangle$

lemma *assign-raise-if* [simp]:
assign ($\lambda v (x, s). ((\text{raise-if } (b s v) \text{ xcpt } x, f v s)) v (x, s) =$
 ($\text{raise-if } (b s v) \text{ xcpt } x, \text{if } x = \text{None} \wedge \neg b s v \text{ then } f v s \text{ else } s$)
 $\langle proof \rangle$

definition

init-comp-ty :: $ty \Rightarrow stmt$
where *init-comp-ty* $T = (\text{if } (\exists C. T = \text{Class } C) \text{ then } \text{Init } (\text{the-Class } T) \text{ else } \text{Skip})$

lemma *init-comp-ty-PrimT* [simp]: *init-comp-ty* ($\text{PrimT } pt$) = *Skip*
 $\langle proof \rangle$

definition

invocation-class :: $inv\text{-mode} \Rightarrow st \Rightarrow val \Rightarrow ref\text{-ty} \Rightarrow qname$ **where**
invocation-class $m s a' statT =$
 (case m of
 $\text{Static} \Rightarrow \text{if } (\exists statC. statT = \text{ClassT } statC)$
 then $\text{the-Class } (\text{RefT } statT)$
 else Object
 $\text{SuperM} \Rightarrow \text{the-Class } (\text{RefT } statT)$
 $\text{IntVir} \Rightarrow \text{obj-class } (\text{lookup-obj } s a')$)

definition

invocation-declclass :: $prog \Rightarrow inv\text{-mode} \Rightarrow st \Rightarrow val \Rightarrow ref\text{-ty} \Rightarrow sig \Rightarrow qname$ **where**
invocation-declclass $G m s a' statT sig =$
 $\text{declclass } (\text{the } (\text{dynlookup } G statT$
 ($\text{invocation-class } m s a' statT$)
 $sig))$

lemma *invocation-class-IntVir* [simp]:
invocation-class $\text{IntVir } s a' statT = \text{obj-class } (\text{lookup-obj } s a')$
 $\langle proof \rangle$

lemma *dynclass-SuperM* [simp]:
invocation-class $\text{SuperM } s a' statT = \text{the-Class } (\text{RefT } statT)$
 $\langle proof \rangle$

lemma *invocation-class-Static* [simp]:
invocation-class $\text{Static } s a' statT = (\text{if } (\exists statC. statT = \text{ClassT } statC)$
 then $\text{the-Class } (\text{RefT } statT)$
 else Object)
 $\langle proof \rangle$

definition

init-lvars :: *prog* ⇒ *qname* ⇒ *sig* ⇒ *inv-mode* ⇒ *val* ⇒ *val list* ⇒ *state* ⇒ *state*

where

init-lvars *G C sig mode a' pvs* =
 (λ(*x,s*).
 let *m* = *mthd* (*the* (*methd* *G C sig*));
 l = λ *k*.
 (*case* *k* of
 EName *e*
 ⇒ (*case* *e* of
 VNam *v* ⇒ (*empty* ((*pars* *m*)[*map*]*pvs*)) *v*
 | *Res* ⇒ *None*)
 | *This*
 ⇒ (*if* *mode*=*Static* then *None* else *Some* *a'*))
 in *set-lvars* *l* (*if* *mode* = *Static* then *x* else *np a' x,s*))

lemma *init-lvars-def2*: — better suited for simplification

init-lvars *G C sig mode a' pvs* (*x,s*) =
set-lvars
 (λ *k*.
 (*case* *k* of
 EName *e*
 ⇒ (*case* *e* of
 VNam *v*
 ⇒ (*empty* ((*pars* (*mthd* (*the* (*methd* *G C sig*))))[*map*]*pvs*)) *v*
 | *Res* ⇒ *None*)
 | *This*
 ⇒ (*if* *mode*=*Static* then *None* else *Some* *a'*))
 (*if* *mode* = *Static* then *x* else *np a' x,s*)
 ⟨*proof*⟩

definition

body :: *prog* ⇒ *qname* ⇒ *sig* ⇒ *expr* **where**
body *G C sig* =
 (*let* *m* = *the* (*methd* *G C sig*)
 in *Body* (*declclass* *m*) (*stmt* (*mbody* (*mthd* *m*))))

lemma *body-def2*: — better suited for simplification

body *G C sig* = *Body* (*declclass* (*the* (*methd* *G C sig*)))
 (*stmt* (*mbody* (*mthd* (*the* (*methd* *G C sig*))))
 ⟨*proof*⟩

variables**definition**

lvar :: *lname* ⇒ *st* ⇒ *vvar*
where *lvar* *vn s* = (*the* (*locals* *s vn*), λ*v*. *supd* (*lupd*(*vn*→*v*)))

definition

fvar :: *qname* ⇒ *bool* ⇒ *vname* ⇒ *val* ⇒ *state* ⇒ *vvar* × *state* **where**
fvar *C stat fn a' s* =
 (*let* (*oref,xf*) = *if* *stat* then (*Stat* *C,id*)
 else (*Heap* (*the-Addr* *a'*),*np a'*);
 n = *Inl* (*fn,C*);
 f = (λ*v*. *supd* (*upd-gobj* *oref n v*))

in ((the (values (the (globs (store s) oref)) n),f),abupd xf s))

definition

avar :: *prog* ⇒ *val* ⇒ *val* ⇒ *state* ⇒ *vvar* × *state* **where**

avar *G i' a' s* =

(let oref = Heap (the-Addr a');

i = the-Intg i';

n = Inr i;

(*T,k,cs*) = the-Arr (globs (store s) oref);

f = (λv (x,s). (raise-if (¬G,s⊢v fits *T*)

ArrStore x

,upd-gobj oref n v s))

in ((the (cs n),f),abupd (raise-if (¬i in-bounds k) IndOutBound ∘ np a') s))

lemma *fvar-def2*: — better suited for simplification

fvar *C stat fn a' s* =

((the

(values

(the (globs (store s) (if stat then Stat *C* else Heap (the-Addr a'))))

(Inl (fn,C)))

,(λv. supd (upd-gobj (if stat then Stat *C* else Heap (the-Addr a'))

(Inl (fn,C))

v)))

,abupd (if stat then id else np a') s)

⟨proof⟩

lemma *avar-def2*: — better suited for simplification

avar *G i' a' s* =

((the ((snd(snd(the-Arr (globs (store s) (Heap (the-Addr a'))))))

(Inr (the-Intg i'))

,(λv (x,s'). (raise-if (¬G,s⊢v fits (fst(the-Arr (globs (store s)

(Heap (the-Addr a'))))))

ArrStore x

,upd-gobj (Heap (the-Addr a'))

(Inr (the-Intg i') v s'))

,abupd (raise-if (¬(the-Intg i') in-bounds (fst(snd(the-Arr (globs (store s)

(Heap (the-Addr a')))))) IndOutBound ∘ np a')

s)

⟨proof⟩

definition

check-field-access :: *prog* ⇒ *qname* ⇒ *qname* ⇒ *vname* ⇒ *bool* ⇒ *val* ⇒ *state* ⇒ *state* **where**

check-field-access *G accC statDeclC fn stat a' s* =

(let oref = if stat then Stat statDeclC

else Heap (the-Addr a');

dynC = case oref of

Heap a ⇒ obj-class (the (globs (store s) oref))

| Stat *C* ⇒ *C*;

f = (the (table-of (DeclConcepts.fields *G* dynC) (fn,statDeclC)))

in abupd

(error-if (¬ G⊢Field fn (statDeclC,f) *in* dynC dyn-accessible-from accC)

AccessViolation)

s)

definition

check-method-access :: *prog* ⇒ *qname* ⇒ *ref-ty* ⇒ *inv-mode* ⇒ *sig* ⇒ *val* ⇒ *state* ⇒ *state* **where**

```

check-method-access G accC statT mode sig a' s =
  (let invC = invocation-class mode (store s) a' statT;
    dynM = the (dynlookup G statT invC sig)
    in abrupt
    (error-if (¬ G⊢Methd sig dynM in invC dyn-accessible-from accC)
      AccessViolation)
    s)

```

evaluation judgments

inductive

halloc :: [prog,state,obj-tag,loc,state]⇒bool (⊢- -halloc ->- -> -[61,61,61,61,61]60) **for** G::prog
where — allocating objects on the heap, cf. 12.5

Abrupt:

$G\vdash(\text{Some } x,s) \text{ -halloc } oi \succ \text{undefined} \rightarrow (\text{Some } x,s)$

| *New*: $\llbracket \text{new-Addr } (\text{heap } s) = \text{Some } a;$
 $(x,oi') = (\text{if atleast-free } (\text{heap } s) (\text{Suc } (\text{Suc } 0)) \text{ then } (\text{None},oi)$
 $\text{ else } (\text{Some } (\text{Xcpt } (\text{Loc } a)),\text{CInst } (\text{SXcpt } \text{OutOfMemory}))) \rrbracket$
 \implies
 $G\vdash \text{Norm } s \text{ -halloc } oi \succ a \rightarrow (x,\text{init-obj } G \text{ } oi' (\text{Heap } a) s)$

inductive **sxalloc** :: [prog,state,state]⇒bool (⊢- -sxalloc ->- -> -[61,61,61]60) **for** G::prog
where — allocating exception objects for standard exceptions (other than OutOfMemory)

Norm: $G\vdash \text{Norm } s \text{ -sxalloc} \rightarrow \text{Norm } s$

| *Jmp*: $G\vdash(\text{Some } (\text{Jump } j), s) \text{ -sxalloc} \rightarrow (\text{Some } (\text{Jump } j), s)$

| *Error*: $G\vdash(\text{Some } (\text{Error } e), s) \text{ -sxalloc} \rightarrow (\text{Some } (\text{Error } e), s)$

| *XcptL*: $G\vdash(\text{Some } (\text{Xcpt } (\text{Loc } a)), s) \text{ -sxalloc} \rightarrow (\text{Some } (\text{Xcpt } (\text{Loc } a)), s)$

| *SXcpt*: $\llbracket G\vdash \text{Norm } s0 \text{ -halloc } (\text{CInst } (\text{SXcpt } xn)) \succ a \rightarrow (x,s1) \rrbracket \implies$
 $G\vdash(\text{Some } (\text{Xcpt } (\text{Std } xn)), s0) \text{ -sxalloc} \rightarrow (\text{Some } (\text{Xcpt } (\text{Loc } a)), s1)$

inductive

eval :: [prog,state,term,vals,state]⇒bool (⊢- -->- -> '(-, -)' [61,61,80,0,0]60)
and **exec** :: [prog,state,stmt ,state]⇒bool(⊢- ----> - [61,61,65, 61]60)
and **eval'** :: [prog,state,var ,vvar,state]⇒bool(⊢- --=>- -> -[61,61,90,61,61]60)
and **eval''** :: [prog,state,expr ,val ,state]⇒bool(⊢- ---->- -> -[61,61,80,61,61]60)
and **evals** :: [prog,state,expr list ,
 $\text{val list ,state}] \Rightarrow \text{bool}(\vdash- --\dot{\succ}- \rightarrow -[61,61,61,61,61]60)$

for G::prog

where

$G\vdash s \text{ -c} \rightarrow s' \equiv G\vdash s \text{ -In1r } c \succ \rightarrow (\diamond, s')$
| $G\vdash s \text{ -e-}\succ v \rightarrow s' \equiv G\vdash s \text{ -In1l } e \succ \rightarrow (\text{In1 } v, s')$
| $G\vdash s \text{ -e=}\succ vf \rightarrow s' \equiv G\vdash s \text{ -In2 } e \succ \rightarrow (\text{In2 } vf, s')$
| $G\vdash s \text{ -e\dot{\succ}} v \rightarrow s' \equiv G\vdash s \text{ -In3 } e \succ \rightarrow (\text{In3 } v, s')$

— propagation of abrupt completion

— cf. 14.1, 15.5

| *Abrupt*:

$G\vdash(\text{Some } xc,s) \text{ -t}\succ \rightarrow (\text{undefined3 } t, (\text{Some } xc, s))$

— execution of statements

— cf. 14.5

| *Skip*: $G \vdash \text{Norm } s \text{ -Skip} \rightarrow \text{Norm } s$

— cf. 14.7

| *Expr*: $\llbracket G \vdash \text{Norm } s0 \text{ -}e\text{-}\succ v \rightarrow s1 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ -Expr } e \rightarrow s1$

| *Lab*: $\llbracket G \vdash \text{Norm } s0 \text{ -}c \rightarrow s1 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ -}l \cdot c \rightarrow \text{abupd } (\text{absorb } l) s1$

— cf. 14.2

| *Comp*: $\llbracket G \vdash \text{Norm } s0 \text{ -}c1 \rightarrow s1;$
 $G \vdash s1 \text{ -}c2 \rightarrow s2 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ -}c1;; c2 \rightarrow s2$

— cf. 14.8.2

| *If*: $\llbracket G \vdash \text{Norm } s0 \text{ -}e\text{-}\succ b \rightarrow s1;$
 $G \vdash s1 \text{ -(if the-Bool } b \text{ then } c1 \text{ else } c2) \rightarrow s2 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ -If}(e) c1 \text{ Else } c2 \rightarrow s2$

— cf. 14.10, 14.10.1

— A continue jump from the while body c is handled by this rule. If a continue jump with the proper label was invoked inside c this label (Cont l) is deleted out of the abrupt component of the state before the iterative evaluation of the while statement. A break jump is handled by the Lab Statement *Lab* l (*while*...).

| *Loop*: $\llbracket G \vdash \text{Norm } s0 \text{ -}e\text{-}\succ b \rightarrow s1;$
 $\text{if the-Bool } b$
 $\text{then } (G \vdash s1 \text{ -}c \rightarrow s2 \wedge$
 $G \vdash (\text{abupd } (\text{absorb } (\text{Cont } l)) s2) \text{ -}l \cdot \text{While}(e) c \rightarrow s3)$
 $\text{else } s3 = s1 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ -}l \cdot \text{While}(e) c \rightarrow s3$

| *Jmp*: $G \vdash \text{Norm } s \text{ -}Jmp j \rightarrow (\text{Some } (\text{Jump } j), s)$

— cf. 14.16

| *Throw*: $\llbracket G \vdash \text{Norm } s0 \text{ -}e\text{-}\succ a' \rightarrow s1 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ -Throw } e \rightarrow \text{abupd } (\text{throw } a') s1$

— cf. 14.18.1

| *Try*: $\llbracket G \vdash \text{Norm } s0 \text{ -}c1 \rightarrow s1; G \vdash s1 \text{ -}s\text{alloc} \rightarrow s2;$
 $\text{if } G, s2 \vdash \text{catch } C \text{ then } G \vdash \text{new-xcpt-var } vn \text{ } s2 \text{ -}c2 \rightarrow s3 \text{ else } s3 = s2 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ -Try } c1 \text{ Catch}(C vn) c2 \rightarrow s3$

— cf. 14.18.2

| *Fin*: $\llbracket G \vdash \text{Norm } s0 \text{ -}c1 \rightarrow (x1, s1);$
 $G \vdash \text{Norm } s1 \text{ -}c2 \rightarrow s2;$
 $s3 = (\text{if } (\exists \text{ err. } x1 = \text{Some } (\text{Error } \text{err}))$
 $\text{then } (x1, s1)$
 $\text{else } \text{abupd } (\text{abrupt-if } (x1 \neq \text{None}) x1) s2) \rrbracket$
 \implies
 $G \vdash \text{Norm } s0 \text{ -}c1 \text{ Finally } c2 \rightarrow s3$

— cf. 12.4.2, 8.5

| *Init*: $\llbracket \text{the } (\text{class } G C) = c;$
 $\text{if inited } C \text{ (globs } s0) \text{ then } s3 = \text{Norm } s0$
 $\text{else } (G \vdash \text{Norm } (\text{init-class-obj } G C s0)$
 $\text{-}(\text{if } C = \text{Object then Skip else Init } (\text{super } c)) \rightarrow s1 \wedge$
 $G \vdash \text{set-lvars empty } s1 \text{ -init } c \rightarrow s2 \wedge s3 = \text{restore-lvars } s1 s2) \rrbracket$

$$\implies$$

$$G \vdash \text{Norm } s0 \text{ -Init } C \rightarrow s3$$

— This class initialisation rule is a little bit inaccurate. Look at the exact sequence: (1) The current class object (the static fields) are initialised (*init-class-obj*), (2) the superclasses are initialised, (3) the static initialiser of the current class is invoked. More precisely we should expect another ordering, namely 2 1 3. But we can't just naively toggle 1 and 2. By calling *init-class-obj* before initialising the superclasses, we also implicitly record that we have started to initialise the current class (by setting an value for the class object). This becomes crucial for the completeness proof of the axiomatic semantics *AxCompl.thy*. Static initialisation requires an induction on the number of classes not yet initialised (or to be more precise, classes were the initialisation has not yet begun). So we could first assign a dummy value to the class before superclass initialisation and afterwards set the correct values. But as long as we don't take memory overflow into account when allocating class objects, we can leave things as they are for convenience.

— evaluation of expressions

— cf. 15.8.1, 12.4.1

$$\begin{aligned} | \text{NewC}: & \llbracket G \vdash \text{Norm } s0 \text{ -Init } C \rightarrow s1; \\ & G \vdash s1 \text{ -halloc } (C \text{Inst } C) \succ a \rightarrow s2 \rrbracket \implies \\ & G \vdash \text{Norm } s0 \text{ -NewC } C \rightarrow \text{Addr } a \rightarrow s2 \end{aligned}$$

— cf. 15.9.1, 12.4.1

$$\begin{aligned} | \text{NewA}: & \llbracket G \vdash \text{Norm } s0 \text{ -init-comp-ty } T \rightarrow s1; G \vdash s1 \text{ -e-}\succ i' \rightarrow s2; \\ & G \vdash \text{abupd } (\text{check-neg } i') s2 \text{ -halloc } (\text{Arr } T \text{ (the-Intg } i')) \succ a \rightarrow s3 \rrbracket \implies \\ & G \vdash \text{Norm } s0 \text{ -New } T[e] \rightarrow \text{Addr } a \rightarrow s3 \end{aligned}$$

— cf. 15.15

$$\begin{aligned} | \text{Cast}: & \llbracket G \vdash \text{Norm } s0 \text{ -e-}\succ v \rightarrow s1; \\ & s2 = \text{abupd } (\text{raise-if } (\neg G, \text{store } s1 \vdash v \text{ fits } T) \text{ ClassCast}) s1 \rrbracket \implies \\ & G \vdash \text{Norm } s0 \text{ -Cast } T \text{ e-}\succ v \rightarrow s2 \end{aligned}$$

— cf. 15.19.2

$$\begin{aligned} | \text{Inst}: & \llbracket G \vdash \text{Norm } s0 \text{ -e-}\succ v \rightarrow s1; \\ & b = (v \neq \text{Null} \wedge G, \text{store } s1 \vdash v \text{ fits } \text{RefT } T) \rrbracket \implies \\ & G \vdash \text{Norm } s0 \text{ -e InstOf } T \rightarrow \text{Bool } b \rightarrow s1 \end{aligned}$$

— cf. 15.7.1

$$| \text{Lit}: G \vdash \text{Norm } s \text{ -Lit } v \rightarrow v \rightarrow \text{Norm } s$$

$$\begin{aligned} | \text{UnOp}: & \llbracket G \vdash \text{Norm } s0 \text{ -e-}\succ v \rightarrow s1 \rrbracket \\ & \implies G \vdash \text{Norm } s0 \text{ -UnOp } \text{unop } e \rightarrow \text{eval-unop } \text{unop } v \rightarrow s1 \end{aligned}$$

$$\begin{aligned} | \text{BinOp}: & \llbracket G \vdash \text{Norm } s0 \text{ -e1-}\succ v1 \rightarrow s1; \\ & G \vdash s1 \text{ -(if need-second-arg binop } v1 \text{ then (In1l } e2) \text{ else (In1r Skip))} \\ & \succ \rightarrow (\text{In1 } v2, s2) \\ & \rrbracket \\ & \implies G \vdash \text{Norm } s0 \text{ -BinOp } \text{binop } e1 \text{ e2} \rightarrow \text{eval-binop } \text{binop } v1 \text{ v2} \rightarrow s2 \end{aligned}$$

— cf. 15.10.2

$$| \text{Super}: G \vdash \text{Norm } s \text{ -Super} \rightarrow \text{val-this } s \rightarrow \text{Norm } s$$

— cf. 15.2

$$\begin{aligned} | \text{Acc}: & \llbracket G \vdash \text{Norm } s0 \text{ -va=}\succ (v, f) \rightarrow s1 \rrbracket \implies \\ & G \vdash \text{Norm } s0 \text{ -Acc } va \rightarrow v \rightarrow s1 \end{aligned}$$

— cf. 15.25.1

$$\begin{aligned} | \text{Ass}: & \llbracket G \vdash \text{Norm } s0 \text{ -va=}\succ (w, f) \rightarrow s1; \\ & G \vdash s1 \text{ -e-}\succ v \rightarrow s2 \rrbracket \implies \\ & G \vdash \text{Norm } s0 \text{ -va:=e-}\succ v \rightarrow \text{assign } f \text{ v } s2 \end{aligned}$$

— cf. 15.24

| *Cond*: $\llbracket G \vdash \text{Norm } s0 \text{ } -e0 \text{ } \rightarrow b \rightarrow s1;$
 $G \vdash s1 \text{ } -(if \text{ the-Bool } b \text{ then } e1 \text{ else } e2) \text{ } \rightarrow v \rightarrow s2 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ } -e0 \text{ } ? e1 : e2 \text{ } \rightarrow v \rightarrow s2$

— The interplay of *Call*, *Method* and *Body*: Method invocation is split up into these three rules:

Call Calculates the target address and evaluates the arguments of the method, and then performs dynamic or static lookup of the method, corresponding to the call mode. Then the *Method* rule is evaluated on the calculated declaration class of the method invocation.

Method A syntactic bridge for the folded method body. It is used by the axiomatic semantics to add the proper hypothesis for recursive calls of the method.

Body An extra syntactic entity for the unfolded method body was introduced to properly trigger class initialisation. Without class initialisation we could just evaluate the body statement.

— cf. 15.11.4.1, 15.11.4.2, 15.11.4.4, 15.11.4.5

| *Call*:
 $\llbracket G \vdash \text{Norm } s0 \text{ } -e \text{ } \rightarrow a' \rightarrow s1; G \vdash s1 \text{ } -args \text{ } \rightarrow vs \rightarrow s2;$
 $D = \text{invocation-declclass } G \text{ mode } (store \ s2) \ a' \ \text{statT } (\!|name=mn,parTs=pTs|);$
 $s3 = \text{init-lvars } G \ D \ (\!|name=mn,parTs=pTs|) \ \text{mode } \ a' \ \text{vs } \ s2;$
 $s3' = \text{check-method-access } G \ \text{accC} \ \text{statT} \ \text{mode} \ (\!|name=mn,parTs=pTs|) \ a' \ s3;$
 $G \vdash s3' \text{ } -\text{Method } D \ (\!|name=mn,parTs=pTs|) \ \rightarrow v \rightarrow s4 \rrbracket$
 \implies
 $G \vdash \text{Norm } s0 \text{ } -\{accC,statT,mode\}e \cdot mn(\{pTs\}args) \text{ } \rightarrow v \rightarrow (\text{restore-lvars } s2 \ s4)$

— The accessibility check is after *init-lvars*, to keep it simple. *init-lvars* already tests for the absence of a null-pointer reference in case of an instance method invocation.

| *Method*: $\llbracket G \vdash \text{Norm } s0 \text{ } -\text{body } G \ D \ \text{sig} \text{ } \rightarrow v \rightarrow s1 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ } -\text{Method } D \ \text{sig} \text{ } \rightarrow v \rightarrow s1$

| *Body*: $\llbracket G \vdash \text{Norm } s0 \text{ } -\text{Init } D \rightarrow s1; G \vdash s1 \text{ } -c \rightarrow s2;$
 $s3 = (if \ (\exists \ l. \ \text{abrupt } s2 = \text{Some } (\text{Jump } (\text{Break } l))) \vee$
 $\text{abrupt } s2 = \text{Some } (\text{Jump } (\text{Cont } l)))$
 $\text{then } \text{abupd } (\lambda \ x. \ \text{Some } (\text{Error } \text{CrossMethodJump})) \ s2$
 $\text{else } s2) \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ } -\text{Body } D \ c \text{ } \rightarrow \text{the } (\text{locals } (store \ s2) \ \text{Result})$
 $\rightarrow \text{abupd } (\text{absorb } \text{Ret}) \ s3$

— cf. 14.15, 12.4.1

— We filter out a break/continue in *s2*, so that we can proof definite assignment correct, without the need of conformance of the state. By this the different parts of the typesafety proof can be disentangled a little.

— evaluation of variables

— cf. 15.13.1, 15.7.2

| *LVar*: $G \vdash \text{Norm } s \text{ } -\text{LVar } vn = \text{ } \rightarrow \text{lvar } vn \ s \rightarrow \text{Norm } s$

— cf. 15.10.1, 12.4.1

| *FVar*: $\llbracket G \vdash \text{Norm } s0 \text{ } -\text{Init } \text{statDeclC} \rightarrow s1; G \vdash s1 \text{ } -e \text{ } \rightarrow a \rightarrow s2;$
 $(v, s2') = \text{fvar } \text{statDeclC} \ \text{stat} \ \text{fn } a \ s2;$
 $s3 = \text{check-field-access } G \ \text{accC} \ \text{statDeclC} \ \text{fn } \text{stat} \ a \ s2' \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ } -\{accC,statDeclC,stat\}e \cdot \text{fn} \text{ } \rightarrow v \rightarrow s3$

— The accessibility check is after *fvar*, to keep it simple. *fvar* already tests for the absence of a null-pointer reference in case of an instance field

— cf. 15.12.1, 15.25.1

| *AVar*: $\llbracket G \vdash \text{Norm } s0 \text{ } -e1 \text{ } \rightarrow a \rightarrow s1; G \vdash s1 \text{ } -e2 \text{ } \rightarrow i \rightarrow s2;$
 $(v, s2') = \text{avar } G \ i \ a \ s2 \rrbracket \implies$
 $G \vdash \text{Norm } s0 \text{ } -e1.[e2] = \text{ } \rightarrow v \rightarrow s2'$

— evaluation of expression lists

— cf. 15.11.4.2

| *Nil*:

$$G \vdash \text{Norm } s0 \text{ -} [\] \dot{=} \succ [\] \rightarrow \text{Norm } s0$$

— cf. 15.6.4

| *Cons*: $\llbracket G \vdash \text{Norm } s0 \text{ -} e \text{ -} \succ v \rightarrow s1;$

$$G \vdash s1 \text{ -} es \dot{=} \succ vs \rightarrow s2 \rrbracket \implies$$

$$G \vdash \text{Norm } s0 \text{ -} e \# es \dot{=} \succ v \# vs \rightarrow s2$$

$\langle ML \rangle$

declare *split-if* [*split del*] *split-if-asm* [*split del*]
option.split [*split del*] *option.split-asm* [*split del*]

inductive-cases *halloc-elim-cases*:

$$G \vdash (\text{Some } xc, s) \text{ -} \text{halloc } oi \succ a \rightarrow s'$$

$$G \vdash (\text{Norm } s) \text{ -} \text{halloc } oi \succ a \rightarrow s'$$

inductive-cases *sxalloc-elim-cases*:

$$G \vdash \text{Norm } s \text{ -} \text{sxalloc} \rightarrow s'$$

$$G \vdash (\text{Some } (\text{Jump } j), s) \text{ -} \text{sxalloc} \rightarrow s'$$

$$G \vdash (\text{Some } (\text{Error } e), s) \text{ -} \text{sxalloc} \rightarrow s'$$

$$G \vdash (\text{Some } (\text{Xcpt } (\text{Loc } a)), s) \text{ -} \text{sxalloc} \rightarrow s'$$

$$G \vdash (\text{Some } (\text{Xcpt } (\text{Std } xn)), s) \text{ -} \text{sxalloc} \rightarrow s'$$

inductive-cases *sxalloc-cases*: $G \vdash s \text{ -} \text{sxalloc} \rightarrow s'$

lemma *sxalloc-elim-cases2*: $\llbracket G \vdash s \text{ -} \text{sxalloc} \rightarrow s';$

$$\bigwedge s. \llbracket s' = \text{Norm } s \rrbracket \implies P;$$

$$\bigwedge j s. \llbracket s' = (\text{Some } (\text{Jump } j), s) \rrbracket \implies P;$$

$$\bigwedge e s. \llbracket s' = (\text{Some } (\text{Error } e), s) \rrbracket \implies P;$$

$$\bigwedge a s. \llbracket s' = (\text{Some } (\text{Xcpt } (\text{Loc } a)), s) \rrbracket \implies P$$

$$\rrbracket \implies P$$

$\langle \text{proof} \rangle$

declare *not-None-eq* [*simp del*]

declare *split-paired-All* [*simp del*] *split-paired-Ex* [*simp del*]

$\langle ML \rangle$

inductive-cases *eval-cases*: $G \vdash s \text{ -} t \succ \rightarrow (v, s')$

inductive-cases *eval-elim-cases* [*cases set*]:

$$G \vdash (\text{Some } xc, s) \text{ -} t \succ \rightarrow (v, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In1r } \text{Skip} \succ \rightarrow (x, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In1r } (\text{Jmp } j) \succ \rightarrow (x, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In1r } (l \cdot c) \succ \rightarrow (x, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In3 } ([\]) \succ \rightarrow (v, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In3 } (e \# es) \succ \rightarrow (v, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In1l } (\text{Lit } w) \succ \rightarrow (v, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In1l } (\text{UnOp } \text{unop } e) \succ \rightarrow (v, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In1l } (\text{BinOp } \text{binop } e1 e2) \succ \rightarrow (v, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In2 } (\text{LVar } vn) \succ \rightarrow (v, s')$$

$$G \vdash \text{Norm } s \text{ -} \text{In1l } (\text{Cast } T e) \succ \rightarrow (v, s')$$

$G \vdash \text{Norm } s - \text{In1l } (e \text{ InstOf } T)$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1l } (\text{Super})$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1l } (\text{Acc } va)$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1r } (\text{Expr } e)$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1r } (c1 ;; c2)$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1l } (\text{Methd } C \text{ sig})$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1l } (\text{Body } D \text{ c})$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1l } (e0 \text{ ? } e1 : e2)$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1r } (\text{If}(e) \text{ c1 Else } c2)$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1r } (l \cdot \text{While}(e) \text{ c})$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1r } (c1 \text{ Finally } c2)$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1r } (\text{Throw } e)$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In1l } (\text{NewC } C)$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1l } (\text{New } T[e])$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1l } (\text{Ass } va \text{ e})$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1r } (\text{Try } c1 \text{ Catch}(tn \text{ vn}) \text{ c2})$	$\succ \rightarrow (x, s')$
$G \vdash \text{Norm } s - \text{In2 } (\{accC, statDeclC, stat\}e..fn)$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In2 } (e1.[e2])$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1l } (\{accC, statT, mode\}e \cdot mn(\{pT\}p))$	$\succ \rightarrow (v, s')$
$G \vdash \text{Norm } s - \text{In1r } (\text{Init } C)$	$\succ \rightarrow (x, s')$

declare *not-None-eq* [simp]

declare *split-paired-All* [simp] *split-paired-Ex* [simp]

$\langle ML \rangle$

declare *split-if* [split] *split-if-asm* [split]
option.split [split] *option.split-asm* [split]

lemma *eval-Inj-elim*:

$G \vdash s - t \succ \rightarrow (w, s')$

\implies case t of

$\text{In1 } ec \implies (\text{case } ec \text{ of}$
 $\text{Inl } e \implies (\exists v. w = \text{In1 } v)$
 $\mid \text{Inr } c \implies w = \diamond$
 $\mid \text{In2 } e \implies (\exists v. w = \text{In2 } v)$
 $\mid \text{In3 } e \implies (\exists v. w = \text{In3 } v)$

$\langle \text{proof} \rangle$

The following simplification procedures set up the proper injections of terms and their corresponding values in the evaluation relation: E.g. an expression (injection *In1l* into terms) always evaluates to ordinary values (injection *In1* into generalised values *vals*).

lemma *eval-expr-eq*: $G \vdash s - \text{In1l } t \succ \rightarrow (w, s') = (\exists v. w = \text{In1 } v \wedge G \vdash s - t \succ \rightarrow v \rightarrow s')$
 $\langle \text{proof} \rangle$

lemma *eval-var-eq*: $G \vdash s - \text{In2 } t \succ \rightarrow (w, s') = (\exists vf. w = \text{In2 } vf \wedge G \vdash s - t \succ \rightarrow vf \rightarrow s')$
 $\langle \text{proof} \rangle$

lemma *eval-exprs-eq*: $G \vdash s - \text{In3 } t \succ \rightarrow (w, s') = (\exists vs. w = \text{In3 } vs \wedge G \vdash s - t \succ \rightarrow vs \rightarrow s')$
 $\langle \text{proof} \rangle$

lemma *eval-stmt-eq*: $G \vdash s - \text{In1r } t \succ \rightarrow (w, s') = (w = \diamond \wedge G \vdash s - t \rightarrow s')$
 $\langle \text{proof} \rangle$

$\langle ML \rangle$

declare *halloc.Abrupt* [intro!] *eval.Abrupt* [intro!] *AbruptIs* [intro!]

Callee, *InsInitE*, *InsInitV*, *FinA* are only used in smallstep semantics, not in the bigstep semantics. So their is no valid evaluation of these terms

lemma *eval-Callee*: $G \vdash \text{Norm } s - \text{Callee } l \ e - \succ v \rightarrow s' = \text{False}$
 ⟨proof⟩

lemma *eval-InsInitE*: $G \vdash \text{Norm } s - \text{InsInitE } c \ e - \succ v \rightarrow s' = \text{False}$
 ⟨proof⟩

lemma *eval-InsInitV*: $G \vdash \text{Norm } s - \text{InsInitV } c \ w - \succ v \rightarrow s' = \text{False}$
 ⟨proof⟩

lemma *eval-FinA*: $G \vdash \text{Norm } s - \text{FinA } a \ c \rightarrow s' = \text{False}$
 ⟨proof⟩

lemma *eval-no-abrupt-lemma*:
 $\bigwedge s \ s'. G \vdash s - t \succ \rightarrow (w, s') \implies \text{normal } s' \longrightarrow \text{normal } s$
 ⟨proof⟩

lemma *eval-no-abrupt*:
 $G \vdash (x, s) - t \succ \rightarrow (w, \text{Norm } s') =$
 $(x = \text{None} \wedge G \vdash \text{Norm } s - t \succ \rightarrow (w, \text{Norm } s'))$
 ⟨proof⟩

⟨ML⟩

lemma *eval-abrupt-lemma*:
 $G \vdash s - t \succ \rightarrow (v, s') \implies \text{abrupt } s = \text{Some } xc \longrightarrow s' = s \wedge v = \text{undefined3 } t$
 ⟨proof⟩

lemma *eval-abrupt*:
 $G \vdash (\text{Some } xc, s) - t \succ \rightarrow (w, s') =$
 $(s' = (\text{Some } xc, s) \wedge w = \text{undefined3 } t \wedge$
 $G \vdash (\text{Some } xc, s) - t \succ \rightarrow (\text{undefined3 } t, (\text{Some } xc, s)))$
 ⟨proof⟩

⟨ML⟩

lemma *LitI*: $G \vdash s - \text{Lit } v - \succ (\text{if normal } s \text{ then } v \text{ else undefined}) \rightarrow s$
 ⟨proof⟩

lemma *SkipI* [intro!]: $G \vdash s - \text{Skip} \rightarrow s$
 ⟨proof⟩

lemma *ExprI*: $G \vdash s - e - \succ v \rightarrow s' \implies G \vdash s - \text{Expr } e \rightarrow s'$
 ⟨proof⟩

lemma CompI: $\llbracket G \vdash s - c1 \rightarrow s1; G \vdash s1 - c2 \rightarrow s2 \rrbracket \implies G \vdash s - c1;; c2 \rightarrow s2$
 ⟨proof⟩

lemma CondI:

$\bigwedge s1. \llbracket G \vdash s - e - \succ b \rightarrow s1; G \vdash s1 - (\text{if the-Bool } b \text{ then } e1 \text{ else } e2) - \succ v \rightarrow s2 \rrbracket \implies$
 $G \vdash s - e ? e1 : e2 - \succ (\text{if normal } s1 \text{ then } v \text{ else undefined}) \rightarrow s2$
 ⟨proof⟩

lemma IfI: $\llbracket G \vdash s - e - \succ v \rightarrow s1; G \vdash s1 - (\text{if the-Bool } v \text{ then } c1 \text{ else } c2) \rightarrow s2 \rrbracket$
 $\implies G \vdash s - \text{If}(e) c1 \text{ Else } c2 \rightarrow s2$
 ⟨proof⟩

lemma MethdI: $G \vdash s - \text{body } G C \text{ sig} - \succ v \rightarrow s'$
 $\implies G \vdash s - \text{Methd } C \text{ sig} - \succ v \rightarrow s'$
 ⟨proof⟩

lemma eval-Call:

$\llbracket G \vdash \text{Norm } s0 - e - \succ a' \rightarrow s1; G \vdash s1 - ps \doteq \succ pvs \rightarrow s2;$
 $D = \text{invocation-declclass } G \text{ mode } (\text{store } s2) a' \text{ statT } (\{ \text{name} = mn, \text{parTs} = pTs \});$
 $s3 = \text{init-lvars } G D (\{ \text{name} = mn, \text{parTs} = pTs \}) \text{ mode } a' pvs s2;$
 $s3' = \text{check-method-access } G \text{ accC } \text{statT } \text{mode } (\{ \text{name} = mn, \text{parTs} = pTs \}) a' s3;$
 $G \vdash s3' - \text{Methd } D (\{ \text{name} = mn, \text{parTs} = pTs \}) - \succ v \rightarrow s4;$
 $s4' = \text{restore-lvars } s2 s4 \rrbracket \implies$
 $G \vdash \text{Norm } s0 - \{ \text{accC}, \text{statT}, \text{mode} \} e \cdot mn(\{ pTs \} ps) - \succ v \rightarrow s4'$
 ⟨proof⟩

lemma eval-Init:

$\llbracket \text{if initd } C (\text{globs } s0) \text{ then } s3 = \text{Norm } s0$
 $\text{else } G \vdash \text{Norm } (\text{init-class-obj } G C s0)$
 $\quad - (\text{if } C = \text{Object then Skip else Init } (\text{super } (\text{the } (\text{class } G C)))) \rightarrow s1 \wedge$
 $G \vdash \text{set-lvars empty } s1 - (\text{init } (\text{the } (\text{class } G C))) \rightarrow s2 \wedge$
 $s3 = \text{restore-lvars } s1 s2 \rrbracket \implies$
 $G \vdash \text{Norm } s0 - \text{Init } C \rightarrow s3$
 ⟨proof⟩

lemma init-done: $\text{initd } C s \implies G \vdash s - \text{Init } C \rightarrow s$
 ⟨proof⟩

lemma eval-StatRef:

$G \vdash s - \text{StatRef } rt - \succ (\text{if abrupt } s = \text{None then Null else undefined}) \rightarrow s$
 ⟨proof⟩

lemma SkipD [dest!]: $G \vdash s - \text{Skip} \rightarrow s' \implies s' = s$
 ⟨proof⟩

lemma Skip-eq [simp]: $G \vdash s - \text{Skip} \rightarrow s' = (s = s')$
 ⟨proof⟩

lemma *init-retains-locals* [rule-format (no-asm)]: $G \vdash s - t \succ \rightarrow (w, s') \implies$
 $(\forall C. t = \text{In1r} (\text{Init } C) \longrightarrow \text{locals} (\text{store } s) = \text{locals} (\text{store } s'))$
 ⟨proof⟩

lemma *halloc-xcpt* [dest!]:
 $\bigwedge s'. G \vdash (\text{Some } xc, s) - \text{halloc } oi \succ a \rightarrow s' \implies s' = (\text{Some } xc, s)$
 ⟨proof⟩

lemma *eval-Method*:
 $G \vdash s - \text{In1l}(\text{body } G \ C \ \text{sig}) \succ \rightarrow (w, s')$
 $\implies G \vdash s - \text{In1l}(\text{Method } C \ \text{sig}) \succ \rightarrow (w, s')$
 ⟨proof⟩

lemma *eval-Body*: $\llbracket G \vdash \text{Norm } s0 - \text{Init } D \rightarrow s1; G \vdash s1 - c \rightarrow s2;$
 $\text{res} = \text{the} (\text{locals} (\text{store } s2) \ \text{Result});$
 $s3 = (\text{if } (\exists l. \text{abrupt } s2 = \text{Some} (\text{Jump} (\text{Break } l))) \vee$
 $\text{abrupt } s2 = \text{Some} (\text{Jump} (\text{Cont } l)))$
 $\text{then } \text{abupd} (\lambda x. \text{Some} (\text{Error } \text{CrossMethodJump})) \ s2$
 $\text{else } s2);$
 $s4 = \text{abupd} (\text{absorb } \text{Ret}) \ s3 \rrbracket \implies$
 $G \vdash \text{Norm } s0 - \text{Body } D \ c \succ \text{res} \rightarrow s4$
 ⟨proof⟩

lemma *eval-binop-arg2-indep*:
 $\neg \text{need-second-arg } \text{binop } v1 \implies \text{eval-binop } \text{binop } v1 \ x = \text{eval-binop } \text{binop } v1 \ y$
 ⟨proof⟩

lemma *eval-BinOp-arg2-indepI*:
assumes *eval-e1*: $G \vdash \text{Norm } s0 - e1 \succ v1 \rightarrow s1$ **and**
no-need: $\neg \text{need-second-arg } \text{binop } v1$
shows $G \vdash \text{Norm } s0 - \text{BinOp } \text{binop } e1 \ e2 \succ (\text{eval-binop } \text{binop } v1 \ v2) \rightarrow s1$
 (**is** *?EvalBinOp* $v2$)
 ⟨proof⟩

single valued

lemma *unique-halloc* [rule-format (no-asm)]:
 $G \vdash s - \text{halloc } oi \succ a \rightarrow s' \implies G \vdash s - \text{halloc } oi \succ a' \rightarrow s'' \longrightarrow a' = a \wedge s'' = s'$
 ⟨proof⟩

lemma *single-valued-halloc*:
 $\text{single-valued} \{((s, oi), (a, s'))\}. G \vdash s - \text{halloc } oi \succ a \rightarrow s'$
 ⟨proof⟩

lemma *unique-sxalloc* [rule-format (no-asm)]:

$G \vdash s \text{ -salloc} \rightarrow s' \implies G \vdash s \text{ -salloc} \rightarrow s'' \longrightarrow s'' = s'$
 ⟨proof⟩

lemma *single-valued-salloc*: *single-valued* $\{(s, s'). G \vdash s \text{ -salloc} \rightarrow s'\}$
 ⟨proof⟩

lemma *split-pairD*: $(x, y) = p \implies x = \text{fst } p \ \& \ y = \text{snd } p$
 ⟨proof⟩

lemma *unique-eval* [*rule-format (no-asm)*]:
 $G \vdash s \text{ -t} \rightarrow (w, s') \implies (\forall w' s''. G \vdash s \text{ -t} \rightarrow (w', s'') \longrightarrow w' = w \wedge s'' = s')$
 ⟨proof⟩

lemma *single-valued-eval*:
single-valued $\{(s, t), (v, s'). G \vdash s \text{ -t} \rightarrow (v, s')\}$
 ⟨proof⟩

end

Chapter 16

Example

43 Example Bali program

```
theory Example
imports Eval WellForm
begin
```

The following example Bali program includes:

- class and interface declarations with inheritance, hiding of fields, overriding of methods (with refined result type), array type,
- method call (with dynamic binding), parameter access, return expressions,
- expression statements, sequential composition, literal values, local assignment, local access, field assignment, type cast,
- exception generation and propagation, try and catch statement, throw statement
- instance creation and (default) static initialization

```
package java_lang

public interface HasFoo {
  public Base foo(Base z);
}

public class Base implements HasFoo {
  static boolean arr[] = new boolean[2];
  public HasFoo vee;
  public Base foo(Base z) {
    return z;
  }
}

public class Ext extends Base {
  public int vee;
  public Ext foo(Base z) {
    ((Ext)z).vee = 1;
    return null;
  }
}

public class Main {
  public static void main(String args[]) throws Throwable {
    Base e = new Ext();
    try {e.foo(null); }
    catch(NullPointerException z) {
      while(Ext.arr[2]) ;
    }
  }
}

declare widen.null [intro]
```

lemma *wf-fdecl-def2*: $\bigwedge fd. wf-fdecl\ G\ P\ fd = is-acc-type\ G\ P\ (type\ (snd\ fd))$
 <proof>

declare *wf-fdecl-def2* [iff]

type and expression names

datatype *tnam'* = *HasFoo'* | *Base'* | *Ext'* | *Main'*

datatype *vnam'* = *arr'* | *vee'* | *z'* | *e'*

datatype *label'* = *lab1'*

axiomatization

tnam' :: *tnam'* \Rightarrow *tnam* **and**

vnam' :: *vnam'* \Rightarrow *vname* **and**

label' :: *label'* \Rightarrow *label*

where

inj-tnam' [simp]: $\bigwedge x\ y. (tnam'\ x = tnam'\ y) = (x = y)$ **and**

inj-vnam' [simp]: $\bigwedge x\ y. (vnam'\ x = vnam'\ y) = (x = y)$ **and**

inj-label' [simp]: $\bigwedge x\ y. (label'\ x = label'\ y) = (x = y)$ **and**

surj-tnam': $\bigwedge n. \exists m. n = tnam'\ m$ **and**

surj-vnam': $\bigwedge n. \exists m. n = vnam'\ m$ **and**

surj-label': $\bigwedge n. \exists m. n = label'\ m$

abbreviation

HasFoo :: *qname* **where**

HasFoo == ($\langle pid=java-lang, tid=TName\ (tnam'\ HasFoo') \rangle$)

abbreviation

Base :: *qname* **where**

Base == ($\langle pid=java-lang, tid=TName\ (tnam'\ Base') \rangle$)

abbreviation

Ext :: *qname* **where**

Ext == ($\langle pid=java-lang, tid=TName\ (tnam'\ Ext') \rangle$)

abbreviation

Main :: *qname* **where**

Main == ($\langle pid=java-lang, tid=TName\ (tnam'\ Main') \rangle$)

abbreviation

arr :: *vname* **where**

arr == (*vnam'* *arr'*)

abbreviation

vee :: *vname* **where**

vee == (*vnam'* *vee'*)

abbreviation

z :: *vname* **where**

z == (*vnam'* *z'*)

abbreviation

e :: *vname* **where**

e == (*vnam'* *e'*)

abbreviation

```
lab1:: label where
lab1 == label' lab1'
```

```
lemma neq-Base-Object [simp]: Base≠Object
⟨proof⟩
```

```
lemma neq-Ext-Object [simp]: Ext≠Object
⟨proof⟩
```

```
lemma neq-Main-Object [simp]: Main≠Object
⟨proof⟩
```

```
lemma neq-Base-SXcpt [simp]: Base≠SXcpt xn
⟨proof⟩
```

```
lemma neq-Ext-SXcpt [simp]: Ext≠SXcpt xn
⟨proof⟩
```

```
lemma neq-Main-SXcpt [simp]: Main≠SXcpt xn
⟨proof⟩
```

classes and interfaces

defs

```
Object-mdecls-def: Object-mdecls ≡ []
SXcpt-mdecls-def: SXcpt-mdecls ≡ []
```

axiomatization

```
foo :: mname
```

definition

```
foo-sig :: sig
where foo-sig = (|name=foo,parTs=[Class Base]|)
```

definition

```
foo-mhead :: mhead
where foo-mhead = (|access=Public,static=False,pars=[z],resT=Class Base|)
```

definition

```
Base-foo :: mdecl
where Base-foo = (foo-sig, (|access=Public,static=False,pars=[z],resT=Class Base,
mbody=(|lcls=[],stmt=Return (!!z)|)|))
```

definition Ext-foo :: mdecl

```
where Ext-foo = (foo-sig,
(|access=Public,static=False,pars=[z],resT=Class Ext,
mbody=(|lcls=|
,stmt=Expr({Ext,Ext,False}Cast (Class Ext) (!!z)..vee :=
Lit (Intg 1) ) ;;
Return (Lit Null)|)
|))
```

definition

arr-viewed-from :: *qname* \Rightarrow *qname* \Rightarrow *var*
where *arr-viewed-from* *accC C* = {*accC*,*Base*,*True*}*StatRef* (*ClassT C*)..*arr*

definition

BaseCl :: *class* **where**
BaseCl = (*access*=*Public*,
cfields=[(*arr*, (*access*=*Public*,*static*=*True*,*type*=*PrimT Boolean*.[])),
(*vee*, (*access*=*Public*,*static*=*False*,*type*=*Iface HasFoo* []))],
methods=[*Base-foo*],
init=*Expr*(*arr-viewed-from Base Base*
:=*New* (*PrimT Boolean*)[*Lit* (*Intg 2*)]),
super=*Object*,
superIfs=[*HasFoo*])

definition

ExtCl :: *class* **where**
ExtCl = (*access*=*Public*,
cfields=[(*vee*, (*access*=*Public*,*static*=*False*,*type*= *PrimT Integer*)]),
methods=[*Ext-foo*],
init=*Skip*,
super=*Base*,
superIfs=[])

definition

MainCl :: *class* **where**
MainCl = (*access*=*Public*,
cfields=[],
methods=[],
init=*Skip*,
super=*Object*,
superIfs=[])

definition

HasFooInt :: *iface*
where *HasFooInt* = (*access*=*Public*,*imethods*=[(*foo-sig*, *foo-mhead*)],*isuperIfs*=[])

definition

Ifaces :: *idecl list*
where *Ifaces* = [(*HasFoo*,*HasFooInt*)]

definition

Classes :: *cdecl list*
where *Classes* = [(*Base*,*BaseCl*),(*Ext*,*ExtCl*),(*Main*,*MainCl*)]@*standard-classes*

lemmas *table-classes-defs* =

Classes-def standard-classes-def ObjectC-def SXcptC-def

lemma *table-ifaces* [*simp*]: *table-of Ifaces* = *empty*(*HasFoo* \rightarrow *HasFooInt*)
<*proof*>

lemma *table-classes-Object* [*simp*]:

table-of Classes Object = *Some* (*access*=*Public*,*cfields*=[]
, *methods*=*Object-mdecls*
, *init*=*Skip*,*super*=*undefined*,*superIfs*=[])

<proof>

lemma *table-classes-SXcpt* [simp]:
table-of Classes (SXcpt xn)
 = *Some* (\backslash *access=Public,cfields=* \backslash *,methods=SXcpt-mdecls,*
init=Skip,
super=if xn = Throwable then Object else SXcpt Throwable,
superIfs= \backslash \backslash *)*

<proof>

lemma *table-classes-HasFoo* [simp]: *table-of Classes HasFoo = None*
<proof>

lemma *table-classes-Base* [simp]: *table-of Classes Base = Some BaseCl*
<proof>

lemma *table-classes-Ext* [simp]: *table-of Classes Ext = Some ExtCl*
<proof>

lemma *table-classes-Main* [simp]: *table-of Classes Main = Some MainCl*
<proof>

program

abbreviation

tprg :: *prog* **where**
tprg == (\backslash *ifaces=Ifaces,classes=Classes*)

definition

test :: (*ty*)*list* \Rightarrow *stmt* **where**
test *pTs* = (*e* ::= *NewC Ext*;;
Try Expr({*Main,ClassT Base,IntVir*}!!*e.foo*({*pTs*}[*Lit Null*]))
Catch((*SXcpt NullPointer*) *z*)
(lab1 • *While*(*Acc*
 (*Acc* (*arr-viewed-from Main Ext*).[*Lit* (*Intg 2*)])) *Skip*))

well-structuredness

lemma *not-Object-subcls-any* [elim!]: (*Object, C*) \in (*subcls1 tprg*)⁺ \Longrightarrow *R*
<proof>

lemma *not-Throwable-subcls-SXcpt* [elim!]:
 (*SXcpt Throwable, SXcpt xn*) \in (*subcls1 tprg*)⁺ \Longrightarrow *R*
<proof>

lemma *not-SXcpt-n-subcls-SXcpt-n* [elim!]:
 (*SXcpt xn, SXcpt xn*) \in (*subcls1 tprg*)⁺ \Longrightarrow *R*
<proof>

lemma *not-Base-subcls-Ext* [elim!]: (*Base, Ext*) \in (*subcls1 tprg*)⁺ \Longrightarrow *R*
<proof>

lemma *not-TName-n-subcls-TName-n* [rule-format (no-asm), elim!]:
 ((|pid=java-lang,tid=TName tn|), (|pid=java-lang,tid=TName tn|))
 ∈ (subcls1 tprg)⁺ → R
 ⟨proof⟩

lemma *ws-idecl-HasFoo*: *ws-idecl tprg HasFoo* []
 ⟨proof⟩

lemma *ws-cdecl-Object*: *ws-cdecl tprg Object any*
 ⟨proof⟩

lemma *ws-cdecl-Throwable*: *ws-cdecl tprg (SXcpt Throwable) Object*
 ⟨proof⟩

lemma *ws-cdecl-SXcpt*: *ws-cdecl tprg (SXcpt xn) (SXcpt Throwable)*
 ⟨proof⟩

lemma *ws-cdecl-Base*: *ws-cdecl tprg Base Object*
 ⟨proof⟩

lemma *ws-cdecl-Ext*: *ws-cdecl tprg Ext Base*
 ⟨proof⟩

lemma *ws-cdecl-Main*: *ws-cdecl tprg Main Object*
 ⟨proof⟩

lemmas *ws-cdecls = ws-cdecl-SXcpt ws-cdecl-Object ws-cdecl-Throwable*
ws-cdecl-Base ws-cdecl-Ext ws-cdecl-Main

declare *not-Object-subcls-any* [rule del]
not-Throwable-subcls-SXcpt [rule del]
not-SXcpt-n-subcls-SXcpt-n [rule del]
not-Base-subcls-Ext [rule del] *not-TName-n-subcls-TName-n* [rule del]

lemma *ws-idecl-all*:
 $G=tprg \implies (\forall (I,i) \in \text{set Ifaces}. \text{ws-idecl } G \ I \ (\text{isuperIfs } i))$
 ⟨proof⟩

lemma *ws-cdecl-all*: $G=tprg \implies (\forall (C,c) \in \text{set Classes}. \text{ws-cdecl } G \ C \ (\text{super } c))$
 ⟨proof⟩

lemma *ws-tprg*: *ws-prog tprg*
 ⟨proof⟩

misc program properties (independent of well-structuredness)

lemma *single-iface* [simp]: *is-iface tprg I = (I = HasFoo)*
 ⟨proof⟩

lemma *empty-subint1* [simp]: *subint1 tprg = {}*
 ⟨proof⟩

lemma *unique-ifaces*: *unique Ifaces*
 ⟨proof⟩

lemma *unique-classes*: *unique Classes*
 ⟨proof⟩

lemma *SXcpt-subcls-Throwable* [simp]: *tprg ⊢ SXcpt xn ≼_C SXcpt Throwable*
 ⟨proof⟩

lemma *Ext-subclseq-Base* [simp]: *tprg ⊢ Ext ≼_C Base*
 ⟨proof⟩

lemma *Ext-subcls-Base* [simp]: *tprg ⊢ Ext ≺_C Base*
 ⟨proof⟩

fields and method lookup

lemma *fields-tprg-Object* [simp]: *DeclConcepts.fields tprg Object = []*
 ⟨proof⟩

lemma *fields-tprg-Throwable* [simp]:
DeclConcepts.fields tprg (SXcpt Throwable) = []
 ⟨proof⟩

lemma *fields-tprg-SXcpt* [simp]: *DeclConcepts.fields tprg (SXcpt xn) = []*
 ⟨proof⟩

lemmas *fields-rec' = fields-rec* [OF - *ws-tprg*]

lemma *fields-Base* [simp]:
DeclConcepts.fields tprg Base
 = [((*arr*, *Base*), (|*access*=*Public*, *static*=*True*, *type*=*PrimT Boolean*.[])),
 ((*vee*, *Base*), (|*access*=*Public*, *static*=*False*, *type*=*Iface HasFoo* []))]
 ⟨proof⟩

lemma *fields-Ext* [simp]:
DeclConcepts.fields tprg Ext
 = [((*vee*, *Ext*), (|*access*=*Public*, *static*=*False*, *type*= *PrimT Integer*))]
 @ *DeclConcepts.fields tprg Base*
 ⟨proof⟩

lemmas *imethds-rec'* = *imethds-rec* [*OF - ws-tprg*]

lemmas *methd-rec'* = *methd-rec* [*OF - ws-tprg*]

lemma *imethds-HasFoo* [*simp*]:

imethds tprg HasFoo = *Option.set* \circ *empty*(*foo-sig* \mapsto (*HasFoo*, *foo-mhead*))

\langle *proof* \rangle

lemma *methd-tprg-Object* [*simp*]: *methd tprg Object* = *empty*

\langle *proof* \rangle

lemma *methd-Base* [*simp*]:

methd tprg Base = *table-of* $[(\lambda(s,m). (s, Base, m)) Base\text{-}foo]$

\langle *proof* \rangle

lemma *memberid-Base-foo-simp* [*simp*]:

memberid (*mdecl Base-foo*) = *mid foo-sig*

\langle *proof* \rangle

lemma *memberid-Ext-foo-simp* [*simp*]:

memberid (*mdecl Ext-foo*) = *mid foo-sig*

\langle *proof* \rangle

lemma *Base-declares-foo*:

tprg \vdash *mdecl Base-foo declared-in Base*

\langle *proof* \rangle

lemma *foo-sig-not-undeclared-in-Base*:

\neg *tprg* \vdash *mid foo-sig undeclared-in Base*

\langle *proof* \rangle

lemma *Ext-declares-foo*:

tprg \vdash *mdecl Ext-foo declared-in Ext*

\langle *proof* \rangle

lemma *foo-sig-not-undeclared-in-Ext*:

\neg *tprg* \vdash *mid foo-sig undeclared-in Ext*

\langle *proof* \rangle

lemma *Base-foo-not-inherited-in-Ext*:

\neg *tprg* \vdash *Ext inherits (Base, mdecl Base-foo)*

\langle *proof* \rangle

lemma *Ext-method-inheritance*:

filter-tab ($\lambda sig m. tprg \vdash Ext \text{ inherits method sig } m$)

(*empty*(*fst* $((\lambda(s, m). (s, Base, m)) Base\text{-}foo)$ \mapsto

snd $((\lambda(s, m). (s, Base, m)) Base\text{-}foo)$))

= *empty*

\langle *proof* \rangle

lemma *methd-Ext* [simp]: *methd tprg Ext = table-of* $[(\lambda(s,m). (s, Ext, m)) Ext\text{-foo}]$
 ⟨proof⟩

accessibility

lemma *classesDefined*:
 $\llbracket \text{class tprg } C = \text{Some } c; C \neq \text{Object} \rrbracket \implies \exists \text{ sc. class tprg (super } c) = \text{Some } sc$
 ⟨proof⟩

lemma *superclassesBase* [simp]: *superclasses tprg Base* = { *Object* }
 ⟨proof⟩

lemma *superclassesExt* [simp]: *superclasses tprg Ext* = { *Base, Object* }
 ⟨proof⟩

lemma *superclassesMain* [simp]: *superclasses tprg Main* = { *Object* }
 ⟨proof⟩

lemma *HasFoo-accessible* [simp]: *tprg* ⊢ (*Iface HasFoo*) *accessible-in P*
 ⟨proof⟩

lemma *HasFoo-is-acc-iface* [simp]: *is-acc-iface tprg P HasFoo*
 ⟨proof⟩

lemma *HasFoo-is-acc-type* [simp]: *is-acc-type tprg P (Iface HasFoo)*
 ⟨proof⟩

lemma *Base-accessible* [simp]: *tprg* ⊢ (*Class Base*) *accessible-in P*
 ⟨proof⟩

lemma *Base-is-acc-class* [simp]: *is-acc-class tprg P Base*
 ⟨proof⟩

lemma *Base-is-acc-type* [simp]: *is-acc-type tprg P (Class Base)*
 ⟨proof⟩

lemma *Ext-accessible* [simp]: *tprg* ⊢ (*Class Ext*) *accessible-in P*
 ⟨proof⟩

lemma *Ext-is-acc-class* [simp]: *is-acc-class tprg P Ext*
 ⟨proof⟩

lemma *Ext-is-acc-type* [simp]: *is-acc-type tprg P (Class Ext)*

$\langle \text{proof} \rangle$

lemma *accmethd-tprg-Object* [simp]: *accmethd tprg S Object = empty*

$\langle \text{proof} \rangle$

lemma *snd-special-simp*: *snd (($\lambda(s, m).$ (s, a, m)) x) = (a, snd x)*

$\langle \text{proof} \rangle$

lemma *fst-special-simp*: *fst (($\lambda(s, m).$ (s, a, m)) x) = fst x*

$\langle \text{proof} \rangle$

lemma *foo-sig-undeclared-in-Object*:

tprg \vdash *mid foo-sig undeclared-in Object*

$\langle \text{proof} \rangle$

lemma *unique-sig-Base-foo*:

tprg \vdash *mdecl (sig, snd Base-foo) declared-in Base \implies sig=foo-sig*

$\langle \text{proof} \rangle$

lemma *Base-foo-no-override*:

tprg, sig \vdash *(Base, (snd Base-foo)) overrides old \implies P*

$\langle \text{proof} \rangle$

lemma *Base-foo-no-stat-override*:

tprg, sig \vdash *(Base, (snd Base-foo)) overrides_S old \implies P*

$\langle \text{proof} \rangle$

lemma *Base-foo-no-hide*:

tprg, sig \vdash *(Base, (snd Base-foo)) hides old \implies P*

$\langle \text{proof} \rangle$

lemma *Ext-foo-no-hide*:

tprg, sig \vdash *(Ext, (snd Ext-foo)) hides old \implies P*

$\langle \text{proof} \rangle$

lemma *unique-sig-Ext-foo*:

tprg \vdash *mdecl (sig, snd Ext-foo) declared-in Ext \implies sig=foo-sig*

$\langle \text{proof} \rangle$

lemma *Ext-foo-override*:

tprg, sig \vdash *(Ext, (snd Ext-foo)) overrides old*

\implies *old = (Base, (snd Base-foo))*

$\langle \text{proof} \rangle$

lemma *Ext-foo-stat-override*:

tprg, sig \vdash *(Ext, (snd Ext-foo)) overrides_S old*

$\implies old = (Base, (snd\ Base-foo))$
 ⟨proof⟩

lemma *Base-foo-member-of-Base*:
 $tprg \vdash (Base, mdecl\ Base-foo)\ member-of\ Base$
 ⟨proof⟩

lemma *Base-foo-member-in-Base*:
 $tprg \vdash (Base, mdecl\ Base-foo)\ member-in\ Base$
 ⟨proof⟩

lemma *Ext-foo-member-of-Ext*:
 $tprg \vdash (Ext, mdecl\ Ext-foo)\ member-of\ Ext$
 ⟨proof⟩

lemma *Ext-foo-member-in-Ext*:
 $tprg \vdash (Ext, mdecl\ Ext-foo)\ member-in\ Ext$
 ⟨proof⟩

lemma *Base-foo-permits-acc*:
 $tprg \vdash (Base, mdecl\ Base-foo)\ in\ Base\ permits-acc-from\ S$
 ⟨proof⟩

lemma *Base-foo-accessible [simp]*:
 $tprg \vdash (Base, mdecl\ Base-foo)\ of\ Base\ accessible-from\ S$
 ⟨proof⟩

lemma *Base-foo-dyn-accessible [simp]*:
 $tprg \vdash (Base, mdecl\ Base-foo)\ in\ Base\ dyn-accessible-from\ S$
 ⟨proof⟩

lemma *accmethd-Base [simp]*:
 $accmethd\ tprg\ S\ Base = methd\ tprg\ Base$
 ⟨proof⟩

lemma *Ext-foo-permits-acc*:
 $tprg \vdash (Ext, mdecl\ Ext-foo)\ in\ Ext\ permits-acc-from\ S$
 ⟨proof⟩

lemma *Ext-foo-accessible [simp]*:
 $tprg \vdash (Ext, mdecl\ Ext-foo)\ of\ Ext\ accessible-from\ S$
 ⟨proof⟩

lemma *Ext-foo-dyn-accessible [simp]*:
 $tprg \vdash (Ext, mdecl\ Ext-foo)\ in\ Ext\ dyn-accessible-from\ S$
 ⟨proof⟩

lemma *Ext-foo-overrides-Base-foo*:

$\text{tpg}\vdash(\text{Ext},\text{Ext-foo}) \text{ overrides } (\text{Base},\text{Base-foo})$
 $\langle\text{proof}\rangle$

lemma *accmethd-Ext [simp]*:

$\text{accmethd tprg } S \text{ Ext} = \text{methd tprg } \text{Ext}$
 $\langle\text{proof}\rangle$

lemma *cls-Ext*: $\text{class tprg } \text{Ext} = \text{Some ExtCl}$

$\langle\text{proof}\rangle$

lemma *dynmethd-Ext-foo*:

$\text{dynmethd tprg } \text{Base } \text{Ext} (\text{name} = \text{foo}, \text{parTs} = [\text{Class } \text{Base}])$
 $= \text{Some } (\text{Ext}, \text{snd } \text{Ext-foo})$
 $\langle\text{proof}\rangle$

lemma *Base-fields-accessible[simp]*:

$\text{accfield tprg } S \text{ Base}$
 $= \text{table-of}((\text{map } (\lambda((n,d),f).(n,(d,f)))) (\text{DeclConcepts.fields tprg } \text{Base}))$
 $\langle\text{proof}\rangle$

lemma *arr-member-of-Base*:

$\text{tpg}\vdash(\text{Base}, \text{fdecl } (\text{arr},$
 $\quad (\text{access} = \text{Public}, \text{static} = \text{True}, \text{type} = \text{PrimT Boolean.[]]))$
 $\text{member-of } \text{Base}$
 $\langle\text{proof}\rangle$

lemma *arr-member-in-Base*:

$\text{tpg}\vdash(\text{Base}, \text{fdecl } (\text{arr},$
 $\quad (\text{access} = \text{Public}, \text{static} = \text{True}, \text{type} = \text{PrimT Boolean.[]]))$
 $\text{member-in } \text{Base}$
 $\langle\text{proof}\rangle$

lemma *arr-member-of-Ext*:

$\text{tpg}\vdash(\text{Base}, \text{fdecl } (\text{arr},$
 $\quad (\text{access} = \text{Public}, \text{static} = \text{True}, \text{type} = \text{PrimT Boolean.[]]))$
 $\text{member-of } \text{Ext}$
 $\langle\text{proof}\rangle$

lemma *arr-member-in-Ext*:

$\text{tpg}\vdash(\text{Base}, \text{fdecl } (\text{arr},$
 $\quad (\text{access} = \text{Public}, \text{static} = \text{True}, \text{type} = \text{PrimT Boolean.[]]))$
 $\text{member-in } \text{Ext}$
 $\langle\text{proof}\rangle$

lemma *Ext-fields-accessible[simp]*:

$\text{accfield tprg } S \text{ Ext}$
 $= \text{table-of}((\text{map } (\lambda((n,d),f).(n,(d,f)))) (\text{DeclConcepts.fields tprg } \text{Ext}))$
 $\langle\text{proof}\rangle$

lemma *arr-Base-dyn-accessible* [simp]:
 tprg-(Base, fdecl (arr, (|access=Public,static=True ,type=PrimT Boolean.[])))
 in Base dyn-accessible-from S
 ⟨proof⟩

lemma *arr-Ext-dyn-accessible*[simp]:
 tprg-(Base, fdecl (arr, (|access=Public,static=True ,type=PrimT Boolean.[])))
 in Ext dyn-accessible-from S
 ⟨proof⟩

lemma *array-of-PrimT-acc* [simp]:
 is-acc-type tprg java-lang (PrimT t.[])
 ⟨proof⟩

lemma *PrimT-acc* [simp]:
 is-acc-type tprg java-lang (PrimT t)
 ⟨proof⟩

lemma *Object-acc* [simp]:
 is-acc-class tprg java-lang Object
 ⟨proof⟩

well-formedness

lemma *wf-HasFoo*: wf-idecl tprg (HasFoo, HasFooInt)
 ⟨proof⟩

declare *member-is-static-simp* [simp]
declare *wt.Skip* [rule del] *wt.Init* [rule del]
 ⟨ML⟩
lemmas *wtIs* = *wt-Call wt-Super wt-FVar wt-StatRef wt-intros*
lemmas *daIs* = *assigned.select-convs da-Skip da-NewC da-Lit da-Super da.intros*

lemmas *Base-foo-defs* = *Base-foo-def foo-sig-def foo-mhead-def*
lemmas *Ext-foo-defs* = *Ext-foo-def foo-sig-def*

lemma *wf-Base-foo*: wf-mdecl tprg Base Base-foo
 ⟨proof⟩

lemma *wf-Ext-foo*: wf-mdecl tprg Ext Ext-foo
 ⟨proof⟩

declare *mhead-resTy-simp* [simp add]

lemma *wf-BaseC*: wf-cdecl tprg (Base,BaseCl)
 ⟨proof⟩

lemma *wf-ExtC*: *wf-cdecl tprg (Ext,ExtCl)*
 ⟨proof⟩

lemma *wf-MainC*: *wf-cdecl tprg (Main,MainCl)*
 ⟨proof⟩

lemma *wf-idecl-all*: *p=tprg ⇒ Ball (set Ifaces) (wf-idecl p)*
 ⟨proof⟩

lemma *wf-cdecl-all-standard-classes*:
Ball (set standard-classes) (wf-cdecl tprg)
 ⟨proof⟩

lemma *wf-cdecl-all*: *p=tprg ⇒ Ball (set Classes) (wf-cdecl p)*
 ⟨proof⟩

theorem *wf-tprg*: *wf-prog tprg*
 ⟨proof⟩

max spec

lemma *appl-methods-Base-foo*:
appl-methods tprg S (ClassT Base) (⟦name=foo, parTs=[NT]⟧) =
{((ClassT Base, (⟦access=Public,static=False,pars=[z],resT=Class Base⟧))
,[Class Base])}
 ⟨proof⟩

lemma *max-spec-Base-foo*: *max-spec tprg S (ClassT Base) (⟦name=foo,parTs=[NT]⟧) =*
{((ClassT Base, (⟦access=Public,static=False,pars=[z],resT=Class Base⟧))
, [Class Base])}
 ⟨proof⟩

well-typedness

schematic-lemma *wt-test*: *(⟦prg=tprg,cls=Main,lcl=empty(VName e↦Class Base)⟧)⊢-test ?pTs::√*
 ⟨proof⟩

definite assignment

schematic-lemma *da-test*: *(⟦prg=tprg,cls=Main,lcl=empty(VName e↦Class Base)⟧)*
⊢{ } ≫⟨test ?pTs⟩ ≫ (⟦nrm={ VName e },brk=λ l. UNIV⟧)
 ⟨proof⟩

execution

lemma *alloc-one*: *∧a obj. ⟦the (new-Addr h) = a; atleast-free h (Suc n)⟧ ⇒*
new-Addr h = Some a ∧ atleast-free (h(a↦obj)) n
 ⟨proof⟩

declare *fvar-def2 [simp] avar-def2 [simp] init-lvars-def2 [simp]*
declare *init-obj-def [simp] var-tys-def [simp] fields-table-def [simp]*
declare *BaseCl-def [simp] ExtCl-def [simp] Ext-foo-def [simp]*

Base-foo-defs [simp]

<ML>

lemmas *eval-Is = eval-Init eval-StatRef AbruptIs eval-intros*

axiomatization

a :: *loc* **and**

b :: *loc* **and**

c :: *loc*

abbreviation *one* == *Suc 0*

abbreviation *two* == *Suc one*

abbreviation *three* == *Suc two*

abbreviation *four* == *Suc three*

abbreviation

obj-a == (λ tag=Arr (PrimT Boolean) 2
,values= empty(Inr 0 \mapsto Bool False)(Inr 1 \mapsto Bool False))

abbreviation

obj-b == (λ tag=CInst Ext
,values=(empty(Inl (vee, Base) \mapsto Null)
(Inl (vee, Ext) \mapsto Intg 0)))

abbreviation

obj-c == (λ tag=CInst (SXcpt NullPointer),values=CONST empty)

abbreviation *arr-N* == empty(Inl (arr, Base) \mapsto Null)

abbreviation *arr-a* == empty(Inl (arr, Base) \mapsto Addr a)

abbreviation

globs1 == empty(Inr Ext \mapsto (λ tag=undefined, values=empty))
(Inr Base \mapsto (λ tag=undefined, values=arr-N))
(Inr Object \mapsto (λ tag=undefined, values=empty))

abbreviation

globs2 == empty(Inr Ext \mapsto (λ tag=undefined, values=empty))
(Inr Object \mapsto (λ tag=undefined, values=empty))
(Inl a \mapsto obj-a)
(Inr Base \mapsto (λ tag=undefined, values=arr-a))

abbreviation *globs3* == *globs2*(Inl b \mapsto obj-b)

abbreviation *globs8* == *globs3*(Inl c \mapsto obj-c)

abbreviation *locs3* == empty(VName e \mapsto Addr b)

abbreviation *locs8* == *locs3*(VName z \mapsto Addr c)

abbreviation *s0* == *st empty empty*

abbreviation *s0'* == *Norm s0*

abbreviation *s1* == *st globs1 empty*

abbreviation *s1'* == *Norm s1*

abbreviation *s2* == *st globs2 empty*

abbreviation *s2'* == *Norm s2*

abbreviation *s3* == *st globs3 locs3*

abbreviation *s3'* == *Norm s3*

abbreviation *s7'* == (Some (Xcpt (Std NullPointer)), *s3*)

abbreviation *s8* == *st globs8 locs8*

abbreviation *s8'* == *Norm s8*

abbreviation *s9'* == (Some (Xcpt (Std IndOutBound)), *s8*)

```
declare Pair-eq [simp del]  
schematic-lemma exec-test:  
[[the (new-Addr (heap s1)) = a;  
  the (new-Addr (heap ?s2)) = b;  
  the (new-Addr (heap ?s3)) = c]]  $\implies$   
  atleast-free (heap s0) four  $\implies$   
  tprg  $\vdash$  s0'  $\text{-test}$  [Class Base]  $\rightarrow$  ?s9'  
<proof>  
declare Pair-eq [simp]  
end
```


Chapter 17

Conform

44 Conformance notions for the type soundness proof for Java

theory *Conform* imports *State* begin

design issues:

- `lconf` allows for (arbitrary) inaccessible values
- "conforms" does not directly imply that the dynamic types of all objects on the heap are indeed existing classes. Yet this can be inferred for all referenced objs.

type-synonym $env' = prog \times (lname, ty) \text{ table}$

extension of global store

definition $gext :: st \Rightarrow st \Rightarrow bool$ ($- \leq | -$ [71,71] 70) **where**
 $s \leq | s' \equiv \forall r. \forall obj \in globs\ s\ r: \exists obj' \in globs\ s'\ r: tag\ obj' = tag\ obj$

For the the proof of type soundness we will need the property that during execution, objects are not lost and moreover retain the values of their tags. So the object store grows conservatively. Note that if we considered garbage collection, we would have to restrict this property to accessible objects.

lemma *gext-objD*:

$\llbracket s \leq | s'; globs\ s\ r = Some\ obj \rrbracket$
 $\implies \exists obj'. globs\ s'\ r = Some\ obj' \wedge tag\ obj' = tag\ obj$
 $\langle proof \rangle$

lemma *rev-gext-objD*:

$\llbracket globs\ s\ r = Some\ obj; s \leq | s' \rrbracket$
 $\implies \exists obj'. globs\ s'\ r = Some\ obj' \wedge tag\ obj' = tag\ obj$
 $\langle proof \rangle$

lemma *init-class-obj-inited*:

$init\ class\ obj\ G\ C\ s1 \leq | s2 \implies inited\ C\ (globs\ s2)$
 $\langle proof \rangle$

lemma *gext-refl* [*intro!*, *simp*]: $s \leq | s$

$\langle proof \rangle$

lemma *gext-gupd* [*simp*, *elim!*]: $\bigwedge s. globs\ s\ r = None \implies s \leq | gupd(r \mapsto x)s$

$\langle proof \rangle$

lemma *gext-new* [*simp*, *elim!*]: $\bigwedge s. globs\ s\ r = None \implies s \leq | init\ obj\ G\ oi\ r\ s$

$\langle proof \rangle$

lemma *gext-trans* [*elim*]: $\bigwedge X. \llbracket s \leq | s'; s' \leq | s'' \rrbracket \implies s \leq | s''$

$\langle proof \rangle$

lemma *gext-upd-gobj* [*intro!*]: $s \leq | upd\ gobj\ r\ n\ v\ s$

$\langle proof \rangle$

lemma *gext-cong1* [*simp*]: $set\ locals\ l\ s1 \leq | s2 = s1 \leq | s2$

<proof>

lemma *gext-cong2* [simp]: $s1 \leq |set-locals\ l\ s2 = s1 \leq |s2$

<proof>

lemma *gext-lupd1* [simp]: $lupd(vn \mapsto v) s1 \leq |s2 = s1 \leq |s2$

<proof>

lemma *gext-lupd2* [simp]: $s1 \leq |lupd(vn \mapsto v) s2 = s1 \leq |s2$

<proof>

lemma *inited-gext*: $\llbracket inited\ C\ (globs\ s);\ s \leq |s' \rrbracket \implies inited\ C\ (globs\ s')$

<proof>

value conformance

definition *conf* :: $prog \Rightarrow st \Rightarrow val \Rightarrow ty \Rightarrow bool$ ($-, +, \dots, \preceq$ [71, 71, 71, 71] 70)

where $G, s \vdash v :: \preceq T = (\exists T' \in typeof\ (\lambda a. Option.map\ obj-ty\ (heap\ s\ a))\ v:G \vdash T' \preceq T)$

lemma *conf-cong* [simp]: $G, set-locals\ l\ s \vdash v :: \preceq T = G, s \vdash v :: \preceq T$

<proof>

lemma *conf-lupd* [simp]: $G, lupd(vn \mapsto va) s \vdash v :: \preceq T = G, s \vdash v :: \preceq T$

<proof>

lemma *conf-PrimT* [simp]: $\forall dt. typeof\ dt\ v = Some\ (PrimT\ t) \implies G, s \vdash v :: \preceq PrimT\ t$

<proof>

lemma *conf-Boolean*: $G, s \vdash v :: \preceq PrimT\ Boolean \implies \exists b. v = Bool\ b$

<proof>

lemma *conf-litval* [rule-format (no-asm)]:

$typeof\ (\lambda a. None)\ v = Some\ T \longrightarrow G, s \vdash v :: \preceq T$

<proof>

lemma *conf-Null* [simp]: $G, s \vdash Null :: \preceq T = G \vdash NT \preceq T$

<proof>

lemma *conf-Addr*:

$G, s \vdash Addr\ a :: \preceq T = (\exists obj. heap\ s\ a = Some\ obj \wedge G \vdash obj-ty\ obj \preceq T)$

<proof>

lemma *conf-AddrI*: $\llbracket heap\ s\ a = Some\ obj; G \vdash obj-ty\ obj \preceq T \rrbracket \implies G, s \vdash Addr\ a :: \preceq T$

<proof>

lemma *lconf-ext*: $\llbracket G, s \vdash l[::\preceq]L; G, s \vdash v::\preceq T \rrbracket \implies G, s \vdash l(vn \mapsto v)[::\preceq]L(vn \mapsto T)$
 ⟨proof⟩

lemma *lconf-map-sum* [*simp*]:
 $G, s \vdash l1 (+) l2[::\preceq]L1 (+) L2 = (G, s \vdash l1[::\preceq]L1 \wedge G, s \vdash l2[::\preceq]L2)$
 ⟨proof⟩

lemma *lconf-ext-list* [*rule-format* (*no-asm*)]:
 $\bigwedge X. \llbracket G, s \vdash l[::\preceq]L \rrbracket \implies$
 $\forall vs Ts. \text{distinct } vns \longrightarrow \text{length } Ts = \text{length } vns$
 $\longrightarrow \text{list-all2 } (\text{conf } G \ s) \ vs \ Ts \longrightarrow G, s \vdash l(vns \mapsto vs)[::\preceq]L(vns \mapsto Ts)$
 ⟨proof⟩

lemma *lconf-deallocL*: $\llbracket G, s \vdash l[::\preceq]L(vn \mapsto T); L \ vn = \text{None} \rrbracket \implies G, s \vdash l[::\preceq]L$
 ⟨proof⟩

lemma *lconf-geat* [*elim*]: $\llbracket G, s \vdash l[::\preceq]L; s \leq |s| \rrbracket \implies G, s \vdash l[::\preceq]L$
 ⟨proof⟩

lemma *lconf-empty* [*simp*, *intro!*]: $G, s \vdash vs[::\preceq] \text{empty}$
 ⟨proof⟩

lemma *lconf-init-vals* [*intro!*]:
 $\forall n. \forall T \in fs \ n:\text{is-type } G \ T \implies G, s \vdash \text{init-vals } fs[::\preceq]fs$
 ⟨proof⟩

weak value list conformance

Only if the value is defined it has to conform to its type. This is the contribution of the definite assignment analysis to the notion of conformance. The definite assignment analysis ensures that the program only attempts to access local variables that actually have a defined value in the state. So conformance must only ensure that the defined values are of the right type, and not also that the value is defined.

definition

wlconf :: *prog* \Rightarrow *st* \Rightarrow (*a*, *val*) *table* \Rightarrow (*a*, *ty*) *table* \Rightarrow *bool* ($\neg, \vdash, \sim[::\preceq]$ - [71,71,71,71] 70)
where $G, s \vdash vs[\sim[::\preceq]Ts = (\forall n. \forall T \in Ts \ n: \forall v \in vs \ n: G, s \vdash v::\preceq T)$

lemma *wlconfD*: $\llbracket G, s \vdash vs[\sim[::\preceq]Ts; Ts \ n = \text{Some } T; vs \ n = \text{Some } v \rrbracket \implies G, s \vdash v::\preceq T$
 ⟨proof⟩

lemma *wlconf-cong* [*simp*]: $\bigwedge s. G, \text{set-locals } x \ s \vdash l[\sim[::\preceq]L = G, s \vdash l[\sim[::\preceq]L$
 ⟨proof⟩

lemma *wlconf-lupd* [*simp*]: $G, \text{lupd}(vn \mapsto v) \ s \vdash l[\sim[::\preceq]L = G, s \vdash l[\sim[::\preceq]L$

<proof>

lemma *wlconf-upd*: $\llbracket G, s \vdash l[\sim::\preceq]L; G, s \vdash v::\preceq T; L \text{ vn} = \text{Some } T \rrbracket \implies G, s \vdash l(\text{vn} \mapsto v)[\sim::\preceq]L$

<proof>

lemma *wlconf-ext*: $\llbracket G, s \vdash l[\sim::\preceq]L; G, s \vdash v::\preceq T \rrbracket \implies G, s \vdash l(\text{vn} \mapsto v)[\sim::\preceq]L(\text{vn} \mapsto T)$

<proof>

lemma *wlconf-map-sum* [*simp*]:

$G, s \vdash l1 (+) l2[\sim::\preceq]L1 (+) L2 = (G, s \vdash l1[\sim::\preceq]L1 \wedge G, s \vdash l2[\sim::\preceq]L2)$

<proof>

lemma *wlconf-ext-list* [*rule-format (no-asm)*]:

$\bigwedge X. \llbracket G, s \vdash l[\sim::\preceq]L \rrbracket \implies \forall \text{ vs } Ts. \text{distinct vns} \longrightarrow \text{length } Ts = \text{length vns} \longrightarrow \text{list-all2 (conf } G \text{ s) vs } Ts \longrightarrow G, s \vdash l(\text{vns}[\mapsto] \text{vs})[\sim::\preceq]L(\text{vns}[\mapsto] \text{Ts})$

<proof>

lemma *wlconf-deallocL*: $\llbracket G, s \vdash l[\sim::\preceq]L(\text{vn} \mapsto T); L \text{ vn} = \text{None} \rrbracket \implies G, s \vdash l[\sim::\preceq]L$

<proof>

lemma *wlconf-geat* [*elim*]: $\llbracket G, s \vdash l[\sim::\preceq]L; s \leq |s'| \rrbracket \implies G, s \uparrow l[\sim::\preceq]L$

<proof>

lemma *wlconf-empty* [*simp, intro!*]: $G, s \vdash \text{vs}[\sim::\preceq] \text{empty}$

<proof>

lemma *wlconf-empty-vals*: $G, s \vdash \text{empty}[\sim::\preceq] \text{ts}$

<proof>

lemma *wlconf-init-vals* [*intro!*]:

$\forall n. \forall T \in \text{fs } n: \text{is-type } G \text{ } T \implies G, s \vdash \text{init-vals } \text{fs}[\sim::\preceq] \text{fs}$

<proof>

lemma *lconf-wlconf*:

$G, s \vdash l[\preceq]L \implies G, s \vdash l[\sim::\preceq]L$

<proof>

object conformance

definition

$\text{oconf} :: \text{prog} \Rightarrow \text{st} \Rightarrow \text{obj} \Rightarrow \text{oref} \Rightarrow \text{bool}$ ($-, +, \preceq, \sqrt{-}$ [71, 71, 71, 71] 70) **where**
 $(G, s \vdash \text{obj}::\preceq\sqrt{r}) = (G, s \vdash \text{values } \text{obj}[\preceq] \text{var-tys } G \text{ (tag } \text{obj}) } r \wedge$
 (case r of
 Heap $a \Rightarrow \text{is-type } G \text{ (obj-ty } \text{obj})$)

| Stat C ⇒ True))

lemma *oconf-is-type*: $G, s \vdash \text{obj} :: \preceq \sqrt{r} \text{Heap } a \implies \text{is-type } G \text{ (obj-ty obj)}$
 ⟨proof⟩

lemma *oconf-lconf*: $G, s \vdash \text{obj} :: \preceq \sqrt{r} \implies G, s \vdash \text{values obj} [:: \preceq] \text{var-tys } G \text{ (tag obj) } r$
 ⟨proof⟩

lemma *oconf-cong [simp]*: $G, \text{set-locals } l \vdash \text{obj} :: \preceq \sqrt{r} = G, s \vdash \text{obj} :: \preceq \sqrt{r}$
 ⟨proof⟩

lemma *oconf-init-obj-lemma*:

$\llbracket \wedge C \text{ c. class } G \text{ C} = \text{Some } c \implies \text{unique (DeclConcepts.fields } G \text{ C)}$;
 $\wedge C \text{ c f fld. } \llbracket \text{class } G \text{ C} = \text{Some } c$;
 $\text{table-of (DeclConcepts.fields } G \text{ C) } f = \text{Some fld} \rrbracket$
 $\implies \text{is-type } G \text{ (type fld)}$;
 (case r of
 $\text{Heap } a \implies \text{is-type } G \text{ (obj-ty obj)}$
 $| \text{Stat } C \implies \text{is-class } G \text{ C}$)
 $\rrbracket \implies G, s \vdash \text{obj} (\text{values} := \text{init-vals (var-tys } G \text{ (tag obj) } r)) :: \preceq \sqrt{r}$
 ⟨proof⟩

state conformance

definition

conforms :: $\text{state} \Rightarrow \text{env}' \Rightarrow \text{bool} \text{ (-} :: \preceq \text{- [71,71] 70)}$ **where**
 $\text{xs} :: \preceq E =$
 $(\text{let } (G, L) = E; s = \text{snd } \text{xs}; l = \text{locals } s \text{ in}$
 $(\forall r. \forall \text{obj} \in \text{globs } s \text{ r: } G, s \vdash \text{obj} :: \preceq \sqrt{r}) \wedge G, s \vdash l [\sim :: \preceq] L \wedge$
 $(\forall a. \text{fst } \text{xs} = \text{Some} (\text{Xcpt (Loc } a)) \longrightarrow G, s \vdash \text{Addr } a :: \preceq \text{Class (SXcpt Throwable)}) \wedge$
 $(\text{fst } \text{xs} = \text{Some} (\text{Jump Ret}) \longrightarrow l \text{ Result} \neq \text{None}))$

conforms

lemma *conforms-globsD*:

$\llbracket (x, s) :: \preceq (G, L); \text{globs } s \text{ r} = \text{Some obj} \rrbracket \implies G, s \vdash \text{obj} :: \preceq \sqrt{r}$
 ⟨proof⟩

lemma *conforms-localD*: $(x, s) :: \preceq (G, L) \implies G, s \vdash \text{locals } s [\sim :: \preceq] L$
 ⟨proof⟩

lemma *conforms-XcptLocD*: $\llbracket (x, s) :: \preceq (G, L); x = \text{Some} (\text{Xcpt (Loc } a)) \rrbracket \implies$
 $G, s \vdash \text{Addr } a :: \preceq \text{Class (SXcpt Throwable)}$
 ⟨proof⟩

lemma *conforms-RetD*: $\llbracket (x, s) :: \preceq (G, L); x = \text{Some} (\text{Jump Ret}) \rrbracket \implies$
 $(\text{locals } s) \text{ Result} \neq \text{None}$
 ⟨proof⟩

lemma *conforms-RefTD*:

$\llbracket G, s \vdash a' :: \preceq_{\text{RefT}} t; a' \neq \text{Null}; (x, s) :: \preceq(G, L) \rrbracket \implies$
 $\exists a \text{ obj. } a' = \text{Addr } a \wedge \text{globs } s (\text{Inl } a) = \text{Some obj} \wedge$
 $G \vdash \text{obj-ty obj} \preceq_{\text{RefT}} t \wedge \text{is-type } G (\text{obj-ty obj})$
 <proof>

lemma conforms-Jump [iff]:
 $j = \text{Ret} \longrightarrow \text{locals } s \text{ Result} \neq \text{None}$
 $\implies ((\text{Some } (\text{Jump } j), s) :: \preceq(G, L)) = (\text{Norm } s :: \preceq(G, L))$
 <proof>

lemma conforms-StdXcpt [iff]:
 $((\text{Some } (\text{Xcpt } (\text{Std } xn)), s) :: \preceq(G, L)) = (\text{Norm } s :: \preceq(G, L))$
 <proof>

lemma conforms-Err [iff]:
 $((\text{Some } (\text{Error } e), s) :: \preceq(G, L)) = (\text{Norm } s :: \preceq(G, L))$
 <proof>

lemma conforms-raise-if [iff]:
 $((\text{raise-if } c \text{ xn } x, s) :: \preceq(G, L)) = ((x, s) :: \preceq(G, L))$
 <proof>

lemma conforms-error-if [iff]:
 $((\text{error-if } c \text{ err } x, s) :: \preceq(G, L)) = ((x, s) :: \preceq(G, L))$
 <proof>

lemma conforms-NormI: $(x, s) :: \preceq(G, L) \implies \text{Norm } s :: \preceq(G, L)$
 <proof>

lemma conforms-absorb [rule-format]:
 $(a, b) :: \preceq(G, L) \longrightarrow (\text{absorb } j \ a, b) :: \preceq(G, L)$
 <proof>

lemma conformsI: $\llbracket \forall r. \forall \text{obj} \in \text{globs } s \ r: G, s \vdash \text{obj} :: \preceq \sqrt{r};$
 $G, s \vdash \text{locals } s [\sim :: \preceq] L;$
 $\forall a. x = \text{Some } (\text{Xcpt } (\text{Loc } a)) \longrightarrow G, s \vdash \text{Addr } a :: \preceq \text{Class } (\text{SXcpt } \text{Throwable});$
 $x = \text{Some } (\text{Jump } \text{Ret}) \longrightarrow \text{locals } s \text{ Result} \neq \text{None} \rrbracket \implies$
 $(x, s) :: \preceq(G, L)$
 <proof>

lemma conforms-xconf: $\llbracket (x, s) :: \preceq(G, L);$
 $\forall a. x' = \text{Some } (\text{Xcpt } (\text{Loc } a)) \longrightarrow G, s \vdash \text{Addr } a :: \preceq \text{Class } (\text{SXcpt } \text{Throwable});$
 $x' = \text{Some } (\text{Jump } \text{Ret}) \longrightarrow \text{locals } s \text{ Result} \neq \text{None} \rrbracket \implies$
 $(x', s) :: \preceq(G, L)$
 <proof>

lemma conforms-lupd:
 $\llbracket (x, s) :: \preceq(G, L); L \text{ vn} = \text{Some } T; G, s \vdash v :: \preceq T \rrbracket \implies (x, \text{lupd}(vn \mapsto v) s) :: \preceq(G, L)$
 <proof>

lemmas *conforms-allocL-aux* = *conforms-localD* [THEN *wlconf-ext*]

lemma *conforms-allocL*:

$\llbracket (x, s) :: \preceq (G, L); G, s \vdash v :: \preceq T \rrbracket \implies (x, \text{lupd}(vn \mapsto v) s) :: \preceq (G, L(vn \mapsto T))$
 ⟨proof⟩

lemmas *conforms-deallocL-aux* = *conforms-localD* [THEN *wlconf-deallocL*]

lemma *conforms-deallocL*: $\bigwedge s. \llbracket s :: \preceq (G, L(vn \mapsto T)); L \text{ vn} = \text{None} \rrbracket \implies s :: \preceq (G, L)$

⟨proof⟩

lemma *conforms-gext*: $\llbracket (x, s) :: \preceq (G, L); s \leq | s' ;$

$\forall r. \forall \text{obj} \in \text{globs } s' r: G, s \vdash \text{obj} :: \preceq \sqrt{r};$
 $\text{locals } s' = \text{locals } s \rrbracket \implies (x, s') :: \preceq (G, L)$

⟨proof⟩

lemma *conforms-xgext*:

$\llbracket (x, s) :: \preceq (G, L); (x', s') :: \preceq (G, L); s' \leq | s; \text{dom } (\text{locals } s') \subseteq \text{dom } (\text{locals } s) \rrbracket$
 $\implies (x', s) :: \preceq (G, L)$

⟨proof⟩

lemma *conforms-gupd*: $\bigwedge \text{obj}. \llbracket (x, s) :: \preceq (G, L); G, s \vdash \text{obj} :: \preceq \sqrt{r}; s \leq | \text{gupd}(r \mapsto \text{obj}) s \rrbracket$

$\implies (x, \text{gupd}(r \mapsto \text{obj}) s) :: \preceq (G, L)$

⟨proof⟩

lemma *conforms-upd-gobj*: $\llbracket (x, s) :: \preceq (G, L); \text{globs } s r = \text{Some } \text{obj};$

$\text{var-tys } G (\text{tag } \text{obj}) r n = \text{Some } T; G, s \vdash v :: \preceq T \rrbracket \implies (x, \text{upd-gobj } r n v s) :: \preceq (G, L)$

⟨proof⟩

lemma *conforms-set-locals*:

$\llbracket (x, s) :: \preceq (G, L); G, s \vdash l [\sim :: \preceq] L; x = \text{Some } (\text{Jump Ret}) \longrightarrow l \text{ Result} \neq \text{None} \rrbracket$
 $\implies (x, \text{set-locals } l s) :: \preceq (G, L)$

⟨proof⟩

lemma *conforms-locals*:

$\llbracket (a, b) :: \preceq (G, L); L x = \text{Some } T; \text{locals } b x \neq \text{None} \rrbracket$
 $\implies G, b \vdash \text{the } (\text{locals } b x) :: \preceq T$

⟨proof⟩

lemma *conforms-return*:

$\bigwedge s'. \llbracket (x, s) :: \preceq (G, L); (x', s') :: \preceq (G, L); s \leq | s'; x' \neq \text{Some } (\text{Jump Ret}) \rrbracket \implies$
 $(x', \text{set-locals } (\text{locals } s) s') :: \preceq (G, L)$

⟨proof⟩

end

Chapter 18

DefiniteAssignmentCorrect

45 Correctness of Definite Assignment

theory *DefiniteAssignmentCorrect* **imports** *WellForm Eval begin*

declare $[[\text{simproc del: wt-expr wt-var wt-exprs wt-stmt}]]$

lemma *sxalloc-no-jump*:

assumes *sxalloc*: $G \vdash s0 \text{ --sxalloc} \rightarrow s1$ **and**
no-jmp: $\text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$

$\langle \text{proof} \rangle$

lemma *sxalloc-no-jump'*:

assumes *sxalloc*: $G \vdash s0 \text{ --sxalloc} \rightarrow s1$ **and**
jump: $\text{abrupt } s1 = \text{Some } (\text{Jump } j)$
shows $\text{abrupt } s0 = \text{Some } (\text{Jump } j)$

$\langle \text{proof} \rangle$

lemma *halloc-no-jump*:

assumes *halloc*: $G \vdash s0 \text{ --halloc } oi \succ a \rightarrow s1$ **and**
no-jmp: $\text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$

$\langle \text{proof} \rangle$

lemma *halloc-no-jump'*:

assumes *halloc*: $G \vdash s0 \text{ --halloc } oi \succ a \rightarrow s1$ **and**
jump: $\text{abrupt } s1 = \text{Some } (\text{Jump } j)$
shows $\text{abrupt } s0 = \text{Some } (\text{Jump } j)$

$\langle \text{proof} \rangle$

lemma *Body-no-jump*:

assumes *eval*: $G \vdash s0 \text{ --Body } D \text{ c} \rightarrow v \rightarrow s1$ **and**
jump: $\text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$

$\langle \text{proof} \rangle$

lemma *Methd-no-jump*:

assumes *eval*: $G \vdash s0 \text{ --Methd } D \text{ sig} \rightarrow v \rightarrow s1$ **and**
jump: $\text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$

$\langle \text{proof} \rangle$

lemma *jumpNestingOkS-mono*:

assumes *jumpNestingOk-l'*: $\text{jumpNestingOkS } jmps' \text{ c}$
and *subset*: $jmps' \subseteq jmps$

shows $\text{jumpNestingOkS } jmps \text{ c}$

$\langle \text{proof} \rangle$

corollary *jumpNestingOk-mono*:

assumes *jmpOk*: $\text{jumpNestingOk } jmps' \text{ t}$
and *subset*: $jmps' \subseteq jmps$

shows $\text{jumpNestingOk } jmps \text{ t}$

<proof>

lemma *assign-abrupt-propagation*:

assumes *f-ok*: $\text{abrupt } (f \ n \ s) \neq x$
and *ass*: $\text{abrupt } (\text{assign } f \ n \ s) = x$
shows $\text{abrupt } s = x$

<proof>

lemma *wt-init-comp-ty'*:

is-acc-type (*prg Env*) (*pid* (*cls Env*)) $T \implies \text{Env} \vdash \text{init-comp-ty } T :: \checkmark$

<proof>

lemma *fvar-upd-no-jump*:

assumes *upd*: $\text{upd} = \text{snd } (\text{fst } (\text{fvar } \text{statDeclC } \text{stat } \text{fn } a \ s'))$
and *noJmp*: $\text{abrupt } s \neq \text{Some } (\text{Jump } j)$
shows $\text{abrupt } (\text{upd } \text{val } s) \neq \text{Some } (\text{Jump } j)$

<proof>

lemma *avar-state-no-jump*:

assumes *jmp*: $\text{abrupt } (\text{snd } (\text{avar } G \ i \ a \ s)) = \text{Some } (\text{Jump } j)$
shows $\text{abrupt } s = \text{Some } (\text{Jump } j)$

<proof>

lemma *avar-upd-no-jump*:

assumes *upd*: $\text{upd} = \text{snd } (\text{fst } (\text{avar } G \ i \ a \ s'))$
and *noJmp*: $\text{abrupt } s \neq \text{Some } (\text{Jump } j)$
shows $\text{abrupt } (\text{upd } \text{val } s) \neq \text{Some } (\text{Jump } j)$

<proof>

The next theorem expresses: If jumps (breaks, continues, returns) are nested correctly, we won't find an unexpected jump in the result state of the evaluation. For example, a break can't leave its enclosing loop, an return can't leave its enclosing method. To prove this, the method call is critical. Although the wellformedness of the whole program guarantees that the jumps (breaks, continues and returns) are nested correctly in all method bodies, the call rule alone does not guarantee that I will call a method or even a class that is part of the program due to dynamic binding! To be able to ensure this we need a kind of conformance of the state, like in the typesafety proof. But then we will redo the typesafety proof here. It would be nice if we could find an easy precondition that will guarantee that all calls will actually call classes and methods of the current program, which can be instantiated in the typesafety proof later on. To fix this problem, I have instrumented the semantic definition of a call to filter out any breaks in the state and to throw an error instead.

To get an induction hypothesis which is strong enough to perform the proof, we can't just assume *jumpNestingOk* for the empty set and conclude, that no jump at all will be in the resulting state, because the set is altered by the statements *Lab* and *While*.

The wellformedness of the program is used to ensure that for all class initialisations and methods the nesting of jumps is wellformed, too.

theorem *jumpNestingOk-eval*:

assumes *eval*: $G \vdash s0 \text{ -t> } \rightarrow (v, s1)$
and *jmpOk*: $\text{jumpNestingOk } \text{jmps } t$
and *wt*: $\text{Env} \vdash t :: T$
and *wf*: $\text{wf-prog } G$

and $G: \text{prg Env} = G$
and $\text{no-jmp}: \forall j. \text{abrupt } s0 = \text{Some } (\text{Jump } j) \longrightarrow j \in \text{jmps}$
 $(\text{is } ?\text{Jmp } \text{jmps } s0)$
shows $(\forall j. \text{fst } s1 = \text{Some } (\text{Jump } j) \longrightarrow j \in \text{jmps}) \wedge$
 $(\text{normal } s1 \longrightarrow$
 $(\forall w \text{ upd}. v = \text{In2 } (w, \text{upd})$
 $\longrightarrow (\forall s \text{ j val}.$
 $\text{abrupt } s \neq \text{Some } (\text{Jump } j) \longrightarrow$
 $\text{abrupt } (\text{upd val } s) \neq \text{Some } (\text{Jump } j))))$
 $(\text{is } ?\text{Jmp } \text{jmps } s1 \wedge ?\text{Upd } v \text{ } s1)$
 $\langle \text{proof} \rangle$

lemmas $\text{jumpNestingOk-evalE} = \text{jumpNestingOk-eval} [\text{THEN } \text{conjE}, \text{rule-format}]$

lemma $\text{jumpNestingOk-eval-no-jump}$:
assumes $\text{eval}: \text{prg Env} \vdash s0 -t \succ \rightarrow (v, s1)$ **and**
 $\text{jmpOk}: \text{jumpNestingOk } \{ \} t$ **and**
 $\text{no-jmp}: \text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$ **and**
 $\text{wt}: \text{Env} \vdash t :: T$ **and**
 $\text{wf}: \text{wf-prog } (\text{prg Env})$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j) \wedge$
 $(\text{normal } s1 \longrightarrow v = \text{In2 } (w, \text{upd})$
 $\longrightarrow \text{abrupt } s \neq \text{Some } (\text{Jump } j')$
 $\longrightarrow \text{abrupt } (\text{upd val } s) \neq \text{Some } (\text{Jump } j'))$
 $\langle \text{proof} \rangle$

lemmas $\text{jumpNestingOk-eval-no-jumpE}$
 = $\text{jumpNestingOk-eval-no-jump} [\text{THEN } \text{conjE}, \text{rule-format}]$

corollary $\text{eval-expression-no-jump}$:
assumes $\text{eval}: \text{prg Env} \vdash s0 -e \succ v \rightarrow s1$ **and**
 $\text{no-jmp}: \text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$ **and**
 $\text{wt}: \text{Env} \vdash e :: -T$ **and**
 $\text{wf}: \text{wf-prog } (\text{prg Env})$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$
 $\langle \text{proof} \rangle$

corollary eval-var-no-jump :
assumes $\text{eval}: \text{prg Env} \vdash s0 -\text{var} \Rightarrow \succ (w, \text{upd}) \rightarrow s1$ **and**
 $\text{no-jmp}: \text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$ **and**
 $\text{wt}: \text{Env} \vdash \text{var} ::= T$ **and**
 $\text{wf}: \text{wf-prog } (\text{prg Env})$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j) \wedge$
 $(\text{normal } s1 \longrightarrow$
 $(\text{abrupt } s \neq \text{Some } (\text{Jump } j')$
 $\longrightarrow \text{abrupt } (\text{upd val } s) \neq \text{Some } (\text{Jump } j'))$
 $\langle \text{proof} \rangle$

lemmas $\text{eval-var-no-jumpE} = \text{eval-var-no-jump} [\text{THEN } \text{conjE}, \text{rule-format}]$

corollary $\text{eval-statement-no-jump}$:
assumes $\text{eval}: \text{prg Env} \vdash s0 -c \rightarrow s1$ **and**
 $\text{jmpOk}: \text{jumpNestingOkS } \{ \} c$ **and**
 $\text{no-jmp}: \text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$ **and**
 $\text{wt}: \text{Env} \vdash c :: \surd$ **and**
 $\text{wf}: \text{wf-prog } (\text{prg Env})$
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$

\langle proof \rangle

corollary *eval-expression-list-no-jump*:

assumes *eval*: $\text{prg Env} \vdash s0 \text{ --es--> } v \rightarrow s1$ **and**

no-jmp: $\text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$ **and**

wt: $\text{Env} \vdash \text{es} :: \doteq T$ **and**

wf: $\text{wf-prog } (\text{prg Env})$

shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$

\langle proof \rangle

lemma *union-subseteq-elim* [*elim*]: $\llbracket A \cup B \subseteq C; \llbracket A \subseteq C; B \subseteq C \rrbracket \implies P \rrbracket \implies P$

\langle proof \rangle

lemma *dom-locals-halloc-mono*:

assumes *halloc*: $G \vdash s0 \text{ --halloc } oi \text{ --> } a \rightarrow s1$

shows $\text{dom } (\text{locals } (\text{store } s0)) \subseteq \text{dom } (\text{locals } (\text{store } s1))$

\langle proof \rangle

lemma *dom-locals-sxalloc-mono*:

assumes *sxalloc*: $G \vdash s0 \text{ --sxalloc--> } s1$

shows $\text{dom } (\text{locals } (\text{store } s0)) \subseteq \text{dom } (\text{locals } (\text{store } s1))$

\langle proof \rangle

lemma *dom-locals-assign-mono*:

assumes *f-ok*: $\text{dom } (\text{locals } (\text{store } s)) \subseteq \text{dom } (\text{locals } (\text{store } (f \ n \ s)))$

shows $\text{dom } (\text{locals } (\text{store } s)) \subseteq \text{dom } (\text{locals } (\text{store } (\text{assign } f \ n \ s)))$

\langle proof \rangle

lemma *dom-locals-lvar-mono*:

$\text{dom } (\text{locals } (\text{store } s)) \subseteq \text{dom } (\text{locals } (\text{store } (\text{snd } (\text{lvar } vn \ s') \ \text{val } s)))$

\langle proof \rangle

lemma *dom-locals-fvar-vvar-mono*:

$\text{dom } (\text{locals } (\text{store } s))$

$\subseteq \text{dom } (\text{locals } (\text{store } (\text{snd } (\text{fst } (\text{fvar } \text{statDeclC } \text{stat } fn \ a \ s') \ \text{val } s))))$

\langle proof \rangle

lemma *dom-locals-fvar-mono*:

$\text{dom } (\text{locals } (\text{store } s))$

$\subseteq \text{dom } (\text{locals } (\text{store } (\text{snd } (\text{fvar } \text{statDeclC } \text{stat } fn \ a \ s))))$

\langle proof \rangle

lemma *dom-locals-avar-vvar-mono*:

$\text{dom } (\text{locals } (\text{store } s))$

$\subseteq \text{dom } (\text{locals } (\text{store } (\text{snd } (\text{fst } (\text{avar } G \ i \ a \ s') \ \text{val } s))))$

<proof>

lemma *dom-locals-avar-mono*:

$dom (locals (store s))$
 $\subseteq dom (locals (store (snd (avar G i a s))))$
<proof>

Since assignments are modelled as functions from states to states, we must take into account these functions. They appear only in the assignment rule and as result from evaluating a variable. That's why we need the complicated second part of the conjunction in the goal. The reason for the very generic way to treat assignments was the aim to omit redundancy. There is only one evaluation rule for each kind of variable (locals, fields, arrays). These rules are used for both accessing variables and updating variables. That's why the evaluation rules for variables result in a pair consisting of a value and an update function. Of course we could also think of a pair of a value and a reference in the store, instead of the generic update function. But as only array updates can cause a special exception (if the types mismatch) and not array reads we then have to introduce two different rules to handle array reads and updates

lemma *dom-locals-eval-mono*:

assumes $eval: G \vdash s0 \dashv t \rightarrow (v, s1)$
shows $dom (locals (store s0)) \subseteq dom (locals (store s1)) \wedge$
 $(\forall vv. v = In2 vv \wedge normal s1$
 $\rightarrow (\forall s val. dom (locals (store s))$
 $\subseteq dom (locals (store ((snd vv) val s))))$

<proof>

lemma *dom-locals-eval-mono-elim*:

assumes $eval: G \vdash s0 \dashv t \rightarrow (v, s1)$
obtains $dom (locals (store s0)) \subseteq dom (locals (store s1))$ **and**
 $\wedge vv s val. \llbracket v = In2 vv; normal s1 \rrbracket$
 $\implies dom (locals (store s))$
 $\subseteq dom (locals (store ((snd vv) val s)))$

<proof>

lemma *halloc-no-abrupt*:

assumes $halloc: G \vdash s0 \dashv halloc oi \rightarrow a \rightarrow s1$ **and**
 $normal: normal s1$

shows $normal s0$

<proof>

lemma *sxalloc-mono-no-abrupt*:

assumes $sxalloc: G \vdash s0 \dashv sxalloc \rightarrow s1$ **and**
 $normal: normal s1$

shows $normal s0$

<proof>

lemma *union-subseteqI*: $\llbracket A \cup B \subseteq C; A' \subseteq A; B' \subseteq B \rrbracket \implies A' \cup B' \subseteq C$

<proof>

lemma *union-subseteqII*: $\llbracket A \cup B \subseteq C; A' \subseteq A \rrbracket \implies A' \cup B \subseteq C$

<proof>

lemma *union-subseteqIr*: $\llbracket A \cup B \subseteq C; B' \subseteq B \rrbracket \implies A \cup B' \subseteq C$
 ⟨proof⟩

lemma *subseteq-union-transl* [trans]: $\llbracket A \subseteq B; B \cup C \subseteq D \rrbracket \implies A \cup C \subseteq D$
 ⟨proof⟩

lemma *subseteq-union-transr* [trans]: $\llbracket A \subseteq B; C \cup B \subseteq D \rrbracket \implies A \cup C \subseteq D$
 ⟨proof⟩

lemma *union-subseteq-weaken*: $\llbracket A \cup B \subseteq C; \llbracket A \subseteq C; B \subseteq C \rrbracket \implies P \rrbracket \implies P$
 ⟨proof⟩

lemma *assigns-good-approx*:
assumes
eval: $G \vdash s0 \text{ -t> } \rightarrow (v, s1)$ **and**
normal: *normal s1*
shows $\text{assigns } t \subseteq \text{dom } (\text{locals } (\text{store } s1))$
 ⟨proof⟩

corollary *assignsE-good-approx*:
assumes
eval: $\text{prg Env} \vdash s0 \text{ -e-> } v \rightarrow s1$ **and**
normal: *normal s1*
shows $\text{assignsE } e \subseteq \text{dom } (\text{locals } (\text{store } s1))$
 ⟨proof⟩

corollary *assignsV-good-approx*:
assumes
eval: $\text{prg Env} \vdash s0 \text{ -v=> } vf \rightarrow s1$ **and**
normal: *normal s1*
shows $\text{assignsV } v \subseteq \text{dom } (\text{locals } (\text{store } s1))$
 ⟨proof⟩

corollary *assignsEs-good-approx*:
assumes
eval: $\text{prg Env} \vdash s0 \text{ -es=> } vs \rightarrow s1$ **and**
normal: *normal s1*
shows $\text{assignsEs } es \subseteq \text{dom } (\text{locals } (\text{store } s1))$
 ⟨proof⟩

lemma *constVal-eval*:
assumes *const*: $\text{constVal } e = \text{Some } c$ **and**
eval: $G \vdash \text{Norm } s0 \text{ -e-> } v \rightarrow s$
shows $v = c \wedge \text{normal } s$
 ⟨proof⟩

lemmas *constVal-eval-elim* = *constVal-eval* [THEN conjE]

lemma *eval-unop-type*:
typeof dt ($\text{eval-unop } \text{unop } v$) = *Some* (*PrimT* (*unop-type unop*))
 ⟨proof⟩

lemma *eval-binop-type*:

typeof dt (eval-binop binop v1 v2) = Some (PrimT (binop-type binop))
 ⟨proof⟩

lemma *constVal-Boolean*:

assumes *const: constVal e = Some c* **and**
wt: Env⊢e::-PrimT Boolean
shows *typeof empty-dt c = Some (PrimT Boolean)*
 ⟨proof⟩

lemma *assigns-if-good-approx*:

assumes
eval: prg Env⊢ s0 -e-⤵b→ s1 **and**
normal: normal s1 **and**
bool: Env⊢ e::-PrimT Boolean
shows *assigns-if (the-Bool b) e ⊆ dom (locals (store s1))*
 ⟨proof⟩

lemma *assigns-if-good-approx'*:

assumes *eval: G⊢s0 -e-⤵b→ s1*
and *normal: normal s1*
and *bool: (⊢prg=G,cls=C,lcl=L)⊢e::- (PrimT Boolean)*
shows *assigns-if (the-Bool b) e ⊆ dom (locals (store s1))*
 ⟨proof⟩

lemma *subset-Intl: A ⊆ C ⇒ A ∩ B ⊆ C*

⟨proof⟩

lemma *subset-Intr: B ⊆ C ⇒ A ∩ B ⊆ C*

⟨proof⟩

lemma *da-good-approx*:

assumes *eval: prg Env⊢s0 -t⤵→ (v, s1)* **and**
wt: Env⊢t::T (**is** *?Wt Env t T*) **and**
da: Env⊢ dom (locals (store s0)) ⤵t⤵ A (**is** *?Da Env s0 t A*) **and**
wf: wf-prog (prg Env)
shows (*normal s1 ⇒ (nrm A ⊆ dom (locals (store s1)))*) ∧
 (*∀ l. abrupt s1 = Some (Jump (Break l)) ∧ normal s0*
→ (brk A l ⊆ dom (locals (store s1)))) ∧
 (*abrupt s1 = Some (Jump Ret) ∧ normal s0*
→ Result ∈ dom (locals (store s1)))
 (**is** *?NormalAssigned s1 A ∧ ?BreakAssigned s0 s1 A ∧ ?ResAssigned s0 s1*)
 ⟨proof⟩

lemma *da-good-approxE*:

assumes
prg Env⊢s0 -t⤵→ (v, s1) **and** *Env⊢t::T* **and**
Env⊢ dom (locals (store s0)) ⤵t⤵ A **and** *wf-prog (prg Env)*
obtains
normal s1 ⇒ nrm A ⊆ dom (locals (store s1)) **and**
∧ l. [abrupt s1 = Some (Jump (Break l)); normal s0]

$\implies \text{brk } A \ l \subseteq \text{dom } (\text{locals } (\text{store } s1))$ **and**
 $\llbracket \text{abrupt } s1 = \text{Some } (\text{Jump } \text{Ret}); \text{normal } s0 \rrbracket \implies \text{Result} \in \text{dom } (\text{locals } (\text{store } s1))$
 <proof>

lemma *da-good-approxE'*:

assumes *eval*: $G \vdash s0 \text{ -t>-} \rightarrow (v, s1)$
and *wt*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash t :: T$
and *da*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } s0)) \gg t \gg A$
and *wf*: *wf-prog* *G*
obtains *normal* *s1* $\implies \text{norm } A \subseteq \text{dom } (\text{locals } (\text{store } s1))$ **and**
 $\wedge l. \llbracket \text{abrupt } s1 = \text{Some } (\text{Jump } (\text{Break } l)); \text{normal } s0 \rrbracket$
 $\implies \text{brk } A \ l \subseteq \text{dom } (\text{locals } (\text{store } s1))$ **and**
 $\llbracket \text{abrupt } s1 = \text{Some } (\text{Jump } \text{Ret}); \text{normal } s0 \rrbracket$
 $\implies \text{Result} \in \text{dom } (\text{locals } (\text{store } s1))$
 <proof>

declare $\llbracket \text{simproc } \text{add}: \text{wt-expr } \text{wt-var } \text{wt-exprs } \text{wt-stmt} \rrbracket$

end

Chapter 19

TypeSafe

46 The type soundness proof for Java

theory *TypeSafe*

imports *DefiniteAssignmentCorrect Conform*

begin

error free

lemma *error-free-halloc*:

assumes *halloc*: $G \vdash s0 \text{ --halloc } oi \triangleright a \rightarrow s1$ **and**
error-free-s0: *error-free s0*

shows *error-free s1*

<proof>

lemma *error-free-sxalloc*:

assumes *sxalloc*: $G \vdash s0 \text{ --sxalloc } \rightarrow s1$ **and** *error-free-s0*: *error-free s0*
shows *error-free s1*

<proof>

lemma *error-free-check-field-access-eq*:

error-free (check-field-access G accC statDeclC fn stat a s)
 $\implies (check-field-access G accC statDeclC fn stat a s) = s$

<proof>

lemma *error-free-check-method-access-eq*:

error-free (check-method-access G accC statT mode sig a' s)
 $\implies (check-method-access G accC statT mode sig a' s) = s$

<proof>

lemma *error-free-FVar-lemma*:

error-free s

$\implies error-free (abupd (if stat then id else np a) s)$

<proof>

lemma *error-free-init-lvars* [*simp,intro*]:

error-free s \implies

error-free (init-lvars G C sig mode a pvs s)

<proof>

lemma *error-free-LVar-lemma*:

error-free s $\implies error-free (assign (\lambda v. supd lupd(vn \mapsto v)) w s)$

<proof>

lemma *error-free-throw* [*simp,intro*]:

error-free s $\implies error-free (abupd (throw x) s)$

<proof>

result conformance

definition

assign-conforms :: $st \Rightarrow (val \Rightarrow state \Rightarrow state) \Rightarrow ty \Rightarrow env' \Rightarrow bool$ ($\leq | \preceq | \preceq :: \preceq$ - [71,71,71,71] 70)

where

$s \leq | f \preceq T :: \preceq E =$

$$((\forall s' w. \text{Norm } s'::\leq E \longrightarrow \text{fst } E, s \vdash w::\leq T \longrightarrow s \leq |s' \longrightarrow \text{assign } f w (\text{Norm } s')::\leq E) \wedge \\ (\forall s' w. \text{error-free } s' \longrightarrow (\text{error-free } (\text{assign } f w s'))))$$

definition

$$rconf :: \text{prog} \Rightarrow \text{lenv} \Rightarrow \text{st} \Rightarrow \text{term} \Rightarrow \text{vals} \Rightarrow \text{tys} \Rightarrow \text{bool} \quad (-, -, \vdash, \succ, \leq, \leq - \text{ [71, 71, 71, 71, 71, 71] } 70)$$

where

$$G, L, s \vdash t \succ v::\leq T = \\ (\text{case } T \text{ of} \\ \text{Inl } T \Rightarrow \text{if } (\exists \text{ var. } t = \text{In2 } \text{var}) \\ \text{then } (\forall n. (\text{the-In2 } t) = \text{LVar } n \\ \longrightarrow (\text{fst } (\text{the-In2 } v) = \text{the } (\text{locals } s n)) \wedge \\ (\text{locals } s n \neq \text{None} \longrightarrow G, s \vdash \text{fst } (\text{the-In2 } v)::\leq T)) \wedge \\ (\neg (\exists n. \text{the-In2 } t = \text{LVar } n) \longrightarrow (G, s \vdash \text{fst } (\text{the-In2 } v)::\leq T)) \wedge \\ (s \leq | \text{snd } (\text{the-In2 } v) \leq T::\leq (G, L)) \\ \text{else } G, s \vdash \text{the-In1 } v::\leq T \\ | \text{Inr } Ts \Rightarrow \text{list-all2 } (\text{conf } G s) (\text{the-In3 } v) Ts)$$

With *rconf* we describe the conformance of the result value of a term. This definition gets rather complicated because of the relations between the injections of the different terms, types and values. The main case distinction is between single values and value lists. In case of value lists, every value has to conform to its type. For single values we have to do a further case distinction, between values of variables $\exists \text{ var. } t = \text{In2 } \text{var}$ and ordinary values. Values of variables are modelled as pairs consisting of the current value and an update function which will perform an assignment to the variable. This stems from the decision, that we only have one evaluation rule for each kind of variable. The decision if we read or write to the variable is made by syntactic enclosing rules. So conformance of variable-values must ensure that both the current value and an update will conform to the type. With the introduction of definite assignment of local variables we have to do another case distinction. For the notion of conformance local variables are allowed to be *None*, since the definedness is not ensured by conformance but by definite assignment. Field and array variables must contain a value.

lemma *rconf-In1* [simp]:

$$G, L, s \vdash \text{In1 } ec \succ \text{In1 } v::\leq \text{Inl } T = G, s \vdash v::\leq T \\ \langle \text{proof} \rangle$$

lemma *rconf-In2-no-LVar* [simp]:

$$\forall n. va \neq \text{LVar } n \implies \\ G, L, s \vdash \text{In2 } va \succ \text{In2 } vf::\leq \text{Inl } T = (G, s \vdash \text{fst } vf::\leq T \wedge s \leq | \text{snd } vf \leq T::\leq (G, L)) \\ \langle \text{proof} \rangle$$

lemma *rconf-In2-LVar* [simp]:

$$va = \text{LVar } n \implies \\ G, L, s \vdash \text{In2 } va \succ \text{In2 } vf::\leq \text{Inl } T \\ = ((\text{fst } vf = \text{the } (\text{locals } s n)) \wedge \\ (\text{locals } s n \neq \text{None} \longrightarrow G, s \vdash \text{fst } vf::\leq T) \wedge s \leq | \text{snd } vf \leq T::\leq (G, L)) \\ \langle \text{proof} \rangle$$

lemma *rconf-In3* [simp]:

$$G, L, s \vdash \text{In3 } es \succ \text{In3 } vs::\leq \text{Inr } Ts = \text{list-all2 } (\lambda v T. G, s \vdash v::\leq T) \text{ vs } Ts \\ \langle \text{proof} \rangle$$

fits and conf

$$\text{lemma } \text{conf-fits}: G, s \vdash v::\leq T \implies G, s \vdash v \text{ fits } T$$

<proof>

lemma *fits-conf*:

$\llbracket G, s \vdash v :: \leq T; G \vdash T \leq ? T'; G, s \vdash v \text{ fits } T'; \text{ws-prog } G \rrbracket \implies G, s \vdash v :: \leq T'$
<proof>

lemma *fits-Array*:

$\llbracket G, s \vdash v :: \leq T; G \vdash T'. \llbracket \leq T. \rrbracket; G, s \vdash v \text{ fits } T'; \text{ws-prog } G \rrbracket \implies G, s \vdash v :: \leq T'$
<proof>

gext

lemma *halloc-gext*: $\bigwedge s1\ s2. G \vdash s1 \text{ -halloc } oi \succ a \rightarrow s2 \implies \text{snd } s1 \leq | \text{snd } s2$
<proof>

lemma *salloc-gext*: $\bigwedge s1\ s2. G \vdash s1 \text{ -salloc } \rightarrow s2 \implies \text{snd } s1 \leq | \text{snd } s2$
<proof>

lemma *eval-gext-lemma* [*rule-format* (*no-asm*)]:

$G \vdash s \text{ -t} \succ \rightarrow (w, s')$ $\implies \text{snd } s \leq | \text{snd } s' \wedge (\text{case } w \text{ of}$
 $\text{In1 } v \Rightarrow \text{True}$
 $| \text{In2 } vf \Rightarrow \text{normal } s \longrightarrow (\forall v\ x\ s. s \leq | \text{snd } (\text{assign } (\text{snd } vf) v (x, s)))$
 $| \text{In3 } vs \Rightarrow \text{True})$
<proof>

lemma *evar-gext-f*:

$G \vdash \text{Norm } s1 \text{ -e} \succ vf \rightarrow s2 \implies s \leq | \text{snd } (\text{assign } (\text{snd } vf) v (x, s))$
<proof>

lemmas *eval-gext* = *eval-gext-lemma* [*THEN* *conjunct1*]

lemma *eval-gext'*: $G \vdash (x1, s1) \text{ -t} \succ \rightarrow (w, (x2, s2)) \implies s1 \leq | s2$
<proof>

lemma *init-yields-initd*: $G \vdash \text{Norm } s1 \text{ -Init } C \rightarrow s2 \implies \text{initd } C\ s2$
<proof>

Lemmas

lemma *obj-ty-obj-class1*:

$\llbracket \text{wf-prog } G; \text{is-type } G (\text{obj-ty } \text{obj}) \rrbracket \implies \text{is-class } G (\text{obj-class } \text{obj})$
<proof>

lemma *oconf-init-obj*:

$\llbracket \text{wf-prog } G;$
 (*case* *r* of *Heap* *a* \Rightarrow *is-type* *G* (*obj-ty* *obj*) | *Stat* *C* \Rightarrow *is-class* *G* *C*)
 $\rrbracket \implies G, s \vdash \text{obj } (\text{values} := \text{init-vals } (\text{var-tys } G (\text{tag } \text{obj})\ r)) :: \leq \sqrt{r}$
<proof>

lemma *conforms-newG*: $\llbracket \text{globs } s \text{ oref} = \text{None}; (x, s) :: \leq (G, L);$

wf-prog G ; *case oref of Heap* $a \Rightarrow$ *is-type* G (*obj-ty* (\downarrow tag=oi,values=vs))
 | *Stat* $C \Rightarrow$ *is-class* G $C \]] \Longrightarrow$
 $(x, \text{init-obj } G \text{ oi oref } s) :: \preceq(G, L)$
 $\langle \text{proof} \rangle$

lemma *conforms-init-class-obj*:

$\llbracket (x, s) :: \preceq(G, L); \text{wf-prog } G; \text{class } G \text{ } C = \text{Some } y; \neg \text{inited } C \text{ (globs } s) \rrbracket \Longrightarrow$
 $(x, \text{init-class-obj } G \text{ } C \text{ } s) :: \preceq(G, L)$
 $\langle \text{proof} \rangle$

lemma *fst-init-lvars[simp]*:

fst (*init-lvars* G C *sig* (*invmode* m e) a' *pvs* (x, s)) =
 (*if is-static* m *then* x *else* (*np* a') x)
 $\langle \text{proof} \rangle$

lemma *halloc-conforms*: $\bigwedge s1. \llbracket G \vdash s1 \text{ -halloc } oi \succ a \rightarrow s2; \text{wf-prog } G; s1 :: \preceq(G, L);$

is-type G (*obj-ty* (\downarrow tag=oi,values=fs)) $\rrbracket \Longrightarrow s2 :: \preceq(G, L)$
 $\langle \text{proof} \rangle$

lemma *halloc-type-sound*:

$\bigwedge s1. \llbracket G \vdash s1 \text{ -halloc } oi \succ a \rightarrow (x, s); \text{wf-prog } G; s1 :: \preceq(G, L);$
 $T = \text{obj-ty } (\downarrow$ tag=oi,values=fs); *is-type* G $T \rrbracket \Longrightarrow$
 $(x, s) :: \preceq(G, L) \wedge (x = \text{None} \rightarrow G, s \vdash \text{Addr } a :: \preceq T)$
 $\langle \text{proof} \rangle$

lemma *sxalloc-type-sound*:

$\bigwedge s1 \ s2. \llbracket G \vdash s1 \text{ -sxalloc} \rightarrow s2; \text{wf-prog } G \rrbracket \Longrightarrow$
case *fst* $s1$ *of*
None $\Rightarrow s2 = s1$
 | *Some* *abr* \Rightarrow (*case* *abr* *of*
 Xcpt $x \Rightarrow (\exists a. \text{fst } s2 = \text{Some}(\text{Xcpt } (\text{Loc } a)) \wedge$
 $(\forall L. s1 :: \preceq(G, L) \rightarrow s2 :: \preceq(G, L)))$
 | *Jump* $j \Rightarrow s2 = s1$
 | *Error* $e \Rightarrow s2 = s1$)
 $\langle \text{proof} \rangle$

lemma *wt-init-comp-ty*:

is-acc-type G (*pid* C) $T \Longrightarrow (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{init-comp-ty } T :: \checkmark$
 $\langle \text{proof} \rangle$

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

declare *fun-upd-apply* [*simp del*]

definition

DynT-prop :: [*prog*, *inv-mode*, *qtname*, *ref-ty*] \Rightarrow *bool* ($\dashv \dashrightarrow \preceq$ [71, 71, 71, 71] 70)

where

$G \vdash \text{mode} \rightarrow D \preceq t = (\text{mode} = \text{IntVir} \rightarrow \text{is-class } G \text{ } D \wedge$
 (*if* $(\exists T. t = \text{ArrayT } T)$ *then* $D = \text{Object}$ *else* $G \vdash \text{Class } D \preceq \text{RefT } t)$)

lemma *DynT-propI*:

$$\begin{aligned} & \llbracket (x,s)::\preceq(G, L); G, s \vdash a'::\preceq \text{RefT } \text{statT}; \text{wf-prog } G; \text{mode} = \text{IntVir} \longrightarrow a' \neq \text{Null} \rrbracket \\ & \implies G \vdash \text{mode} \rightarrow \text{invocation-class mode } s \ a' \ \text{statT} \preceq \text{statT} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *invocation-methd*:

$$\begin{aligned} & \llbracket \text{wf-prog } G; \text{statT} \neq \text{NullT}; \\ & (\forall \text{ statC}. \text{statT} = \text{ClassT } \text{statC} \longrightarrow \text{is-class } G \ \text{statC}); \\ & (\forall \ I. \ \text{statT} = \text{IfaceT } I \longrightarrow \text{is-iface } G \ I \wedge \text{mode} \neq \text{SuperM}); \\ & (\forall \ T. \ \text{statT} = \text{ArrayT } T \longrightarrow \text{mode} \neq \text{SuperM}); \\ & G \vdash \text{mode} \rightarrow \text{invocation-class mode } s \ a' \ \text{statT} \preceq \text{statT}; \\ & \text{dynlookup } G \ \text{statT} \ (\text{invocation-class mode } s \ a' \ \text{statT}) \ \text{sig} = \text{Some } m \rrbracket \\ & \implies \text{methd } G \ (\text{invocation-declclass } G \ \text{mode } s \ a' \ \text{statT} \ \text{sig}) \ \text{sig} = \text{Some } m \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *DynT-mheadsD*:

$$\begin{aligned} & \llbracket G \vdash \text{invmode } sm \ e \rightarrow \text{invC} \preceq \text{statT}; \\ & \text{wf-prog } G; (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash e::-\text{RefT } \text{statT}; \\ & (\text{statDeclT}, sm) \in \text{mheads } G \ C \ \text{statT} \ \text{sig}; \\ & \text{invC} = \text{invocation-class } (\text{invmode } sm \ e) \ s \ a' \ \text{statT}; \\ & \text{declC} = \text{invocation-declclass } G \ (\text{invmode } sm \ e) \ s \ a' \ \text{statT} \ \text{sig} \\ & \rrbracket \implies \\ & \exists \ dm. \\ & \text{methd } G \ \text{declC} \ \text{sig} = \text{Some } dm \wedge \text{dynlookup } G \ \text{statT} \ \text{invC} \ \text{sig} = \text{Some } dm \wedge \\ & G \vdash \text{resTy } (\text{methd } dm) \preceq \text{resTy } sm \wedge \\ & \text{wf-mdecl } G \ \text{declC} \ (\text{sig}, \text{methd } dm) \wedge \\ & \text{declC} = \text{declclass } dm \wedge \\ & \text{is-static } dm = \text{is-static } sm \wedge \\ & \text{is-class } G \ \text{invC} \wedge \text{is-class } G \ \text{declC} \wedge G \vdash \text{invC} \preceq_C \ \text{declC} \wedge \\ & (\text{if } \text{invmode } sm \ e = \text{IntVir} \\ & \quad \text{then } (\forall \ \text{statC}. \ \text{statT} = \text{ClassT } \text{statC} \longrightarrow G \vdash \text{invC} \preceq_C \ \text{statC}) \\ & \quad \text{else } ((\exists \ \text{statC}. \ \text{statT} = \text{ClassT } \text{statC} \wedge G \vdash \text{statC} \preceq_C \ \text{declC}) \\ & \quad \vee (\forall \ \text{statC}. \ \text{statT} \neq \text{ClassT } \text{statC} \wedge \text{declC} = \text{Object})) \wedge \\ & \quad \text{statDeclT} = \text{ClassT } (\text{declclass } dm)) \\ & \langle \text{proof} \rangle \end{aligned}$$

corollary *DynT-mheadsE* [consumes γ]:

— Same as *DynT-mheadsD* but better suited for application in typesafety proof

assumes *invC-compatible*: $G \vdash \text{mode} \rightarrow \text{invC} \preceq \text{statT}$

and *wf*: $\text{wf-prog } G$
and *wt-e*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash e::-\text{RefT } \text{statT}$
and *mheads*: $(\text{statDeclT}, sm) \in \text{mheads } G \ C \ \text{statT} \ \text{sig}$
and *mode*: $\text{mode} = \text{invmode } sm \ e$
and *invC*: $\text{invC} = \text{invocation-class mode } s \ a' \ \text{statT}$
and *declC*: $\text{declC} = \text{invocation-declclass } G \ \text{mode } s \ a' \ \text{statT} \ \text{sig}$
and *dm*: $\bigwedge \ dm. \llbracket \text{methd } G \ \text{declC} \ \text{sig} = \text{Some } dm; \\ \text{dynlookup } G \ \text{statT} \ \text{invC} \ \text{sig} = \text{Some } dm; \\ G \vdash \text{resTy } (\text{methd } dm) \preceq \text{resTy } sm; \\ \text{wf-mdecl } G \ \text{declC} \ (\text{sig}, \text{methd } dm); \\ \text{declC} = \text{declclass } dm; \\ \text{is-static } dm = \text{is-static } sm; \\ \text{is-class } G \ \text{invC}; \text{is-class } G \ \text{declC}; G \vdash \text{invC} \preceq_C \ \text{declC}; \\ (\text{if } \text{invmode } sm \ e = \text{IntVir} \\ \text{then } (\forall \ \text{statC}. \ \text{statT} = \text{ClassT } \text{statC} \longrightarrow G \vdash \text{invC} \preceq_C \ \text{statC}) \\ \text{else } ((\exists \ \text{statC}. \ \text{statT} = \text{ClassT } \text{statC} \wedge G \vdash \text{statC} \preceq_C \ \text{declC}) \\ \vee (\forall \ \text{statC}. \ \text{statT} \neq \text{ClassT } \text{statC} \wedge \text{declC} = \text{Object})) \wedge$

$$\text{statDeclT} = \text{ClassT} (\text{declclass } dm) \implies P$$

shows P

$\langle \text{proof} \rangle$

lemma *DynT-conf*: $\llbracket G \vdash \text{invocation-class mode } s \text{ } a' \text{ } \text{statT} \preceq_C \text{ declC}; \text{wf-prog } G;$
 $\text{isrtype } G (\text{statT});$
 $G, s \vdash a' :: \preceq_{\text{RefT}} \text{statT}; \text{mode} = \text{IntVir} \longrightarrow a' \neq \text{Null};$
 $\text{mode} \neq \text{IntVir} \longrightarrow (\exists \text{statC}. \text{statT} = \text{ClassT } \text{statC} \wedge G \vdash \text{statC} \preceq_C \text{ declC})$
 $\quad \vee (\forall \text{statC}. \text{statT} \neq \text{ClassT } \text{statC} \wedge \text{declC} = \text{Object}) \rrbracket$
 $\implies G, s \vdash a' :: \preceq \text{Class declC}$

$\langle \text{proof} \rangle$

lemma *Ass-lemma*:

$\llbracket G \vdash \text{Norm } s0 \text{ } -\text{var} \rightarrow (w, f) \rightarrow \text{Norm } s1; G \vdash \text{Norm } s1 \text{ } -\text{e} \rightarrow v \rightarrow \text{Norm } s2;$
 $G, s2 \vdash v :: \preceq_e T; s1 \leq |s2 \longrightarrow \text{assign } f \text{ } v (\text{Norm } s2) :: \preceq (G, L) \rrbracket$
 $\implies \text{assign } f \text{ } v (\text{Norm } s2) :: \preceq (G, L) \wedge$
 $(\text{normal } (\text{assign } f \text{ } v (\text{Norm } s2)) \longrightarrow G, \text{store } (\text{assign } f \text{ } v (\text{Norm } s2)) \vdash v :: \preceq_e T)$

$\langle \text{proof} \rangle$

lemma *Throw-lemma*: $\llbracket G \vdash \text{tn} \preceq_C \text{SXcpt Throwable}; \text{wf-prog } G; (x1, s1) :: \preceq (G, L);$
 $x1 = \text{None} \longrightarrow G, s1 \vdash a' :: \preceq \text{Class tn} \rrbracket \implies (\text{throw } a' \text{ } x1, s1) :: \preceq (G, L)$

$\langle \text{proof} \rangle$

lemma *Try-lemma*: $\llbracket G \vdash \text{obj-ty } (\text{the } (\text{globs } s1' (\text{Heap } a))) \preceq \text{Class tn};$
 $(\text{Some } (\text{Xcpt } (\text{Loc } a)), s1') :: \preceq (G, L); \text{wf-prog } G \rrbracket$
 $\implies \text{Norm } (\text{lupd}(vn \mapsto \text{Addr } a) \text{ } s1') :: \preceq (G, L(vn \mapsto \text{Class } tn))$

$\langle \text{proof} \rangle$

lemma *Fin-lemma*:

$\llbracket G \vdash \text{Norm } s1 \text{ } -\text{c2} \rightarrow (x2, s2); \text{wf-prog } G; (\text{Some } a, s1) :: \preceq (G, L); (x2, s2) :: \preceq (G, L);$
 $\text{dom } (\text{locals } s1) \subseteq \text{dom } (\text{locals } s2) \rrbracket$
 $\implies (\text{abrupt-if True } (\text{Some } a) \text{ } x2, s2) :: \preceq (G, L)$

$\langle \text{proof} \rangle$

lemma *FVar-lemma1*:

$\llbracket \text{table-of } (\text{DeclConcepts.fields } G \text{ } \text{statC}) (\text{fn}, \text{statDeclC}) = \text{Some } f ;$
 $x2 = \text{None} \longrightarrow G, s2 \vdash a :: \preceq \text{Class } \text{statC}; \text{wf-prog } G; G \vdash \text{statC} \preceq_C \text{statDeclC};$
 $\text{statDeclC} \neq \text{Object};$
 $\text{class } G \text{ } \text{statDeclC} = \text{Some } y; (x2, s2) :: \preceq (G, L); s1 \leq |s2;$
 $\text{inited } \text{statDeclC} (\text{globs } s1);$
 $(\text{if static } f \text{ then id else np } a) \text{ } x2 = \text{None} \rrbracket$
 \implies
 $\exists \text{obj}. \text{globs } s2 (\text{if static } f \text{ then Inr } \text{statDeclC} \text{ else Inl } (\text{the-Addr } a))$
 $\quad = \text{Some obj} \wedge$
 $\text{var-tys } G (\text{tag obj}) (\text{if static } f \text{ then Inr } \text{statDeclC} \text{ else Inl } (\text{the-Addr } a))$
 $\quad (\text{Inl}(\text{fn}, \text{statDeclC})) = \text{Some } (\text{type } f)$

$\langle \text{proof} \rangle$

lemma *FVar-lemma2*: *error-free state*

$\implies \text{error-free}$
 $(\text{assign}$

```

      (λv. supd
        (upd-gobj
          (if static field then Inr statDeclC
            else Inl (the-Addr a))
          (Inl (fn, statDeclC)) v))
      w state)
⟨proof⟩

```

```

declare split-paired-All [simp del] split-paired-Ex [simp del]
declare split-if [split del] split-if-asm [split del]
      option.split [split del] option.split-asm [split del]
⟨ML⟩

```

lemma *FVar-lemma*:

```

[[ (v, f), Norm s2' ] = fvar statDeclC (static field) fn a (x2, s2);
  G ⊢ statC ⊆C statDeclC;
  table-of (DeclConcepts.fields G statC) (fn, statDeclC) = Some field;
  wf-prog G;
  x2 = None ⟶ G, s2 ⊢ a :: ⊆ Class statC;
  statDeclC ≠ Object; class G statDeclC = Some y;
  (x2, s2) :: ⊆ (G, L); s1 ≤ |s2; inited statDeclC (globs s1)] ⟹
  G, s2 ⊢ v :: ⊆ type field ∧ s2' ≤ |f ⊆ type field :: ⊆ (G, L)
⟨proof⟩
declare split-paired-All [simp] split-paired-Ex [simp]
declare split-if [split] split-if-asm [split]
      option.split [split] option.split-asm [split]
⟨ML⟩

```

lemma *AVar-lemma1*: [[globs s (Inl a) = Some obj; tag obj = Arr ty i; the-Intg i' in-bounds i; wf-prog G; G ⊢ ty.[] ⊆ Tb.[]; Norm s :: ⊆ (G, L)] ⟹ G, s ⊢ the ((values obj) (Inr (the-Intg i')) :: ⊆ Tb

⟨proof⟩

lemma *obj-split*: ∃ t vs. obj = (tag=t, values=vs)

⟨proof⟩

lemma *AVar-lemma2*: error-free state

```

⟹ error-free
  (assign
    (λv (x, s').
      ((raise-if (¬ G, s ⊢ v fits T) ArrStore) x,
        upd-gobj (Inl a) (Inr (the-Intg i)) v s')))
  w state)
⟨proof⟩

```

lemma *AVar-lemma*: [[wf-prog G; G ⊢ (x1, s1) -e2- > i → (x2, s2); ((v, f), Norm s2') = avar G i a (x2, s2); x1 = None ⟶ G, s1 ⊢ a :: ⊆ Ta.[]; (x2, s2) :: ⊆ (G, L); s1 ≤ |s2]] ⟹ G, s2 ⊢ v :: ⊆ Ta ∧ s2' ≤ |f ⊆ Ta :: ⊆ (G, L)

⟨proof⟩

Call

lemma *conforms-init-lvars-lemma*: [[wf-prog G;

$wf\text{-mhead } G \ P \ sig \ mh;$
 $list\text{-all2 } (conf \ G \ s) \ pvs \ pTsa; \ G \vdash \ pTsa[\preceq](parTs \ sig)] \implies$
 $G, s \vdash \text{empty } (pars \ mh[\mapsto] pvs)$
 $[\sim::\preceq] \text{table-of lvars}(pars \ mh[\mapsto] parTs \ sig)$
 $\langle \text{proof} \rangle$

lemma $lconf\text{-map-lname}$ $[simp]:$
 $G, s \vdash (lname\text{-case } l1 \ l2)[::\preceq](lname\text{-case } L1 \ L2)$
 $=$
 $(G, s \vdash l1[::\preceq] L1 \wedge G, s \vdash (\lambda x::unit . l2)[::\preceq](\lambda x::unit. L2))$
 $\langle \text{proof} \rangle$

lemma $wlconf\text{-map-lname}$ $[simp]:$
 $G, s \vdash (lname\text{-case } l1 \ l2)[\sim::\preceq](lname\text{-case } L1 \ L2)$
 $=$
 $(G, s \vdash l1[\sim::\preceq] L1 \wedge G, s \vdash (\lambda x::unit . l2)[\sim::\preceq](\lambda x::unit. L2))$
 $\langle \text{proof} \rangle$

lemma $lconf\text{-map-ename}$ $[simp]:$
 $G, s \vdash (ename\text{-case } l1 \ l2)[::\preceq](ename\text{-case } L1 \ L2)$
 $=$
 $(G, s \vdash l1[::\preceq] L1 \wedge G, s \vdash (\lambda x::unit. l2)[::\preceq](\lambda x::unit. L2))$
 $\langle \text{proof} \rangle$

lemma $wlconf\text{-map-ename}$ $[simp]:$
 $G, s \vdash (ename\text{-case } l1 \ l2)[\sim::\preceq](ename\text{-case } L1 \ L2)$
 $=$
 $(G, s \vdash l1[\sim::\preceq] L1 \wedge G, s \vdash (\lambda x::unit. l2)[\sim::\preceq](\lambda x::unit. L2))$
 $\langle \text{proof} \rangle$

lemma $defval\text{-conf1}$ $[rule\text{-format } (no\text{-asm}), \text{elim}]:$
 $is\text{-type } G \ T \longrightarrow (\exists v \in \text{Some } (default\text{-val } T): G, s \vdash v::\preceq T)$
 $\langle \text{proof} \rangle$

lemma $np\text{-no-jump}: x \neq \text{Some } (Jump \ j) \implies (np \ a') \ x \neq \text{Some } (Jump \ j)$
 $\langle \text{proof} \rangle$

declare $split\text{-paired-All}$ $[simp \ del]$ $split\text{-paired-Ex}$ $[simp \ del]$
declare $split\text{-if}$ $[split \ del]$ $split\text{-if-asm}$ $[split \ del]$
 $option.\text{split}$ $[split \ del]$ $option.\text{split-asm}$ $[split \ del]$
 $\langle ML \rangle$

lemma $conforms\text{-init-lvars}:$
 $[[wf\text{-mhead } G \ (pid \ declC) \ sig \ (mhead \ (mthd \ dm)); wf\text{-prog } G;$
 $list\text{-all2 } (conf \ G \ s) \ pvs \ pTsa; \ G \vdash \ pTsa[\preceq](parTs \ sig);$
 $(x, s)::\preceq(G, L);$
 $methd \ G \ declC \ sig = \text{Some } dm;$
 $isrtype \ G \ statT;$
 $G \vdash \text{inv}C \preceq_C \ declC;$

$G, s \vdash a' :: \preceq_{\text{RefT}} \text{statT};$
 $\text{invmode}(\text{mhd } \text{sm}) e = \text{IntVir} \longrightarrow a' \neq \text{Null};$
 $\text{invmode}(\text{mhd } \text{sm}) e \neq \text{IntVir} \longrightarrow$
 $(\exists \text{statC}. \text{statT} = \text{ClassT } \text{statC} \wedge G \vdash \text{statC} \preceq_C \text{declC})$
 $\vee (\forall \text{statC}. \text{statT} \neq \text{ClassT } \text{statC} \wedge \text{declC} = \text{Object});$
 $\text{invC} = \text{invocation-class}(\text{invmode}(\text{mhd } \text{sm}) e) s a' \text{statT};$
 $\text{declC} = \text{invocation-declclass } G(\text{invmode}(\text{mhd } \text{sm}) e) s a' \text{statT sig};$
 $x \neq \text{Some}(\text{Jump Ret})$
 $\parallel \implies$
 $\text{init-lvars } G \text{ declC sig}(\text{invmode}(\text{mhd } \text{sm}) e) a'$
 $\text{pvs}(x, s) :: \preceq(G, \lambda k.$
 $\quad (\text{case } k \text{ of}$
 $\quad \quad \text{ENam } e \Rightarrow (\text{case } e \text{ of}$
 $\quad \quad \quad \text{VNam } v$
 $\quad \quad \quad \Rightarrow (\text{table-of}(\text{lcls}(\text{mbody}(\text{mthd } \text{dm})))$
 $\quad \quad \quad \quad (\text{pars}(\text{mthd } \text{dm})[\mapsto] \text{parTs sig})) v$
 $\quad \quad \quad | \text{Res} \Rightarrow \text{Some}(\text{resTy}(\text{mthd } \text{dm})))$
 $\quad \quad | \text{This} \Rightarrow \text{if}(\text{is-static}(\text{mthd } \text{sm}))$
 $\quad \quad \quad \text{then None else Some}(\text{Class declC}))$
 $\langle \text{proof} \rangle$
declare *split-paired-All* [*simp*] *split-paired-Ex* [*simp*]
declare *split-if* [*split*] *split-if-asm* [*split*]
 option.split [*split*] option.split-asm [*split*]
 $\langle \text{ML} \rangle$

47 accessibility

theorem *dynamic-field-access-ok*:

assumes *wf*: *wf-prog* *G* **and**
 $\text{not-Null}: \neg \text{stat} \longrightarrow a \neq \text{Null}$ **and**
 $\text{conform-a}: G, (\text{store } s) \vdash a :: \preceq \text{Class } \text{statC}$ **and**
 $\text{conform-s}: s :: \preceq(G, L)$ **and**
 $\text{normal-s}: \text{normal } s$ **and**
 $\text{wt-e}: (\text{prg} = G, \text{cls} = \text{accC}, \text{lcl} = L) \vdash e :: - \text{Class } \text{statC}$ **and**
 $f: \text{accfield } G \text{ accC } \text{statC } \text{fn} = \text{Some } f$ **and**
 $\text{dynC}: \text{if } \text{stat} \text{ then } \text{dynC} = \text{declclass } f$
 $\quad \text{else } \text{dynC} = \text{obj-class}(\text{lookup-obj}(\text{store } s) a)$ **and**
 $\text{stat}: \text{if } \text{stat} \text{ then } (\text{is-static } f) \text{ else } (\neg \text{is-static } f)$
shows $\text{table-of}(\text{DeclConcepts.fields } G \text{ dynC})(\text{fn}, \text{declclass } f) = \text{Some}(\text{fld } f) \wedge$
 $G \vdash \text{Field } \text{fn } f \text{ in } \text{dynC } \text{dyn-accessible-from } \text{accC}$

$\langle \text{proof} \rangle$

lemma *error-free-field-access*:

assumes *accfield*: $\text{accfield } G \text{ accC } \text{statC } \text{fn} = \text{Some}(\text{statDeclC}, f)$ **and**
 $\text{wt-e}: (\text{prg} = G, \text{cls} = \text{accC}, \text{lcl} = L) \vdash e :: - \text{Class } \text{statC}$ **and**
 $\text{eval-init}: G \vdash \text{Norm } s0 - \text{Init } \text{statDeclC} \rightarrow s1$ **and**
 $\text{eval-e}: G \vdash s1 - e \rightarrow a \rightarrow s2$ **and**
 $\text{conf-s2}: s2 :: \preceq(G, L)$ **and**
 $\text{conf-a}: \text{normal } s2 \implies G, \text{store } s2 \vdash a :: \preceq \text{Class } \text{statC}$ **and**
 $\text{fvar}: (v, s2') = \text{fvar } \text{statDeclC}(\text{is-static } f) \text{fn } a \text{ } s2$ **and**
 $\text{wf}: \text{wf-prog } G$

shows $\text{check-field-access } G \text{ accC } \text{statDeclC } \text{fn}(\text{is-static } f) a \text{ } s2' = s2'$

$\langle \text{proof} \rangle$

lemma *call-access-ok*:

assumes *invC-prop*: $G \vdash \text{invmode } \text{statM } e \rightarrow \text{invC} \preceq \text{statT}$
and $\text{wf}: \text{wf-prog } G$

and $wt-e: (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash e :: -\text{RefT } \text{statT}$
and $\text{statM}: (\text{statDeclT}, \text{statM}) \in \text{mheads } G \text{ accC } \text{statT } \text{sig}$
and $\text{invC}: \text{invC} = \text{invocation-class } (\text{invmode } \text{statM } e) \text{ s } a \text{ statT}$
shows $\exists \text{ dynM}. \text{dynlookup } G \text{ statT } \text{invC } \text{sig} = \text{Some } \text{dynM} \wedge$
 $G \vdash \text{Method } \text{sig } \text{dynM} \text{ in } \text{invC } \text{dyn-accessible-from } \text{accC}$
 $\langle \text{proof} \rangle$

lemma *error-free-call-access*:

assumes
 $\text{eval-args}: G \vdash s1 \text{ -args} \dot{=} \text{vs} \rightarrow s2$ **and**
 $wt-e: (\text{prg} = G, \text{cls} = \text{accC}, \text{lcl} = L) \vdash e :: -(\text{RefT } \text{statT})$ **and**
 $\text{statM}: \text{max-spec } G \text{ accC } \text{statT } (\text{name} = \text{mn}, \text{parTs} = \text{pTs})$
 $= \{((\text{statDeclT}, \text{statM}), \text{pTs}')\}$ **and**
 $\text{conf-s2}: s2 :: \preceq(G, L)$ **and**
 $\text{conf-a}: \text{normal } s1 \implies G, \text{store } s1 \vdash a :: \preceq \text{RefT } \text{statT}$ **and**
 $\text{invProp}: \text{normal } s3 \implies$
 $G \vdash \text{invmode } \text{statM } e \rightarrow \text{invC} \preceq \text{statT}$ **and**
 $s3: s3 = \text{init-lvars } G \text{ invDeclC } (\text{name} = \text{mn}, \text{parTs} = \text{pTs}')$
 $(\text{invmode } \text{statM } e) \text{ a vs } s2$ **and**
 $\text{invC}: \text{invC} = \text{invocation-class } (\text{invmode } \text{statM } e) (\text{store } s2) \text{ a } \text{statT}$ **and**
 $\text{invDeclC}: \text{invDeclC} = \text{invocation-declclass } G (\text{invmode } \text{statM } e) (\text{store } s2)$
 $\text{a } \text{statT } (\text{name} = \text{mn}, \text{parTs} = \text{pTs}')$ **and**
 $wf: wf\text{-prog } G$
shows $\text{check-method-access } G \text{ accC } \text{statT } (\text{invmode } \text{statM } e) (\text{name}=\text{mn}, \text{parTs}=\text{pTs}') \text{ a } s3$
 $= s3$
 $\langle \text{proof} \rangle$

lemma *map-upds-eq-length-append-simp*:

$\bigwedge \text{tab } qs. \text{length } ps = \text{length } qs \implies \text{tab}(ps[\mapsto]qs @ zs) = \text{tab}(ps[\mapsto]qs)$
 $\langle \text{proof} \rangle$

lemma *map-upds-upd-eq-length-simp*:

$\bigwedge \text{tab } qs \text{ x y}. \text{length } ps = \text{length } qs$
 $\implies \text{tab}(ps[\mapsto]qs)(x \mapsto y) = \text{tab}(ps @ [x][\mapsto]qs @ [y])$
 $\langle \text{proof} \rangle$

lemma *map-upd-cong*: $\text{tab} = \text{tab}' \implies \text{tab}(x \mapsto y) = \text{tab}'(x \mapsto y)$

$\langle \text{proof} \rangle$

lemma *map-upd-cong-ext*: $\text{tab } z = \text{tab}' z \implies (\text{tab}(x \mapsto y)) z = (\text{tab}'(x \mapsto y)) z$

$\langle \text{proof} \rangle$

lemma *map-upds-cong*: $\text{tab} = \text{tab}' \implies \text{tab}(xs[\mapsto]ys) = \text{tab}'(xs[\mapsto]ys)$

$\langle \text{proof} \rangle$

lemma *map-upds-cong-ext*:

$\bigwedge \text{tab } \text{tab}' \text{ ys}. \text{tab } z = \text{tab}' z \implies (\text{tab}(xs[\mapsto]ys)) z = (\text{tab}'(xs[\mapsto]ys)) z$
 $\langle \text{proof} \rangle$

lemma *map-upd-override*: $(\text{tab}(x \mapsto y)) x = (\text{tab}'(x \mapsto y)) x$

$\langle proof \rangle$

lemma *map-upds-eq-length-suffix*: $\bigwedge tab\ qs.$

$$length\ ps = length\ qs \implies tab(ps@xs[\mapsto]qs) = tab(ps[\mapsto]qs)(xs[\mapsto][])$$

$\langle proof \rangle$

lemma *map-upds-upds-eq-length-prefix-simp*:

$$\bigwedge tab\ qs.\ length\ ps = length\ qs$$

$$\implies tab(ps[\mapsto]qs)(xs[\mapsto]ys) = tab(ps@xs[\mapsto]qs@ys)$$

$\langle proof \rangle$

lemma *map-upd-cut-irrelevant*:

$$\llbracket (tab(x\mapsto y))\ vn = Some\ el;\ (tab'(x\mapsto y))\ vn = None \rrbracket$$

$$\implies tab\ vn = Some\ el$$

$\langle proof \rangle$

lemma *map-upd-Some-expand*:

$$\llbracket tab\ vn = Some\ z \rrbracket$$

$$\implies \exists z.\ (tab(x\mapsto y))\ vn = Some\ z$$

$\langle proof \rangle$

lemma *map-upds-Some-expand*:

$$\bigwedge tab\ ys\ z.\ \llbracket tab\ vn = Some\ z \rrbracket$$

$$\implies \exists z.\ (tab(xs[\mapsto]ys))\ vn = Some\ z$$

$\langle proof \rangle$

lemma *map-upd-Some-swap*:

$$(tab(r\mapsto w)(u\mapsto v))\ vn = Some\ z \implies \exists z.\ (tab(u\mapsto v)(r\mapsto w))\ vn = Some\ z$$

$\langle proof \rangle$

lemma *map-upd-None-swap*:

$$(tab(r\mapsto w)(u\mapsto v))\ vn = None \implies (tab(u\mapsto v)(r\mapsto w))\ vn = None$$

$\langle proof \rangle$

lemma *map-eq-upd-eq*: $tab\ vn = tab'\ vn \implies (tab(x\mapsto y))\ vn = (tab'(x\mapsto y))\ vn$

$\langle proof \rangle$

lemma *map-upd-in-expansion-map-swap*:

$$\llbracket (tab(x\mapsto y))\ vn = Some\ z;\ tab\ vn \neq Some\ z \rrbracket$$

$$\implies (tab'(x\mapsto y))\ vn = Some\ z$$

$\langle proof \rangle$

lemma *map-upds-in-expansion-map-swap*:

$$\bigwedge tab\ tab'\ ys\ z.\ \llbracket (tab(xs[\mapsto]ys))\ vn = Some\ z;\ tab\ vn \neq Some\ z \rrbracket$$

$$\implies (tab'(xs[\mapsto]ys))\ vn = Some\ z$$

$\langle proof \rangle$

lemma *map-upds-Some-swap*:

assumes $r\text{-}u$: $(\text{tab}(r\mapsto w)(u\mapsto v)(xs[\mapsto]ys))\ vn = \text{Some } z$
shows $\exists z. (\text{tab}(u\mapsto v)(r\mapsto w)(xs[\mapsto]ys))\ vn = \text{Some } z$
 $\langle\text{proof}\rangle$

lemma *map-upds-Some-insert*:

assumes z : $(\text{tab}(xs[\mapsto]ys))\ vn = \text{Some } z$
shows $\exists z. (\text{tab}(u\mapsto v)(xs[\mapsto]ys))\ vn = \text{Some } z$
 $\langle\text{proof}\rangle$

lemma *map-upds-None-cut*:

assumes *expand-None*: $(\text{tab}(xs[\mapsto]ys))\ vn = \text{None}$
shows $\text{tab } vn = \text{None}$
 $\langle\text{proof}\rangle$

lemma *map-upds-cut-irrelevant*:

$\bigwedge \text{tab } \text{tab}'\ ys. \llbracket (\text{tab}(xs[\mapsto]ys))\ vn = \text{Some } el; (\text{tab}'(xs[\mapsto]ys))\ vn = \text{None} \rrbracket$
 $\implies \text{tab } vn = \text{Some } el$
 $\langle\text{proof}\rangle$

lemma *dom-vname-split*:

$\text{dom } (\text{lname-case } (\text{ename-case } (\text{tab}(x\mapsto y)(xs[\mapsto]ys))\ a)\ b)$
 $= \text{dom } (\text{lname-case } (\text{ename-case } (\text{tab}(x\mapsto y))\ a)\ b) \cup$
 $\text{dom } (\text{lname-case } (\text{ename-case } (\text{tab}(xs[\mapsto]ys))\ a)\ b)$
 $(\text{is } ?\text{List } x\ xs\ y\ ys = ?\text{Hd } x\ y \cup ?\text{Tl } xs\ ys)$
 $\langle\text{proof}\rangle$

lemma *dom-map-upd*: $\bigwedge \text{tab}. \text{dom } (\text{tab}(x\mapsto y)) = \text{dom } \text{tab} \cup \{x\}$

$\langle\text{proof}\rangle$

lemma *dom-map-upds*: $\bigwedge \text{tab } ys. \text{length } xs = \text{length } ys$

$\implies \text{dom } (\text{tab}(xs[\mapsto]ys)) = \text{dom } \text{tab} \cup \text{set } xs$
 $\langle\text{proof}\rangle$

lemma *dom-ename-case-None-simp*:

$\text{dom } (\text{ename-case } \text{vname-tab } \text{None}) = \text{VName } \text{' } (\text{dom } \text{vname-tab})$
 $\langle\text{proof}\rangle$

lemma *dom-ename-case-Some-simp*:

$\text{dom } (\text{ename-case } \text{vname-tab } (\text{Some } a)) = \text{VName } \text{' } (\text{dom } \text{vname-tab}) \cup \{\text{Res}\}$
 $\langle\text{proof}\rangle$

lemma *dom-lname-case-None-simp*:

$\text{dom } (\text{lname-case } \text{ename-tab } \text{None}) = \text{EName } \text{' } (\text{dom } \text{ename-tab})$
 $\langle\text{proof}\rangle$

lemma *dom-lname-case-Some-simp*:

$dom (lname\text{-}case\ ensame\text{-}tab (Some\ a)) = EName\ ' (dom\ ensame\text{-}tab) \cup \{This\}$
 ⟨proof⟩

lemmas *dom-lname-ename-case-simps* =

dom-ename-case-None-simp dom-ename-case-Some-simp

dom-lname-case-None-simp dom-lname-case-Some-simp

lemma *image-comp*:

$f\ ' g\ ' A = (f\ \circ\ g)\ ' A$
 ⟨proof⟩

lemma *dom-locals-init-lvars*:

assumes *m*: $m = (mthd\ (the\ (methd\ G\ C\ sig)))$

assumes *len*: $length\ (pars\ m) = length\ pvs$

shows $dom\ (locals\ (store\ (init\text{-}lvars\ G\ C\ sig\ (invmode\ m\ e)\ a\ pvs\ s)))$
 $= parameters\ m$

⟨proof⟩

lemma *da-e2-BinOp*:

assumes *da*: $(\prg = G, cls = accC, lcl = L)$

$\vdash dom\ (locals\ (store\ s0)) \gg \langle BinOp\ binop\ e1\ e2 \rangle_e \gg A$

and *wt-e1*: $(\prg = G, cls = accC, lcl = L) \vdash e1 :: -e1T$

and *wt-e2*: $(\prg = G, cls = accC, lcl = L) \vdash e2 :: -e2T$

and *wt-binop*: $wt\text{-}binop\ G\ binop\ e1T\ e2T$

and *conf-s0*: $s0 :: \preceq (G, L)$

and *normal-s1*: $normal\ s1$

and *eval-e1*: $G \vdash s0\ -e1 \text{-} \succ v1 \rightarrow s1$

and *conf-v1*: $G, store\ s1 \vdash v1 :: \preceq e1T$

and *wf*: $wf\text{-}prog\ G$

shows $\exists E2. (\prg = G, cls = accC, lcl = L) \vdash dom\ (locals\ (store\ s1))$

$\gg (if\ need\text{-}second\text{-}arg\ binop\ v1\ then\ \langle e2 \rangle_e\ else\ \langle Skip \rangle_s) \gg E2$

⟨proof⟩

main proof of type safety

lemma *eval-type-sound*:

assumes *eval*: $G \vdash s0\ -t \succ \rightarrow (v, s1)$

and *wt*: $(\prg = G, cls = accC, lcl = L) \vdash t :: T$

and *da*: $(\prg = G, cls = accC, lcl = L) \vdash dom\ (locals\ (store\ s0)) \gg t \gg A$

and *wf*: $wf\text{-}prog\ G$

and *conf-s0*: $s0 :: \preceq (G, L)$

shows $s1 :: \preceq (G, L) \wedge (normal\ s1 \rightarrow G, L, store\ s1 \vdash t \succ v :: \preceq T) \wedge$
 $(error\text{-}free\ s0 = error\text{-}free\ s1)$

⟨proof⟩

corollary *eval-type-soundE* [consumes 5]:

assumes *eval*: $G \vdash s0\ -t \succ \rightarrow (v, s1)$

and *conf*: $s0 :: \preceq (G, L)$

and *wt*: $(\prg = G, cls = accC, lcl = L) \vdash t :: T$

and *da*: $(\prg = G, cls = accC, lcl = L) \vdash dom\ (locals\ (snd\ s0)) \gg t \gg A$

and *wf*: $wf\text{-}prog\ G$

and *elim*: $\llbracket s1 :: \preceq (G, L); normal\ s1 \implies G, L, snd\ s1 \vdash t \succ v :: \preceq T \rrbracket$

$$\text{error-free } s0 = \text{error-free } s1 \Longrightarrow P$$

shows P

$\langle \text{proof} \rangle$

corollary *eval-ts*:

$$\begin{aligned} & \llbracket G \vdash s - e \rightarrow v \rightarrow s'; \text{wf-prog } G; s::\preceq(G,L); (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash e::-T; \\ & \quad (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } s)) \gg \text{In1l } e \gg A \rrbracket \\ \implies & \quad s'::\preceq(G,L) \wedge (\text{normal } s' \longrightarrow G, \text{store } s \uparrow v::\preceq T) \wedge \\ & \quad (\text{error-free } s = \text{error-free } s') \end{aligned}$$

$\langle \text{proof} \rangle$

corollary *evals-ts*:

$$\begin{aligned} & \llbracket G \vdash s - es \rightarrow vs \rightarrow s'; \text{wf-prog } G; s::\preceq(G,L); (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash es::\doteq Ts; \\ & \quad (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } s)) \gg \text{In3 } es \gg A \rrbracket \\ \implies & \quad s'::\preceq(G,L) \wedge (\text{normal } s' \longrightarrow \text{list-all2 } (\text{conf } G (\text{store } s')) \text{ vs } Ts) \wedge \\ & \quad (\text{error-free } s = \text{error-free } s') \end{aligned}$$

$\langle \text{proof} \rangle$

corollary *evar-ts*:

$$\begin{aligned} & \llbracket G \vdash s - v \rightarrow vf \rightarrow s'; \text{wf-prog } G; s::\preceq(G,L); (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash v::=T; \\ & \quad (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } s)) \gg \text{In2 } v \gg A \rrbracket \implies \\ & \quad s'::\preceq(G,L) \wedge (\text{normal } s' \longrightarrow G, L, (\text{store } s') \vdash \text{In2 } v \gg \text{In2 } vf::\preceq \text{Inl } T) \wedge \\ & \quad (\text{error-free } s = \text{error-free } s') \end{aligned}$$

$\langle \text{proof} \rangle$

theorem *exec-ts*:

$$\begin{aligned} & \llbracket G \vdash s - c \rightarrow s'; \text{wf-prog } G; s::\preceq(G,L); (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash c::\surd; \\ & \quad (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } s)) \gg \text{In1r } c \gg A \rrbracket \\ \implies & \quad s'::\preceq(G,L) \wedge (\text{error-free } s \longrightarrow \text{error-free } s') \end{aligned}$$

$\langle \text{proof} \rangle$

lemma *wf-eval-Fin*:

assumes *wf*: $\text{wf-prog } G$

and *wt-c1*: $(\text{prg} = G, \text{cls} = C, \text{lcl} = L) \vdash \text{In1r } c1::\text{Inl } (\text{PrimT } \text{Void})$

and *da-c1*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } (\text{Norm } s0))) \gg \text{In1r } c1 \gg A$

and *conf-s0*: $\text{Norm } s0::\preceq(G, L)$

and *eval-c1*: $G \vdash \text{Norm } s0 - c1 \rightarrow (x1, s1)$

and *eval-c2*: $G \vdash \text{Norm } s1 - c2 \rightarrow s2$

and $s3: s3 = \text{abupd } (\text{abrupt-if } (x1 \neq \text{None}) x1) s2$

shows $G \vdash \text{Norm } s0 - c1 \text{ Finally } c2 \rightarrow s3$

$\langle \text{proof} \rangle$

48 Ideas for the future

In the type soundness proof and the correctness proof of definite assignment we perform induction on the evaluation relation with the further preconditions that the term is welltyped and definitely assigned. During the proofs we have to establish the welltypedness and definite assignment of the subterms to be able to apply the induction hypothesis. So large parts of both proofs are the same work in propagating welltypedness and definite assignment. So we can derive a new induction rule for induction on the evaluation of a wellformed term, were these propagations is already done, once and forever. Then we can do the proofs with this rule and can enjoy the time we have saved. Here is a first and incomplete sketch of such a rule.

theorem *wellformed-eval-induct* [*consumes 4, case-names Abrupt Skip Expr Lab Comp If*]:

assumes *eval*: $G \vdash s0 - t \rightarrow (v, s1)$

and $wt: (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash t::T$
and $da: (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash \text{dom} (\text{locals} (\text{store } s0)) \gg t \gg A$
and $wf: wf\text{-prog } G$
and $\text{abrupt}: \bigwedge s \ t \ \text{abr} \ L \ \text{acc}C \ T \ A.$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash t::T;$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash \text{dom} (\text{locals} (\text{store} (\text{Some } \text{abr}, s))) \gg t \gg A$
 $\rrbracket \implies P \ L \ \text{acc}C \ (\text{Some } \text{abr}, s) \ t \ (\text{undefined3 } t) \ (\text{Some } \text{abr}, s)$
and $\text{skip}: \bigwedge s \ L \ \text{acc}C. P \ L \ \text{acc}C \ (\text{Norm } s) \ \langle \text{Skip} \rangle_s \ \diamond (\text{Norm } s)$
and $\text{expr}: \bigwedge e \ s0 \ s1 \ v \ L \ \text{acc}C \ eT \ E.$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash e:: -eT;$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L)$
 $\vdash \text{dom} (\text{locals} (\text{store} ((\text{Norm } s0)::\text{state}))) \gg \langle e \rangle_e \gg E;$
 $P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle e \rangle_e \ [v]_e \ s1 \rrbracket$
 $\implies P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle \text{Expr } e \rangle_s \ \diamond s1$
and $\text{lab}: \bigwedge c \ l \ s0 \ s1 \ L \ \text{acc}C \ C.$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash c::\sqrt{;};$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L)$
 $\vdash \text{dom} (\text{locals} (\text{store} ((\text{Norm } s0)::\text{state}))) \gg \langle c \rangle_s \gg C;$
 $P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle c \rangle_s \ \diamond s1 \rrbracket$
 $\implies P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle l \cdot c \rangle_s \ \diamond (\text{abupd} (\text{absorb } l) \ s1)$
and $\text{comp}: \bigwedge c1 \ c2 \ s0 \ s1 \ s2 \ L \ \text{acc}C \ C1.$
 $\llbracket G \vdash \text{Norm } s0 \ -c1 \ \rightarrow \ s1; G \vdash s1 \ -c2 \ \rightarrow \ s2;$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash c1::\sqrt{;};$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash c2::\sqrt{;};$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash$
 $\text{dom} (\text{locals} (\text{store} ((\text{Norm } s0)::\text{state}))) \gg \langle c1 \rangle_s \gg C1;$
 $P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle c1 \rangle_s \ \diamond s1;$
 $\wedge Q. \llbracket \text{normal } s1;$
 $\wedge C2. \llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L)$
 $\vdash \text{dom} (\text{locals} (\text{store } s1)) \gg \langle c2 \rangle_s \gg C2;$
 $P \ L \ \text{acc}C \ s1 \ \langle c2 \rangle_s \ \diamond s2 \rrbracket \implies Q$
 $\rrbracket \implies Q$
 $\rrbracket \implies P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle c1;; c2 \rangle_s \ \diamond s2$
and $\text{if}: \bigwedge b \ c1 \ c2 \ e \ s0 \ s1 \ s2 \ L \ \text{acc}C \ E.$
 $\llbracket G \vdash \text{Norm } s0 \ -e \ \rightarrow b \rightarrow s1;$
 $G \vdash s1 \ -(\text{if the-Bool } b \ \text{then } c1 \ \text{else } c2) \rightarrow s2;$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash e:: -\text{PrimT Boolean};$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash (\text{if the-Bool } b \ \text{then } c1 \ \text{else } c2)::\sqrt{;};$
 $\llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash$
 $\text{dom} (\text{locals} (\text{store} ((\text{Norm } s0)::\text{state}))) \gg \langle e \rangle_e \gg E;$
 $P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle e \rangle_e \ [b]_e \ s1;$
 $\wedge Q. \llbracket \text{normal } s1;$
 $\wedge C. \llbracket (\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash (\text{dom} (\text{locals} (\text{store } s1)))$
 $\gg \langle \text{if the-Bool } b \ \text{then } c1 \ \text{else } c2 \rangle_s \gg C;$
 $P \ L \ \text{acc}C \ s1 \ \langle \text{if the-Bool } b \ \text{then } c1 \ \text{else } c2 \rangle_s \ \diamond s2$
 $\rrbracket \implies Q$
 $\rrbracket \implies Q$
 $\rrbracket \implies P \ L \ \text{acc}C \ (\text{Norm } s0) \ \langle \text{If}(e) \ c1 \ \text{Else } c2 \rangle_s \ \diamond s2$

shows $P \ L \ \text{acc}C \ s0 \ t \ v \ s1$

$\langle \text{proof} \rangle$

end

Chapter 20

Evaln

49 Operational evaluation (big-step) semantics of Java expressions and statements

theory *Evaln* imports *TypeSafe* begin

Variant of *eval* relation with counter for bounded recursive depth. In principal *evaln* could replace *eval*.

Validity of the axiomatic semantics builds on *evaln*. For recursive method calls the axiomatic semantics rule assumes the method ok to derive a proof for the body. To prove the method rule sound we need to perform induction on the recursion depth. For the completeness proof of the axiomatic semantics the notion of the most general formula is used. The most general formula right now builds on the ordinary evaluation relation *eval*. So sometimes we have to switch between *evaln* and *eval* and vice versa. To make this switch easy *evaln* also does all the technical accessibility tests *check-field-access* and *check-method-access* like *eval*. If it would omit them *evaln* and *eval* would only be equivalent for welltyped, and definitely assigned terms.

inductive

```

evaln :: [prog, state, term, nat, vals, state] => bool
  (+- -->----> '(-, -') [61,61,80,61,0,0] 60)
and evaln :: [prog, state, var, vvar, nat, state] => bool
  (+- --=>----> - [61,61,90,61,61,61] 60)
and evaln :: [prog, state, expr, val, nat, state] => bool
  (+- ---->----> - [61,61,80,61,61,61] 60)
and evalsn :: [prog, state, expr list, val list, nat, state] => bool
  (+- --≡>----> - [61,61,61,61,61,61] 60)
and execn :: [prog, state, stmt, nat, state] => bool
  (+- ---->----> - [61,61,65, 61,61] 60)
for G :: prog

```

where

```

  G⊢s -c -n→ s' ≡ G⊢s -In1r c>-n→ (◇ , s')
| G⊢s -e->v -n→ s' ≡ G⊢s -In1l e>-n→ (In1 v , s')
| G⊢s -e=>vf -n→ s' ≡ G⊢s -In2 e>-n→ (In2 vf , s')
| G⊢s -e≡>v -n→ s' ≡ G⊢s -In3 e>-n→ (In3 v , s')

```

— propagation of abrupt completion

```
| Abrupt: G⊢(Some xc,s) -t>-n→ (undefined3 t,(Some xc,s))
```

— evaluation of variables

```

| LVar: G⊢Norm s -LVar vn=>lvar vn s-n→ Norm s
| FVar: [[G⊢Norm s0 -Init statDeclC-n→ s1; G⊢s1 -e->a-n→ s2;
  (v,s2') = fvar statDeclC stat fn a s2;
  s3 = check-field-access G accC statDeclC fn stat a s2']] =>
  G⊢Norm s0 -{accC,statDeclC,stat}e..fn=>v-n→ s3
| AVar: [[G⊢ Norm s0 -e1->a-n→ s1 ; G⊢s1 -e2->i-n→ s2;
  (v,s2') = avar G i a s2]] =>
  G⊢Norm s0 -e1.[e2]=>v-n→ s2'

```

— evaluation of expressions

```
| NewC: [[G⊢Norm s0 -Init C-n→ s1;
```

- $$G \vdash \quad s1 \text{ -halloc } (CInst \ C) \succ a \rightarrow s2 \implies \\ G \vdash Norm \ s0 \text{ -NewC } C \rightarrow Addr \ a \text{ -n} \rightarrow s2$$
- | *NewA*: $\llbracket G \vdash Norm \ s0 \text{ -init-comp-ty } T \text{ -n} \rightarrow s1; G \vdash s1 \text{ -e} \rightarrow i' \text{ -n} \rightarrow s2; \\ G \vdash abupd \ (check\text{-neg } i') \ s2 \text{ -halloc } (Arr \ T \ (the\text{-Intg } i')) \succ a \rightarrow s3 \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -New } T[e] \rightarrow Addr \ a \text{ -n} \rightarrow s3$
- | *Cast*: $\llbracket G \vdash Norm \ s0 \text{ -e} \rightarrow v \text{ -n} \rightarrow s1; \\ s2 = abupd \ (raise\text{-if } (\neg G, \text{snd } s1 \vdash v \text{ fits } T) \ ClassCast) \ s1 \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -Cast } T \ e \rightarrow v \text{ -n} \rightarrow s2$
- | *Inst*: $\llbracket G \vdash Norm \ s0 \text{ -e} \rightarrow v \text{ -n} \rightarrow s1; \\ b = (v \neq Null \wedge G, \text{store } s1 \vdash v \text{ fits } RefT \ T) \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -e } InstOf \ T \rightarrow Bool \ b \text{ -n} \rightarrow s1$
- | *Lit*: $G \vdash Norm \ s \text{ -Lit } v \rightarrow v \text{ -n} \rightarrow Norm \ s$
- | *UnOp*: $\llbracket G \vdash Norm \ s0 \text{ -e} \rightarrow v \text{ -n} \rightarrow s1 \rrbracket \\ \implies G \vdash Norm \ s0 \text{ -UnOp } unop \ e \rightarrow (eval\text{-unop } unop \ v) \text{ -n} \rightarrow s1$
- | *BinOp*: $\llbracket G \vdash Norm \ s0 \text{ -e1} \rightarrow v1 \text{ -n} \rightarrow s1; \\ G \vdash s1 \text{ -(if need-second-arg binop v1 then (In1l e2) else (In1r Skip))} \\ \rightarrow \text{-n} \rightarrow (In1 \ v2, s2) \rrbracket \\ \implies G \vdash Norm \ s0 \text{ -BinOp } binop \ e1 \ e2 \rightarrow (eval\text{-binop } binop \ v1 \ v2) \text{ -n} \rightarrow s2$
- | *Super*: $G \vdash Norm \ s \text{ -Super} \rightarrow val\text{-this } s \text{ -n} \rightarrow Norm \ s$
- | *Acc*: $\llbracket G \vdash Norm \ s0 \text{ -va} \rightarrow (v, f) \text{ -n} \rightarrow s1 \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -Acc } va \rightarrow v \text{ -n} \rightarrow s1$
- | *Ass*: $\llbracket G \vdash Norm \ s0 \text{ -va} \rightarrow (w, f) \text{ -n} \rightarrow s1; \\ G \vdash \quad s1 \text{ -e} \rightarrow v \quad \text{-n} \rightarrow s2 \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -va} := e \rightarrow v \text{ -n} \rightarrow assign \ f \ v \ s2$
- | *Cond*: $\llbracket G \vdash Norm \ s0 \text{ -e0} \rightarrow b \text{ -n} \rightarrow s1; \\ G \vdash \quad s1 \text{ -(if the-Bool } b \text{ then } e1 \text{ else } e2) \rightarrow v \text{ -n} \rightarrow s2 \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -e0 } ? \ e1 : e2 \rightarrow v \text{ -n} \rightarrow s2$
- | *Call*:
 $\llbracket G \vdash Norm \ s0 \text{ -e} \rightarrow a' \text{ -n} \rightarrow s1; G \vdash s1 \text{ -args} \rightarrow vs \text{ -n} \rightarrow s2; \\ D = invocation\text{-declclass } G \ mode \ (store \ s2) \ a' \ statT \ (\{name=mn, parTs=pTs\}); \\ s3 = init\text{-lvars } G \ D \ (\{name=mn, parTs=pTs\}) \ mode \ a' \ vs \ s2; \\ s3' = check\text{-method-access } G \ accC \ statT \ mode \ (\{name=mn, parTs=pTs\}) \ a' \ s3; \\ G \vdash s3' \text{ -Methd } D \ (\{name=mn, parTs=pTs\}) \rightarrow v \text{ -n} \rightarrow s4 \\ \rrbracket \\ \implies \\ G \vdash Norm \ s0 \text{ -}\{accC, statT, mode\} \ e \cdot mn \ (\{pTs\} \ args) \rightarrow v \text{ -n} \rightarrow (restore\text{-lvars } s2 \ s4)$
- | *Methd*: $\llbracket G \vdash Norm \ s0 \text{ -body } G \ D \ sig \rightarrow v \text{ -n} \rightarrow s1 \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -Methd } D \ sig \rightarrow v \text{ -Suc } n \rightarrow s1$
- | *Body*: $\llbracket G \vdash Norm \ s0 \text{ -Init } D \text{ -n} \rightarrow s1; G \vdash s1 \text{ -c} \text{ -n} \rightarrow s2; \\ s3 = (if \ (\exists \ l. abrupt \ s2 = Some \ (Jump \ (Break \ l))) \vee \\ abrupt \ s2 = Some \ (Jump \ (Cont \ l))) \\ then \ abupd \ (\lambda \ x. Some \ (Error \ CrossMethodJump)) \ s2 \\ else \ s2) \rrbracket \implies \\ G \vdash Norm \ s0 \text{ -Body } D \ c \\ \rightarrow the \ (locals \ (store \ s2) \ Result) \text{ -n} \rightarrow abupd \ (absorb \ Ret) \ s3$

— evaluation of expression lists

| *Nil*:
$$G \vdash \text{Norm } s0 \text{ --} [\dot{=} \succ] \text{--} n \rightarrow \text{Norm } s0$$

| *Cons*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} e \text{ --} \succ v \text{ --} n \rightarrow s1; \\ & \quad G \vdash \quad s1 \text{ --} es \dot{=} \succ vs \text{ --} n \rightarrow s2 \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} e \# es \dot{=} \succ v \# vs \text{ --} n \rightarrow s2 \end{aligned}$$

— execution of statements

| *Skip*:
$$G \vdash \text{Norm } s \text{ --} \text{Skip} \text{--} n \rightarrow \text{Norm } s$$

| *Expr*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} e \text{ --} \succ v \text{ --} n \rightarrow s1 \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} \text{Expr } e \text{--} n \rightarrow s1 \end{aligned}$$

| *Lab*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} c \text{ --} n \rightarrow s1 \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} l \cdot c \text{--} n \rightarrow \text{abupd } (\text{absorb } l) s1 \end{aligned}$$

| *Comp*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} c1 \text{ --} n \rightarrow s1; \\ & \quad G \vdash \quad s1 \text{ --} c2 \text{ --} n \rightarrow s2 \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} c1;; c2 \text{--} n \rightarrow s2 \end{aligned}$$

| *If*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} e \text{ --} \succ b \text{--} n \rightarrow s1; \\ & \quad G \vdash \quad s1 \text{ --} (\text{if the-Bool } b \text{ then } c1 \text{ else } c2) \text{--} n \rightarrow s2 \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} \text{If}(e) c1 \text{ Else } c2 \text{--} n \rightarrow s2 \end{aligned}$$

| *Loop*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} e \text{ --} \succ b \text{--} n \rightarrow s1; \\ & \quad \text{if the-Bool } b \\ & \quad \quad \text{then } (G \vdash s1 \text{ --} c \text{--} n \rightarrow s2 \wedge \\ & \quad \quad \quad G \vdash (\text{abupd } (\text{absorb } (\text{Cont } l)) s2) \text{ --} l \cdot \text{While}(e) c \text{--} n \rightarrow s3) \\ & \quad \quad \text{else } s3 = s1 \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} l \cdot \text{While}(e) c \text{--} n \rightarrow s3 \end{aligned}$$

| *Jmp*:
$$G \vdash \text{Norm } s \text{ --} \text{Jmp } j \text{--} n \rightarrow (\text{Some } (\text{Jump } j), s)$$

| *Throw*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} e \text{ --} \succ a' \text{--} n \rightarrow s1 \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} \text{Throw } e \text{--} n \rightarrow \text{abupd } (\text{throw } a') s1 \end{aligned}$$

| *Try*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} c1 \text{--} n \rightarrow s1; G \vdash s1 \text{ --} \text{salloc} \rightarrow s2; \\ & \quad \text{if } G, s2 \vdash \text{catch } tn \text{ then } G \vdash \text{new-xcpt-var } vn \text{ } s2 \text{ --} c2 \text{--} n \rightarrow s3 \text{ else } s3 = s2 \rrbracket \\ & \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} \text{Try } c1 \text{ Catch}(tn \text{ } vn) \text{ } c2 \text{--} n \rightarrow s3 \end{aligned}$$

| *Fin*:
$$\begin{aligned} & \llbracket G \vdash \text{Norm } s0 \text{ --} c1 \text{--} n \rightarrow (x1, s1); \\ & \quad G \vdash \text{Norm } s1 \text{ --} c2 \text{--} n \rightarrow s2; \\ & \quad s3 = (\text{if } (\exists \text{ err. } x1 = \text{Some } (\text{Error } \text{err})) \\ & \quad \quad \text{then } (x1, s1) \\ & \quad \quad \text{else } \text{abupd } (\text{abrupt-if } (x1 \neq \text{None}) x1) s2) \rrbracket \implies \\ & \quad G \vdash \text{Norm } s0 \text{ --} c1 \text{ Finally } c2 \text{--} n \rightarrow s3 \end{aligned}$$

| *Init*:
$$\begin{aligned} & \llbracket \text{the } (\text{class } G \text{ } C) = c; \\ & \quad \text{if } \text{inited } C \text{ (globs } s0) \text{ then } s3 = \text{Norm } s0 \\ & \quad \text{else } (G \vdash \text{Norm } (\text{init-class-obj } G \text{ } C \text{ } s0) \\ & \quad \quad \text{--} (\text{if } C = \text{Object then Skip else Init } (\text{super } c)) \text{--} n \rightarrow s1 \wedge \\ & \quad \quad G \vdash \text{set-lvars empty } s1 \text{ --} \text{init } c \text{--} n \rightarrow s2 \wedge \\ & \quad \quad s3 = \text{restore-lvars } s1 \text{ } s2) \rrbracket \\ & \implies \end{aligned}$$

$$G \vdash \text{Norm } s0 \text{ --Init } C \text{ --}n \rightarrow s3$$

monos

if-bool-eq-conj

declare *split-if* [*split del*] *split-if-asm* [*split del*]
option.split [*split del*] *option.split-asm* [*split del*]
not-None-eq [*simp del*]
split-paired-All [*simp del*] *split-paired-Ex* [*simp del*]

$\langle ML \rangle$

inductive-cases *evaln-cases*: $G \vdash s \text{ --}t \succ \text{--}n \rightarrow (v, s')$

inductive-cases *evaln-elim-cases*:

$G \vdash (\text{Some } xc, s) \text{ --}t$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1r } \text{Skip}$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1r } (\text{Jmp } j)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1r } (l \cdot c)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In3 } (\llbracket \rrbracket)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In3 } (e \# es)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{Lit } w)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{UnOp } unop \ e)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{BinOp } binop \ e1 \ e2)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In2 } (\text{LVar } vn)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{Cast } T \ e)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (e \ \text{InstOf } T)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{Super})$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{Acc } va)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1r } (\text{Expr } e)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1r } (c1 ;; c2)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{Methd } C \ \text{sig})$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{Body } D \ c)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1l } (e0 \ ? \ e1 : e2)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1r } (\text{If } (e) \ c1 \ \text{Else } c2)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1r } (l \cdot \text{While } (e) \ c)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1r } (c1 \ \text{Finally } c2)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1r } (\text{Throw } e)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{NewC } C)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{New } T[e])$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\text{Ass } va \ e)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1r } (\text{Try } c1 \ \text{Catch } (tn \ vn) \ c2)$	$\succ \text{--}n \rightarrow (x, s')$
$G \vdash \text{Norm } s \text{ --In2 } (\{\text{accC}, \text{statDeclC}, \text{stat}\} e..fn)$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In2 } (e1.[e2])$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1l } (\{\text{accC}, \text{statT}, \text{mode}\} e.mn(\{pT\}p))$	$\succ \text{--}n \rightarrow (v, s')$
$G \vdash \text{Norm } s \text{ --In1r } (\text{Init } C)$	$\succ \text{--}n \rightarrow (x, s')$

declare *split-if* [*split*] *split-if-asm* [*split*]
option.split [*split*] *option.split-asm* [*split*]
not-None-eq [*simp*]
split-paired-All [*simp*] *split-paired-Ex* [*simp*]

$\langle ML \rangle$

lemma *evaln-Inj-elim*: $G \vdash s \text{ --}t \succ \text{--}n \rightarrow (w, s') \implies \text{case } t \text{ of In1 } ec \implies$

$(\text{case } ec \text{ of In1 } e \implies (\exists v. w = \text{In1 } v) \mid \text{Inr } c \implies w = \diamond)$

$\mid \text{In2 } e \implies (\exists v. w = \text{In2 } v) \mid \text{In3 } e \implies (\exists v. w = \text{In3 } v)$

$\langle \text{proof} \rangle$

The following simplification procedures set up the proper injections of terms and their corresponding

values in the evaluation relation: E.g. an expression (injection *In1l* into terms) always evaluates to ordinary values (injection *In1* into generalised values *vals*).

lemma *evaln-expr-eq*: $G\vdash s -In1l\ t \succ -n \rightarrow (w, s') = (\exists v. w=In1\ v \wedge G\vdash s -t \succ v -n \rightarrow s')$
 ⟨proof⟩

lemma *evaln-var-eq*: $G\vdash s -In2\ t \succ -n \rightarrow (w, s') = (\exists vf. w=In2\ vf \wedge G\vdash s -t \succ vf -n \rightarrow s')$
 ⟨proof⟩

lemma *evaln-exprs-eq*: $G\vdash s -In3\ t \succ -n \rightarrow (w, s') = (\exists vs. w=In3\ vs \wedge G\vdash s -t \succ vs -n \rightarrow s')$
 ⟨proof⟩

lemma *evaln-stmt-eq*: $G\vdash s -In1r\ t \succ -n \rightarrow (w, s') = (w=\diamond \wedge G\vdash s -t -n \rightarrow s')$
 ⟨proof⟩

⟨ML⟩

declare *evaln-AbruptIs* [intro!]

lemma *evaln-Callee*: $G\vdash Norm\ s -In1l\ (Callee\ l\ e) \succ -n \rightarrow (v, s') = False$
 ⟨proof⟩

lemma *evaln-InsInitE*: $G\vdash Norm\ s -In1l\ (InsInitE\ c\ e) \succ -n \rightarrow (v, s') = False$
 ⟨proof⟩

lemma *evaln-InsInitV*: $G\vdash Norm\ s -In2\ (InsInitV\ c\ w) \succ -n \rightarrow (v, s') = False$
 ⟨proof⟩

lemma *evaln-FinA*: $G\vdash Norm\ s -In1r\ (FinA\ a\ c) \succ -n \rightarrow (v, s') = False$
 ⟨proof⟩

lemma *evaln-abrupt-lemma*: $G\vdash s -e \succ -n \rightarrow (v, s') \implies$
 $fst\ s = Some\ xc \implies s' = s \wedge v = undefined3\ e$
 ⟨proof⟩

lemma *evaln-abrupt*:

$\bigwedge s'. G\vdash (Some\ xc, s) -e \succ -n \rightarrow (w, s') = (s' = (Some\ xc, s) \wedge$
 $w=undefined3\ e \wedge G\vdash (Some\ xc, s) -e \succ -n \rightarrow (undefined3\ e, (Some\ xc, s)))$
 ⟨proof⟩

⟨ML⟩

lemma *evaln-LitI*: $G\vdash s -Lit\ v \succ (if\ normal\ s\ then\ v\ else\ undefined) -n \rightarrow s$
 ⟨proof⟩

lemma *CondI*:

$\bigwedge s1. \llbracket G\vdash s -e \succ b -n \rightarrow s1; G\vdash s1 - (if\ the\ Bool\ b\ then\ e1\ else\ e2) \succ v -n \rightarrow s2 \rrbracket \implies$
 $G\vdash s -e\ ?\ e1 : e2 \succ (if\ normal\ s1\ then\ v\ else\ undefined) -n \rightarrow s2$
 ⟨proof⟩

lemma *evaln-SkipI* [*intro!*]: $G \vdash s - \text{Skip} - n \rightarrow s$
 ⟨*proof*⟩

lemma *evaln-ExprI*: $G \vdash s - e - \succ v - n \rightarrow s' \implies G \vdash s - \text{Expr } e - n \rightarrow s'$
 ⟨*proof*⟩

lemma *evaln-CompI*: $\llbracket G \vdash s - c1 - n \rightarrow s1; G \vdash s1 - c2 - n \rightarrow s2 \rrbracket \implies G \vdash s - c1;; c2 - n \rightarrow s2$
 ⟨*proof*⟩

lemma *evaln-IfI*:
 $\llbracket G \vdash s - e - \succ v - n \rightarrow s1; G \vdash s1 - (\text{if the-Bool } v \text{ then } c1 \text{ else } c2) - n \rightarrow s2 \rrbracket \implies$
 $G \vdash s - \text{If}(e) \ c1 \ \text{Else } c2 - n \rightarrow s2$
 ⟨*proof*⟩

lemma *evaln-SkipD* [*dest!*]: $G \vdash s - \text{Skip} - n \rightarrow s' \implies s' = s$
 ⟨*proof*⟩

lemma *evaln-Skip-eq* [*simp*]: $G \vdash s - \text{Skip} - n \rightarrow s' = (s = s')$
 ⟨*proof*⟩

evaln implies eval

lemma *evaln-eval*:
assumes *evaln*: $G \vdash s0 - t \succ - n \rightarrow (v, s1)$
shows $G \vdash s0 - t \succ \rightarrow (v, s1)$
 ⟨*proof*⟩

lemma *Suc-le-D-lemma*: $\llbracket \text{Suc } n \leq m'; (\bigwedge m. n \leq m \implies P (\text{Suc } m)) \rrbracket \implies P m'$
 ⟨*proof*⟩

lemma *evaln-nonstrict* [*rule-format (no-asm), elim*]:
 $G \vdash s - t \succ - n \rightarrow (w, s') \implies \forall m. n \leq m \longrightarrow G \vdash s - t \succ - m \rightarrow (w, s')$
 ⟨*proof*⟩

lemmas *evaln-nonstrict-Suc = evaln-nonstrict* [*OF - le-refl [THEN le-SucI]*]

lemma *evaln-max2*: $\llbracket G \vdash s1 - t1 \succ - n1 \rightarrow (w1, s1'); G \vdash s2 - t2 \succ - n2 \rightarrow (w2, s2') \rrbracket \implies$
 $G \vdash s1 - t1 \succ - \text{max } n1 \ n2 \rightarrow (w1, s1') \wedge G \vdash s2 - t2 \succ - \text{max } n1 \ n2 \rightarrow (w2, s2')$
 ⟨*proof*⟩

corollary *evaln-max2E* [*consumes 2*]:
 $\llbracket G \vdash s1 - t1 \succ - n1 \rightarrow (w1, s1'); G \vdash s2 - t2 \succ - n2 \rightarrow (w2, s2') \rrbracket$
 $\llbracket G \vdash s1 - t1 \succ - \text{max } n1 \ n2 \rightarrow (w1, s1'); G \vdash s2 - t2 \succ - \text{max } n1 \ n2 \rightarrow (w2, s2') \rrbracket \implies P \rrbracket \implies P$
 ⟨*proof*⟩

lemma *evaln-max3*:
 $\llbracket G \vdash s1 - t1 \succ - n1 \rightarrow (w1, s1'); G \vdash s2 - t2 \succ - n2 \rightarrow (w2, s2'); G \vdash s3 - t3 \succ - n3 \rightarrow (w3, s3') \rrbracket \implies$

$G \vdash s1 -t1 \succ -\max (\max n1 n2) n3 \rightarrow (w1, s1')$ \wedge
 $G \vdash s2 -t2 \succ -\max (\max n1 n2) n3 \rightarrow (w2, s2')$ \wedge
 $G \vdash s3 -t3 \succ -\max (\max n1 n2) n3 \rightarrow (w3, s3')$
 <proof>

corollary *evaln-max3E*:

$\llbracket G \vdash s1 -t1 \succ -n1 \rightarrow (w1, s1'); G \vdash s2 -t2 \succ -n2 \rightarrow (w2, s2'); G \vdash s3 -t3 \succ -n3 \rightarrow (w3, s3') \rrbracket$
 $\llbracket G \vdash s1 -t1 \succ -\max (\max n1 n2) n3 \rightarrow (w1, s1')$
 $G \vdash s2 -t2 \succ -\max (\max n1 n2) n3 \rightarrow (w2, s2')$
 $G \vdash s3 -t3 \succ -\max (\max n1 n2) n3 \rightarrow (w3, s3')$
 $\rrbracket \implies P$
 $\rrbracket \implies P$
 <proof>

lemma *le-max3I1*: $(n2 :: nat) \leq \max n1 (\max n2 n3)$
 <proof>

lemma *le-max3I2*: $(n3 :: nat) \leq \max n1 (\max n2 n3)$
 <proof>

declare $\llbracket \text{simproc del: wt-expr wt-var wt-exprs wt-stmt} \rrbracket$

eval implies evaln

lemma *eval-evaln*:

assumes *eval*: $G \vdash s0 -t \succ \rightarrow (v, s1)$
shows $\exists n. G \vdash s0 -t \succ -n \rightarrow (v, s1)$
 <proof>

end

Chapter 21

Trans

theory *Trans* **imports** *Evaln* **begin**

definition

```
groundVar :: var ⇒ bool where
groundVar v ⇔ (case v of
  LVar ln ⇒ True
  | {accC,statDeclC,stat}e..fn ⇒ ∃ a. e=Lit a
  | e1.[e2] ⇒ ∃ a i. e1 = Lit a ∧ e2 = Lit i
  | InsInitV c v ⇒ False)
```

lemma *groundVar-cases*:

```
assumes ground: groundVar v
obtains (LVar) ln where v=LVar ln
  | (FVar) accC statDeclC stat a fn where v={accC,statDeclC,stat}(Lit a)..fn
  | (AVar) a i where v=(Lit a).[Lit i]
⟨proof⟩
```

definition

```
groundExprs :: expr list ⇒ bool
where groundExprs es ⇔ (∀ e ∈ set es. ∃ v. e = Lit v)
```

primrec *the-val*:: expr ⇒ val

```
where the-val (Lit v) = v
```

primrec *the-var*:: prog ⇒ state ⇒ var ⇒ (vvar × state) **where**

```
the-var G s (LVar ln) = (lvar ln (store s),s)
| the-var-FVar-def: the-var G s ({accC,statDeclC,stat}a..fn) = fvar statDeclC stat fn (the-val a) s
| the-var-AVar-def: the-var G s (a.[i]) = avar G (the-val i) (the-val a) s
```

lemma *the-var-FVar-simp*[*simp*]:

```
the-var G s ({accC,statDeclC,stat}(Lit a)..fn) = fvar statDeclC stat fn a s
```

⟨proof⟩

declare *the-var-FVar-def* [*simp del*]

lemma *the-var-AVar-simp*:

```
the-var G s ((Lit a).[Lit i]) = avar G i a s
```

⟨proof⟩

declare *the-var-AVar-def* [*simp del*]

abbreviation

$Ref :: loc \Rightarrow expr$
where $Ref\ a == Lit\ (Addr\ a)$

abbreviation

$SKIP :: expr$
where $SKIP == Lit\ Unit$

inductive

$step :: [prog, term \times state, term \times state] \Rightarrow bool\ (\dashv\vdash \mapsto 1\ -[61,82,82]\ 81)$
for $G :: prog$

where

$Abrupt:$ $\llbracket \forall v. t \neq \langle Lit\ v \rangle;$
 $\forall t. t \neq \langle l \cdot Skip \rangle;$
 $\forall C\ vn\ c. t \neq \langle Try\ Skip\ Catch\ (C\ vn)\ c \rangle;$
 $\forall x\ c. t \neq \langle Skip\ Finally\ c \rangle \wedge xc \neq Xcpt\ x;$
 $\forall a\ c. t \neq \langle FinA\ a\ c \rangle \rrbracket$
 \implies
 $G \vdash (t, Some\ xc, s) \mapsto 1\ (\langle Lit\ undefined \rangle, Some\ xc, s)$

| $InsInitE:$ $\llbracket G \vdash (\langle c \rangle, Norm\ s) \mapsto 1\ (\langle c \rangle, s') \rrbracket$
 \implies
 $G \vdash (\langle InsInitE\ c\ e \rangle, Norm\ s) \mapsto 1\ (\langle InsInitE\ c' e \rangle, s')$

| $NewC:$ $G \vdash (\langle NewC\ C \rangle, Norm\ s) \mapsto 1\ (\langle InsInitE\ (Init\ C)\ (NewC\ C) \rangle, Norm\ s)$
| $NewCInitd:$ $\llbracket G \vdash Norm\ s \text{ --halloc } (CInst\ C) \succ a \rightarrow s' \rrbracket$
 \implies
 $G \vdash (\langle InsInitE\ Skip\ (NewC\ C) \rangle, Norm\ s) \mapsto 1\ (\langle Ref\ a \rangle, s')$

| $NewA:$
 $G \vdash (\langle New\ T[e] \rangle, Norm\ s) \mapsto 1\ (\langle InsInitE\ (init\ comp\ ty\ T)\ (New\ T[e]) \rangle, Norm\ s)$
| $InsInitNewAIdx:$
 $\llbracket G \vdash (\langle e \rangle, Norm\ s) \mapsto 1\ (\langle e \rangle, s') \rrbracket$
 \implies
 $G \vdash (\langle InsInitE\ Skip\ (New\ T[e]) \rangle, Norm\ s) \mapsto 1\ (\langle InsInitE\ Skip\ (New\ T[e']) \rangle, s')$
| $InsInitNewA:$
 $\llbracket G \vdash abupd\ (check\ neg\ i)\ (Norm\ s) \text{ --halloc } (Arr\ T\ (the\ Intg\ i)) \succ a \rightarrow s' \rrbracket$
 \implies
 $G \vdash (\langle InsInitE\ Skip\ (New\ T[Lit\ i]) \rangle, Norm\ s) \mapsto 1\ (\langle Ref\ a \rangle, s')$

| $CastE:$
 $\llbracket G \vdash (\langle e \rangle, Norm\ s) \mapsto 1\ (\langle e \rangle, s') \rrbracket$
 \implies
 $G \vdash (\langle Cast\ T\ e \rangle, None, s) \mapsto 1\ (\langle Cast\ T\ e \rangle, s')$

| $Cast:$
 $\llbracket s' = abupd\ (raise\ if\ (\neg G, s \vdash v\ fits\ T)\ ClassCast)\ (Norm\ s) \rrbracket$
 \implies

$$G\vdash(\langle\text{Cast } T \text{ (Lit } v)\rangle, \text{Norm } s) \mapsto 1 (\langle\text{Lit } v\rangle, s')$$

$$| \text{InstE: } \llbracket G\vdash(\langle e\rangle, \text{Norm } s) \mapsto 1 (\langle e'::\text{expr}\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle e \text{ InstOf } T\rangle, \text{Norm } s) \mapsto 1 (\langle e'\rangle, s')$$

$$| \text{Inst: } \llbracket b = (v \neq \text{Null} \wedge G, s \vdash v \text{ fits Ref } T) \rrbracket$$

$$\implies$$

$$G\vdash(\langle\text{Lit } v \text{ InstOf } T\rangle, \text{Norm } s) \mapsto 1 (\langle\text{Lit } (\text{Bool } b)\rangle, s')$$

$$| \text{UnOpE: } \llbracket G\vdash(\langle e\rangle, \text{Norm } s) \mapsto 1 (\langle e'\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle\text{UnOp unop } e\rangle, \text{Norm } s) \mapsto 1 (\langle\text{UnOp unop } e'\rangle, s')$$

$$| \text{UnOp: } G\vdash(\langle\text{UnOp unop (Lit } v)\rangle, \text{Norm } s) \mapsto 1 (\langle\text{Lit (eval-unop unop } v)\rangle, \text{Norm } s)$$

$$| \text{BinOpE1: } \llbracket G\vdash(\langle e1\rangle, \text{Norm } s) \mapsto 1 (\langle e1'\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle\text{BinOp binop } e1 \text{ } e2\rangle, \text{Norm } s) \mapsto 1 (\langle\text{BinOp binop } e1' \text{ } e2'\rangle, s')$$

$$| \text{BinOpE2: } \llbracket \text{need-second-arg binop } v1; G\vdash(\langle e2\rangle, \text{Norm } s) \mapsto 1 (\langle e2'\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle\text{BinOp binop (Lit } v1) \text{ } e2\rangle, \text{Norm } s)$$

$$\mapsto 1 (\langle\text{BinOp binop (Lit } v1) \text{ } e2'\rangle, s')$$

$$| \text{BinOpTerm: } \llbracket \neg \text{need-second-arg binop } v1 \rrbracket$$

$$\implies$$

$$G\vdash(\langle\text{BinOp binop (Lit } v1) \text{ } e2\rangle, \text{Norm } s)$$

$$\mapsto 1 (\langle\text{Lit } v1\rangle, \text{Norm } s)$$

$$| \text{BinOp: } G\vdash(\langle\text{BinOp binop (Lit } v1) \text{ (Lit } v2)\rangle, \text{Norm } s)$$

$$\mapsto 1 (\langle\text{Lit (eval-binop binop } v1 \text{ } v2)\rangle, \text{Norm } s)$$

$$| \text{Super: } G\vdash(\langle\text{Super}\rangle, \text{Norm } s) \mapsto 1 (\langle\text{Lit (val-this } s)\rangle, \text{Norm } s)$$

$$| \text{AccVA: } \llbracket G\vdash(\langle va\rangle, \text{Norm } s) \mapsto 1 (\langle va'\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle\text{Acc } va\rangle, \text{Norm } s) \mapsto 1 (\langle\text{Acc } va'\rangle, s')$$

$$| \text{Acc: } \llbracket \text{groundVar } va; ((v, vf), s') = \text{the-var } G (\text{Norm } s) \text{ } va \rrbracket$$

$$\implies$$

$$G\vdash(\langle\text{Acc } va\rangle, \text{Norm } s) \mapsto 1 (\langle\text{Lit } v\rangle, s')$$

$$| \text{AssVA: } \llbracket G\vdash(\langle va\rangle, \text{Norm } s) \mapsto 1 (\langle va'\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle va:=e\rangle, \text{Norm } s) \mapsto 1 (\langle va' := e'\rangle, s')$$

$$| \text{AssE: } \llbracket \text{groundVar } va; G\vdash(\langle e\rangle, \text{Norm } s) \mapsto 1 (\langle e'\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle va:=e\rangle, \text{Norm } s) \mapsto 1 (\langle va := e'\rangle, s')$$

$$| \text{Ass: } \llbracket \text{groundVar } va; ((w, f), s') = \text{the-var } G (\text{Norm } s) \text{ } va \rrbracket$$

$$\implies$$

$$G\vdash(\langle va := (\text{Lit } v)\rangle, \text{Norm } s) \mapsto 1 (\langle\text{Lit } v\rangle, \text{assign } f \text{ } v \text{ } s')$$

$$| \text{CondC: } \llbracket G\vdash(\langle e0\rangle, \text{Norm } s) \mapsto 1 (\langle e0'\rangle, s') \rrbracket$$

$$\implies$$

$$G\vdash(\langle e0? \text{ } e1:e2\rangle, \text{Norm } s) \mapsto 1 (\langle e0'? \text{ } e1:e2\rangle, s')$$

$$| \text{Cond: } G\vdash(\langle\text{Lit } b? \text{ } e1:e2\rangle, \text{Norm } s) \mapsto 1 (\langle\text{if the-Bool } b \text{ then } e1 \text{ else } e2\rangle, \text{Norm } s)$$

<i>CallTarget</i> :	[[$G\vdash(\langle e \rangle, Norm\ s) \mapsto 1\ (\langle e' \rangle, s')$]]
	\implies
	$G\vdash(\langle \{accC, statT, mode\} e \cdot mn(\{pTs\} args) \rangle, Norm\ s)$
	$\mapsto 1\ (\langle \{accC, statT, mode\} e' \cdot mn(\{pTs\} args) \rangle, s')$
<i>CallArgs</i> :	[[$G\vdash(\langle args \rangle, Norm\ s) \mapsto 1\ (\langle args' \rangle, s')$]]
	\implies
	$G\vdash(\langle \{accC, statT, mode\} Lit\ a \cdot mn(\{pTs\} args) \rangle, Norm\ s)$
	$\mapsto 1\ (\langle \{accC, statT, mode\} Lit\ a \cdot mn(\{pTs\} args') \rangle, s')$
<i>Call</i> :	[[<i>groundExprs</i> <i>args</i> ; <i>vs</i> = <i>map the-val args</i> ;
	<i>D</i> = <i>invocation-declclass G mode s a statT</i> (<i>name=mn, parTs=pTs</i>);
	<i>s'</i> = <i>init-lvars G D</i> (<i>name=mn, parTs=pTs</i>) <i>mode a' vs</i> (<i>Norm s</i>)]
	\implies
	$G\vdash(\langle \{accC, statT, mode\} Lit\ a \cdot mn(\{pTs\} args) \rangle, Norm\ s)$
	$\mapsto 1\ (\langle Callee\ (locals\ s)\ (Methd\ D\ (name=mn, parTs=pTs)) \rangle, s')$
<i>Callee</i> :	[[$G\vdash(\langle e \rangle, Norm\ s) \mapsto 1\ (\langle e'::expr \rangle, s')$]]
	\implies
	$G\vdash(\langle Callee\ lcls-caller\ e \rangle, Norm\ s) \mapsto 1\ (\langle e' \rangle, s')$
<i>CalleeRet</i> :	$G\vdash(\langle Callee\ lcls-caller\ (Lit\ v) \rangle, Norm\ s)$
	$\mapsto 1\ (\langle Lit\ v \rangle, (set-lvars\ lcls-caller\ (Norm\ s)))$
<i>Methd</i> :	$G\vdash(\langle Methd\ D\ sig \rangle, Norm\ s) \mapsto 1\ (\langle body\ G\ D\ sig \rangle, Norm\ s)$
<i>Body</i> :	$G\vdash(\langle Body\ D\ c \rangle, Norm\ s) \mapsto 1\ (\langle InsInitE\ (Init\ D)\ (Body\ D\ c) \rangle, Norm\ s)$
<i>InsInitBody</i> :	[[$G\vdash(\langle c \rangle, Norm\ s) \mapsto 1\ (\langle c' \rangle, s')$]]
	\implies
	$G\vdash(\langle InsInitE\ Skip\ (Body\ D\ c) \rangle, Norm\ s) \mapsto 1\ (\langle InsInitE\ Skip\ (Body\ D\ c') \rangle, s')$
<i>InsInitBodyRet</i> :	$G\vdash(\langle InsInitE\ Skip\ (Body\ D\ Skip) \rangle, Norm\ s)$
	$\mapsto 1\ (\langle Lit\ (the\ ((locals\ s)\ Result)) \rangle, abupd\ (absorb\ Ret)\ (Norm\ s))$
<i>FVar</i> :	[[$\neg\ inited\ statDeclC\ (globs\ s)$]]
	\implies
	$G\vdash(\langle \{accC, statDeclC, stat\} e \cdot fn \rangle, Norm\ s)$
	$\mapsto 1\ (\langle InsInitV\ (Init\ statDeclC)\ (\{accC, statDeclC, stat\} e \cdot fn) \rangle, Norm\ s)$
<i>InsInitFVarE</i> :	[[$G\vdash(\langle e \rangle, Norm\ s) \mapsto 1\ (\langle e' \rangle, s')$]]
	\implies
	$G\vdash(\langle InsInitV\ Skip\ (\{accC, statDeclC, stat\} e \cdot fn) \rangle, Norm\ s)$
	$\mapsto 1\ (\langle InsInitV\ Skip\ (\{accC, statDeclC, stat\} e' \cdot fn) \rangle, s')$
<i>InsInitFVar</i> :	$G\vdash(\langle InsInitV\ Skip\ (\{accC, statDeclC, stat\} Lit\ a \cdot fn) \rangle, Norm\ s)$
	$\mapsto 1\ (\langle \{accC, statDeclC, stat\} Lit\ a \cdot fn \rangle, Norm\ s)$
— Notice, that we do not have literal values for <i>vars</i> . The rules for accessing variables (<i>Acc</i>) and assigning to variables (<i>Ass</i>), test this with the predicate <i>groundVar</i> . After initialisation is done and the <i>FVar</i> is evaluated, we can't just throw away the <i>InsInitFVar</i> term and return a literal value, as in the cases of <i>New</i> or <i>NewC</i> . Instead we just return the evaluated <i>FVar</i> and test for initialisation in the rule <i>FVar</i> .	
<i>AVarE1</i> :	[[$G\vdash(\langle e1 \rangle, Norm\ s) \mapsto 1\ (\langle e1' \rangle, s')$]]
	\implies
	$G\vdash(\langle e1 \cdot [e2] \rangle, Norm\ s) \mapsto 1\ (\langle e1' \cdot [e2] \rangle, s')$

$$\begin{aligned}
| \text{AVarE2: } & G\vdash(\langle e2 \rangle, \text{Norm } s) \mapsto 1 (\langle e2' \rangle, s') \\
& \implies \\
& G\vdash(\langle \text{Lit } a.[e2] \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Lit } a.[e2'] \rangle, s')
\end{aligned}$$

— *Nil* is fully evaluated

$$\begin{aligned}
| \text{ConsHd: } & \llbracket G\vdash(\langle e::\text{expr} \rangle, \text{Norm } s) \mapsto 1 (\langle e'::\text{expr} \rangle, s') \rrbracket \\
& \implies \\
& G\vdash(\langle e\#es \rangle, \text{Norm } s) \mapsto 1 (\langle e'\#es \rangle, s')
\end{aligned}$$

$$\begin{aligned}
| \text{ConsTl: } & \llbracket G\vdash(\langle es \rangle, \text{Norm } s) \mapsto 1 (\langle es' \rangle, s') \rrbracket \\
& \implies \\
& G\vdash(\langle (\text{Lit } v)\#es \rangle, \text{Norm } s) \mapsto 1 (\langle (\text{Lit } v)\#es' \rangle, s')
\end{aligned}$$

$$| \text{Skip: } G\vdash(\langle \text{Skip} \rangle, \text{Norm } s) \mapsto 1 (\langle \text{SKIP} \rangle, \text{Norm } s)$$

$$\begin{aligned}
| \text{ExprE: } & \llbracket G\vdash(\langle e \rangle, \text{Norm } s) \mapsto 1 (\langle e' \rangle, s') \rrbracket \\
& \implies \\
& G\vdash(\langle \text{Expr } e \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Expr } e' \rangle, s') \\
| \text{Expr: } & G\vdash(\langle \text{Expr } (\text{Lit } v) \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Skip} \rangle, \text{Norm } s)
\end{aligned}$$

$$\begin{aligned}
| \text{LabC: } & \llbracket G\vdash(\langle c \rangle, \text{Norm } s) \mapsto 1 (\langle c' \rangle, s') \rrbracket \\
& \implies \\
& G\vdash(\langle l \cdot c \rangle, \text{Norm } s) \mapsto 1 (\langle l \cdot c' \rangle, s') \\
| \text{Lab: } & G\vdash(\langle l \cdot \text{Skip} \rangle, s) \mapsto 1 (\langle \text{Skip} \rangle, \text{abupd } (\text{absorb } l) s)
\end{aligned}$$

$$\begin{aligned}
| \text{CompC1: } & \llbracket G\vdash(\langle c1 \rangle, \text{Norm } s) \mapsto 1 (\langle c1' \rangle, s') \rrbracket \\
& \implies \\
& G\vdash(\langle c1;; c2 \rangle, \text{Norm } s) \mapsto 1 (\langle c1';; c2 \rangle, s')
\end{aligned}$$

$$| \text{Comp: } G\vdash(\langle \text{Skip};; c2 \rangle, \text{Norm } s) \mapsto 1 (\langle c2 \rangle, \text{Norm } s)$$

$$\begin{aligned}
| \text{IfE: } & \llbracket G\vdash(\langle e \rangle, \text{Norm } s) \mapsto 1 (\langle e' \rangle, s') \rrbracket \\
& \implies \\
& G\vdash(\langle \text{If } (e) \text{ } s1 \text{ Else } s2 \rangle, \text{Norm } s) \mapsto 1 (\langle \text{If } (e') \text{ } s1 \text{ Else } s2 \rangle, s') \\
| \text{If: } & G\vdash(\langle \text{If } (\text{Lit } v) \text{ } s1 \text{ Else } s2 \rangle, \text{Norm } s) \\
& \mapsto 1 (\langle \text{if the-Bool } v \text{ then } s1 \text{ else } s2 \rangle, \text{Norm } s)
\end{aligned}$$

$$\begin{aligned}
| \text{Loop: } & G\vdash(\langle l \cdot \text{While}(e) \text{ } c \rangle, \text{Norm } s) \\
& \mapsto 1 (\langle \text{If}(e) (\text{Cont } l \cdot c;; l \cdot \text{While}(e) \text{ } c) \text{ Else Skip} \rangle, \text{Norm } s)
\end{aligned}$$

$$| \text{Jmp: } G\vdash(\langle \text{Jmp } j \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Skip} \rangle, (\text{Some } (\text{Jump } j), s))$$

$$\begin{aligned}
| \text{ThrowE: } & \llbracket G\vdash(\langle e \rangle, \text{Norm } s) \mapsto 1 (\langle e' \rangle, s') \rrbracket \\
& \implies \\
& G\vdash(\langle \text{Throw } e \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Throw } e' \rangle, s') \\
| \text{Throw: } & G\vdash(\langle \text{Throw } (\text{Lit } a) \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Skip} \rangle, \text{abupd } (\text{throw } a) (\text{Norm } s))
\end{aligned}$$

| *TryC1*: $\llbracket G \vdash (\langle c1 \rangle, \text{Norm } s) \mapsto 1 (\langle c1 \hat{\cdot} \rangle, s') \rrbracket$
 \implies
 $G \vdash (\langle \text{Try } c1 \text{ Catch}(C \text{ vn}) c2 \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Try } c1' \text{ Catch}(C \text{ vn}) c2 \rangle, s')$

| *Try*: $\llbracket G \vdash s \text{ --salloc--} \rightarrow s' \rrbracket$
 \implies
 $G \vdash (\langle \text{Try Skip Catch}(C \text{ vn}) c2 \rangle, s)$
 $\mapsto 1 (\text{if } G, s \vdash \text{catch } C \text{ then } (\langle c2 \rangle, \text{new-xcpt-var } \text{vn } s') \text{ else } (\langle \text{Skip} \rangle, s'))$

| *FinC1*: $\llbracket G \vdash (\langle c1 \rangle, \text{Norm } s) \mapsto 1 (\langle c1 \hat{\cdot} \rangle, s') \rrbracket$
 \implies
 $G \vdash (\langle c1 \text{ Finally } c2 \rangle, \text{Norm } s) \mapsto 1 (\langle c1' \text{ Finally } c2 \rangle, s')$

| *Fin*: $G \vdash (\langle \text{Skip Finally } c2 \rangle, (a, s)) \mapsto 1 (\langle \text{FinA } a \text{ } c2 \rangle, \text{Norm } s)$

| *FinAC*: $\llbracket G \vdash (\langle c \rangle, s) \mapsto 1 (\langle c \hat{\cdot} \rangle, s') \rrbracket$
 \implies
 $G \vdash (\langle \text{FinA } a \text{ } c \rangle, s) \mapsto 1 (\langle \text{FinA } a \text{ } c \hat{\cdot} \rangle, s')$

| *FinA*: $G \vdash (\langle \text{FinA } a \text{ Skip} \rangle, s) \mapsto 1 (\langle \text{Skip} \rangle, \text{abupd } (\text{abrupt-if } (a \neq \text{None}) a) s)$

| *Init1*: $\llbracket \text{inited } C \text{ (globals } s) \rrbracket$
 \implies
 $G \vdash (\langle \text{Init } C \rangle, \text{Norm } s) \mapsto 1 (\langle \text{Skip} \rangle, \text{Norm } s)$

| *Init*: $\llbracket \text{the (class } G \text{ } C) = c; \neg \text{inited } C \text{ (globals } s) \rrbracket$
 \implies
 $G \vdash (\langle \text{Init } C \rangle, \text{Norm } s)$
 $\mapsto 1 ((\text{if } C = \text{Object then Skip else } (\text{Init } (\text{super } c)));$
 $\text{Expr } (\text{Callee } (\text{locals } s) (\text{InsInitE } (\text{init } c) \text{ SKIP})))$
 $, \text{Norm } (\text{init-class-obj } G \text{ } C \text{ } s))$

— *InsInitE* is just used as trick to embed the statement *init c* into an expression

| *InsInitESKIP*:
 $G \vdash (\langle \text{InsInitE Skip SKIP} \rangle, \text{Norm } s) \mapsto 1 (\langle \text{SKIP} \rangle, \text{Norm } s)$

abbreviation

stepn:: $[\text{prog}, \text{term} \times \text{state}, \text{nat}, \text{term} \times \text{state}] \Rightarrow \text{bool } (\vdash \mapsto - [61, 82, 82] \text{ } 81)$
where $G \vdash p \mapsto n \text{ } p' \equiv (p, p') \in \{(x, y). \text{step } G \text{ } x \text{ } y\}^{\wedge n}$

abbreviation

steptr:: $[\text{prog}, \text{term} \times \text{state}, \text{term} \times \text{state}] \Rightarrow \text{bool } (\vdash \mapsto * - [61, 82, 82] \text{ } 81)$
where $G \vdash p \mapsto * \text{ } p' \equiv (p, p') \in \{(x, y). \text{step } G \text{ } x \text{ } y\}^*$

end

Chapter 22

AxSem

50 Axiomatic semantics of Java expressions and statements (see also Eval.thy)

theory *AxSem* **imports** *Evaln TypeSafe* **begin**

design issues:

- a strong version of validity for triples with premises, namely one that takes the recursive depth needed to complete execution, enables correctness proof
- auxiliary variables are handled first-class ($-i$, Thomas Kleymann)
- expressions not flattened to elementary assignments (as usual for axiomatic semantics) but treated first-class $=i$, explicit result value handling
- intermediate values not on triple, but on assertion level (with result entry)
- multiple results with semantical substitution mechanism not requiring a stack
- because of dynamic method binding, terms need to be dependent on state. this is also useful for conditional expressions and statements
- result values in triples exactly as in eval relation (also for xcpt states)
- validity: additional assumption of state conformance and well-typedness, which is required for soundness and thus rule hazard required of completeness

restrictions:

- all triples in a derivation are of the same type (due to weak polymorphism)

type-synonym *res = vals* — result entry

abbreviation (*input*)

Val **where** *Val* $x == In1\ x$

abbreviation (*input*)

Var **where** *Var* $x == In2\ x$

abbreviation (*input*)

Vals **where** *Vals* $x == In3\ x$

syntax

$-Val \quad :: [pttrn] ==> pttrn \quad (Val:- [951] 950)$

$-Var \quad :: [pttrn] ==> pttrn \quad (Var:- [951] 950)$

$-Vals \quad :: [pttrn] ==> pttrn \quad (Vals:- [951] 950)$

translations

$\lambda Val:v . b == (\lambda v. b) \circ CONST\ the-In1$

$\lambda Var:v . b == (\lambda v. b) \circ CONST\ the-In2$

$\lambda Vals:v . b == (\lambda v. b) \circ CONST\ the-In3$

— relation on result values, state and auxiliary variables

type-synonym $'a\ assn = res \Rightarrow state \Rightarrow 'a \Rightarrow bool$

translations

$(type)\ 'a\ assn <= (type)\ vals \Rightarrow state \Rightarrow 'a \Rightarrow bool$

definition

$assn-imp \quad :: 'a\ assn \Rightarrow 'a\ assn \Rightarrow bool$ (**infix** \Rightarrow 25)

where $(P \Rightarrow Q) = (\forall Y\ s\ Z. P\ Y\ s\ Z \longrightarrow Q\ Y\ s\ Z)$

lemma *assn-imp-def2* [*iff*]: $(P \Rightarrow Q) = (\forall Y s Z. P Y s Z \longrightarrow Q Y s Z)$
 ⟨*proof*⟩

assertion transformers

51 peek-and

definition

peek-and :: 'a assn \Rightarrow (state \Rightarrow bool) \Rightarrow 'a assn (**infixl** \wedge . 13)
 where $(P \wedge. p) = (\lambda Y s Z. P Y s Z \wedge p s)$

lemma *peek-and-def2* [*simp*]: $peek\text{-}and\ P\ p\ Y\ s = (\lambda Z. (P\ Y\ s\ Z\ \wedge\ p\ s))$
 ⟨*proof*⟩

lemma *peek-and-Not* [*simp*]: $(P \wedge. (\lambda s. \neg f s)) = (P \wedge. Not \circ f)$
 ⟨*proof*⟩

lemma *peek-and-and* [*simp*]: $peek\text{-}and\ (peek\text{-}and\ P\ p)\ p = peek\text{-}and\ P\ p$
 ⟨*proof*⟩

lemma *peek-and-commut*: $(P \wedge. p \wedge. q) = (P \wedge. q \wedge. p)$
 ⟨*proof*⟩

abbreviation

Normal :: 'a assn \Rightarrow 'a assn
 where *Normal* $P == P \wedge. normal$

lemma *peek-and-Normal* [*simp*]: $peek\text{-}and\ (Normal\ P)\ p = Normal\ (peek\text{-}and\ P\ p)$
 ⟨*proof*⟩

52 assn-supd

definition

assn-supd :: 'a assn \Rightarrow (state \Rightarrow state) \Rightarrow 'a assn (**infixl** $;$. 13)
 where $(P ;. f) = (\lambda Y s' Z. \exists s. P Y s Z \wedge s' = f s)$

lemma *assn-supd-def2* [*simp*]: $assn\text{-}supd\ P\ f\ Y\ s'\ Z = (\exists s. P\ Y\ s\ Z \wedge s' = f s)$
 ⟨*proof*⟩

53 supd-assn

definition

supd-assn :: (state \Rightarrow state) \Rightarrow 'a assn \Rightarrow 'a assn (**infixr** $;$. 13)
 where $(f ;. P) = (\lambda Y s. P Y (f s))$

lemma *supd-assn-def2* [*simp*]: $(f ;. P)\ Y\ s = P\ Y\ (f\ s)$
 ⟨*proof*⟩

lemma *supd-assn-supdD* [*elim*]: $((f ;. Q) ;. f)\ Y\ s\ Z \Longrightarrow Q\ Y\ s\ Z$
 ⟨*proof*⟩

lemma *supd-assn-supdI* [*elim*]: $Q\ Y\ s\ Z \implies (f\ .; (Q\ ;. f))\ Y\ s\ Z$
 ⟨*proof*⟩

54 subst-res

definition

subst-res :: 'a assn \Rightarrow res \Rightarrow 'a assn (-<- [60,61] 60)
 where $P \leftarrow w = (\lambda Y. P\ w)$

lemma *subst-res-def2* [*simp*]: $(P \leftarrow w)\ Y = P\ w$
 ⟨*proof*⟩

lemma *subst-subst-res* [*simp*]: $P \leftarrow w \leftarrow v = P \leftarrow w$
 ⟨*proof*⟩

lemma *peek-and-subst-res* [*simp*]: $(P \wedge. p) \leftarrow w = (P \leftarrow w \wedge. p)$
 ⟨*proof*⟩

55 subst-Bool

definition

subst-Bool :: 'a assn \Rightarrow bool \Rightarrow 'a assn (-<= [60,61] 60)
 where $P \leftarrow b = (\lambda Y\ s\ Z. \exists v. P\ (Val\ v)\ s\ Z \wedge (normal\ s \longrightarrow the-Bool\ v=b))$

lemma *subst-Bool-def2* [*simp*]:
 $(P \leftarrow b)\ Y\ s\ Z = (\exists v. P\ (Val\ v)\ s\ Z \wedge (normal\ s \longrightarrow the-Bool\ v=b))$
 ⟨*proof*⟩

lemma *subst-Bool-the-BoolI*: $P\ (Val\ b)\ s\ Z \implies (P \leftarrow the-Bool\ b)\ Y\ s\ Z$
 ⟨*proof*⟩

56 peek-res

definition

peek-res :: (res \Rightarrow 'a assn) \Rightarrow 'a assn
 where *peek-res* $Pf = (\lambda Y. Pf\ Y\ Y)$

syntax

-*peek-res* :: *pttrn* \Rightarrow 'a assn \Rightarrow 'a assn ($\lambda \cdot. \cdot$ - [0,3] 3)

translations

$\lambda w. P == CONST\ peek-res\ (\lambda w. P)$

lemma *peek-res-def2* [*simp*]: *peek-res* $P\ Y = P\ Y\ Y$
 ⟨*proof*⟩

lemma *peek-res-subst-res* [*simp*]: *peek-res* $P \leftarrow w = P\ w \leftarrow w$
 ⟨*proof*⟩

lemma *peek-subst-res-allI*:

$(\bigwedge a. T a (P (f a) \leftarrow f a)) \implies \forall a. T a (peek\text{-res } P \leftarrow f a)$
 $\langle proof \rangle$

57 ign-res

definition

ign-res :: 'a assn \Rightarrow 'a assn $(\downarrow [1000] 1000)$
where $P \downarrow = (\lambda Y s Z. \exists Y. P Y s Z)$

lemma *ign-res-def2* [*simp*]: $P \downarrow Y s Z = (\exists Y. P Y s Z)$
 $\langle proof \rangle$

lemma *ign-ign-res* [*simp*]: $P \downarrow \downarrow = P \downarrow$
 $\langle proof \rangle$

lemma *ign-subst-res* [*simp*]: $P \downarrow \leftarrow w = P \downarrow$
 $\langle proof \rangle$

lemma *peek-and-ign-res* [*simp*]: $(P \wedge. p) \downarrow = (P \downarrow \wedge. p)$
 $\langle proof \rangle$

58 peek-st

definition

peek-st :: (st \Rightarrow 'a assn) \Rightarrow 'a assn
where *peek-st* $P = (\lambda Y s. P (store s) Y s)$

syntax

-peek-st :: ptrn \Rightarrow 'a assn \Rightarrow 'a assn $(\lambda \dots - [0, 3] 3)$

translations

$\lambda s.. P == CONST peek\text{-st } (\lambda s. P)$

lemma *peek-st-def2* [*simp*]: $(\lambda s.. P f s) Y s = P f (store s) Y s$
 $\langle proof \rangle$

lemma *peek-st-triv* [*simp*]: $(\lambda s.. P) = P$
 $\langle proof \rangle$

lemma *peek-st-st* [*simp*]: $(\lambda s.. \lambda s'.. P s s') = (\lambda s.. P s s)$
 $\langle proof \rangle$

lemma *peek-st-split* [*simp*]: $(\lambda s.. \lambda Y s'. P s Y s') = (\lambda Y s. P (store s) Y s)$
 $\langle proof \rangle$

lemma *peek-st-subst-res* [*simp*]: $(\lambda s.. P s) \leftarrow w = (\lambda s.. P s \leftarrow w)$
 $\langle proof \rangle$

lemma *peek-st-Normal* [*simp*]: $(\lambda s.. (Normal (P s))) = Normal (\lambda s.. P s)$

<proof>

59 ign-res-eq

definition

$ign-res-eq :: 'a\ assn \Rightarrow res \Rightarrow 'a\ assn \ (-\downarrow=- \ [60,61] \ 60)$
where $P\downarrow=w \equiv (\lambda Y. P\downarrow \wedge. (\lambda s. Y=w))$

lemma $ign-res-eq-def2$ [*simp*]: $(P\downarrow=w) \ Y \ s \ Z = ((\exists Y. P \ Y \ s \ Z) \wedge Y=w)$
<proof>

lemma $ign-ign-res-eq$ [*simp*]: $(P\downarrow=w)\downarrow = P\downarrow$
<proof>

lemma $ign-res-eq-subst-res$: $P\downarrow=w\leftarrow w = P\downarrow$
<proof>

lemma $subst-Bool-ign-res-eq$: $((P\leftarrow=b)\downarrow=x) \ Y \ s \ Z = ((P\leftarrow=b) \ Y \ s \ Z \wedge Y=x)$
<proof>

60 RefVar

definition

$RefVar :: (state \Rightarrow vvar \times state) \Rightarrow 'a\ assn \Rightarrow 'a\ assn \ (\mathbf{infixr} \ ..; \ 13)$
where $(vf \ ..; \ P) = (\lambda Y \ s. \ let \ (v,s') = vf \ s \ in \ P \ (Var \ v) \ s')$

lemma $RefVar-def2$ [*simp*]: $(vf \ ..; \ P) \ Y \ s =$
 $P \ (Var \ (fst \ (vf \ s))) \ (snd \ (vf \ s))$
<proof>

61 allocation

definition

$Alloc :: prog \Rightarrow obj-tag \Rightarrow 'a\ assn \Rightarrow 'a\ assn$
where $Alloc \ G \ otag \ P = (\lambda Y \ s \ Z. \ \forall s' \ a. \ G\vdash s \ -halloc \ otag \succ a \rightarrow s' \longrightarrow P \ (Val \ (Addr \ a)) \ s' \ Z)$

definition

$SXAlloc :: prog \Rightarrow 'a\ assn \Rightarrow 'a\ assn$
where $SXAlloc \ G \ P = (\lambda Y \ s \ Z. \ \forall s'. \ G\vdash s \ -salloc \rightarrow s' \longrightarrow P \ Y \ s' \ Z)$

lemma $Alloc-def2$ [*simp*]: $Alloc \ G \ otag \ P \ Y \ s \ Z =$
 $(\forall s' \ a. \ G\vdash s \ -halloc \ otag \succ a \rightarrow s' \longrightarrow P \ (Val \ (Addr \ a)) \ s' \ Z)$
<proof>

lemma $SXAlloc-def2$ [*simp*]:
 $SXAlloc \ G \ P \ Y \ s \ Z = (\forall s'. \ G\vdash s \ -salloc \rightarrow s' \longrightarrow P \ Y \ s' \ Z)$
<proof>

validity**definition**

type-ok :: *prog* \Rightarrow *term* \Rightarrow *state* \Rightarrow *bool* **where**
type-ok *G t s* =
 $(\exists L T C A. (\text{normal } s \longrightarrow (\text{prg}=G, \text{cls}=C, \text{lcl}=L)) \vdash t :: T \wedge$
 $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } s)) \gg t \gg A)$
 $\wedge s :: \preceq(G, L))$

datatype 'a triple = triple ('a assn) term ('a assn)
 $(\{(1-)\} / \text{->} / \{(1-)\})$ [3,65,3] 75)

type-synonym 'a triples = 'a triple set

abbreviation

var-triple :: ['a assn, var, 'a assn] \Rightarrow 'a triple
 $(\{(1-)\} / \text{-=>} / \{(1-)\})$ [3,80,3] 75)
where $\{P\} e \Rightarrow \{Q\} == \{P\} \text{In2 } e > \{Q\}$

abbreviation

expr-triple :: ['a assn, expr, 'a assn] \Rightarrow 'a triple
 $(\{(1-)\} / \text{->} / \{(1-)\})$ [3,80,3] 75)
where $\{P\} e \rightarrow \{Q\} == \{P\} \text{In1l } e > \{Q\}$

abbreviation

exprs-triple :: ['a assn, expr list, 'a assn] \Rightarrow 'a triple
 $(\{(1-)\} / \text{-\#>} / \{(1-)\})$ [3,65,3] 75)
where $\{P\} e \#> \{Q\} == \{P\} \text{In3 } e > \{Q\}$

abbreviation

stmt-triple :: ['a assn, stmt, 'a assn] \Rightarrow 'a triple
 $(\{(1-)\} / \text{-./} / \{(1-)\})$ [3,65,3] 75)
where $\{P\} .c. \{Q\} == \{P\} \text{In1r } c > \{Q\}$

notation (*xsymbols*)

triple $(\{(1-)\} / \text{->} / \{(1-)\})$ [3,65,3] 75) **and**
var-triple $(\{(1-)\} / \text{-=>} / \{(1-)\})$ [3,80,3] 75) **and**
expr-triple $(\{(1-)\} / \text{->} / \{(1-)\})$ [3,80,3] 75) **and**
exprs-triple $(\{(1-)\} / \text{-\#>} / \{(1-)\})$ [3,65,3] 75)

lemma *inj-triple*: *inj* $(\lambda(P, t, Q). \{P\} t \succ \{Q\})$
 $\langle \text{proof} \rangle$

lemma *triple-inj-eq*: $(\{P\} t \succ \{Q\} = \{P'\} t' \succ \{Q'\}) = (P=P' \wedge t=t' \wedge Q=Q')$
 $\langle \text{proof} \rangle$

definition *mtriples* :: ('c \Rightarrow 'sig \Rightarrow 'a assn) \Rightarrow ('c \Rightarrow 'sig \Rightarrow expr) \Rightarrow
('c \Rightarrow 'sig \Rightarrow 'a assn) \Rightarrow ('c \times 'sig) set \Rightarrow 'a triples $(\{(1-)\} / \text{->} / \{(1-)\} \mid \text{-})$ [3,65,3,65] 75)

where

$\{\{P\} \text{tf} \text{->} \{Q\} \mid \text{ms}\} = (\lambda(C, \text{sig}). \{\text{Normal}(P \ C \ \text{sig})\} \text{tf } C \ \text{sig} \text{->} \{Q \ C \ \text{sig}\}) \text{'ms}$

definition

triple-valid :: *prog* \Rightarrow *nat* \Rightarrow 'a triple \Rightarrow *bool* ($\text{-}\vdash\text{-}$ [61,0, 58] 57)

where

$G \vdash n : t =$
(case *t* of $\{P\} t \succ \{Q\} \Rightarrow$
 $\forall Y s Z. P \ Y \ s \ Z \longrightarrow \text{type-ok } G \ t \ s \longrightarrow$
 $(\forall Y' s'. G \vdash s \text{-} t \succ \text{-} n \rightarrow (Y', s') \longrightarrow Q \ Y' \ s' \ Z))$

abbreviation

triples-valid :: $prog \Rightarrow nat \Rightarrow 'a \text{ triples} \Rightarrow bool$ ($-||=-$:- [61,0, 58] 57)
where $G||=n:ts == Ball \ ts \ (triple\text{-}valid \ G \ n)$

notation (*xsymbols*)

triples-valid ($-||=-$:- [61,0, 58] 57)

definition

ax-valids :: $prog \Rightarrow 'b \text{ triples} \Rightarrow 'a \text{ triples} \Rightarrow bool$ ($-,-||=-$ [61,58,58] 57)
where $(G,A||=ts) = (\forall n. G||=n:A \longrightarrow G||=n:ts)$

abbreviation

ax-valid :: $prog \Rightarrow 'b \text{ triples} \Rightarrow 'a \text{ triple} \Rightarrow bool$ ($-,-||=-$ [61,58,58] 57)
where $G,A \ ||=t == G,A \ ||=\{t\}$

notation (*xsymbols*)

ax-valid ($-,-||=-$ [61,58,58] 57)

lemma *triple-valid-def2*: $G||=n:\{P\} \ t \succ \ \{Q\} =$

$(\forall Y \ s \ Z. P \ Y \ s \ Z$
 $\longrightarrow (\exists L. (normal \ s \longrightarrow (\exists C \ T \ A. (\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash t :: T \wedge$
 $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash_{dom} (locals \ (store \ s)) \gg t \gg A)) \wedge$
 $s :: \preceq(G, L))$
 $\longrightarrow (\forall Y' \ s'. G \vdash s \ -t \succ -n \rightarrow (Y', s') \longrightarrow Q \ Y' \ s' \ Z))$
 $\langle proof \rangle$

declare *split-paired-All* [*simp del*] *split-paired-Ex* [*simp del*]

declare *split-if* [*split del*] *split-if-asm* [*split del*]
option.split [*split del*] *option.split-asm* [*split del*]

$\langle ML \rangle$

inductive

ax-derivs :: $prog \Rightarrow 'a \text{ triples} \Rightarrow 'a \text{ triples} \Rightarrow bool$ ($-,-||=-$ [61,58,58] 57)
and *ax-deriv* :: $prog \Rightarrow 'a \text{ triples} \Rightarrow 'a \text{ triple} \Rightarrow bool$ ($-,-||=-$ [61,58,58] 57)
for $G :: prog$

where

$G, A \ \vdash \ t \equiv G, A \ \vdash \ \{t\}$

| *empty*: $G, A \ \vdash \ \{\}$
| *insert*: $\llbracket G, A \ \vdash \ t; G, A \ \vdash \ ts \rrbracket \Longrightarrow$
 $G, A \ \vdash \ insert \ t \ ts$

| *asm*: $ts \subseteq A \Longrightarrow G, A \ \vdash \ ts$

| *weaken*: $\llbracket G, A \ \vdash \ ts'; ts \subseteq ts' \rrbracket \Longrightarrow G, A \ \vdash \ ts$

| *conseq*: $\forall Y \ s \ Z. P \ Y \ s \ Z \longrightarrow (\exists P' \ Q'. G, A \ \vdash \ \{P'\} \ t \succ \ \{Q'\} \wedge (\forall Y' \ s'.$
 $(\forall Y \ \ Z'. P' \ Y \ s \ Z' \longrightarrow Q' \ Y' \ s' \ Z') \longrightarrow$
 $Q \ Y' \ s' \ Z))$
 $\Longrightarrow G, A \ \vdash \ \{P\} \ t \succ \ \{Q\}$

| *hazard*: $G, A \ \vdash \ \{P \ \wedge. \ Not \ \circ \ type\text{-}ok \ G \ t\} \ t \succ \ \{Q\}$

- | *Abrupt*: $G, A \vdash \{P \leftarrow (\text{undefined} \exists t) \wedge \text{Not} \circ \text{normal}\} t \succ \{P\}$
- variables
- | *LVar*: $G, A \vdash \{\text{Normal} (\lambda s.. P \leftarrow \text{Var} (\text{lvar } vn \ s))\} \text{LVar } vn = \succ \{P\}$
- | *FVar*: $\llbracket G, A \vdash \{\text{Normal } P\} \text{.Init } C. \{Q\};$
 $G, A \vdash \{Q\} e \succ \{\lambda \text{Val}:a.. \text{fvar } C \text{ stat } \text{fn } a \ ..; R\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} \{\text{acc } C, C, \text{stat}\} e.. \text{fn} = \succ \{R\}$
- | *AVar*: $\llbracket G, A \vdash \{\text{Normal } P\} e1 \succ \{Q\};$
 $\forall a. G, A \vdash \{Q \leftarrow \text{Val } a\} e2 \succ \{\lambda \text{Val}:i.. \text{avar } G \ i \ a \ ..; R\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} e1.[e2] = \succ \{R\}$
- expressions
- | *NewC*: $\llbracket G, A \vdash \{\text{Normal } P\} \text{.Init } C. \{\text{Alloc } G \ (C \text{Inst } C) \ Q\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} \text{NewC } C \succ \{Q\}$
- | *NewA*: $\llbracket G, A \vdash \{\text{Normal } P\} \text{.init-comp-ty } T. \{Q\}; G, A \vdash \{Q\} e \succ$
 $\{\lambda \text{Val}:i.. \text{abupd} (\text{check-neg } i) \ .; \text{Alloc } G \ (\text{Arr } T \ (\text{the-Intg } i)) \ R\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} \text{New } T[e] \succ \{R\}$
- | *Cast*: $\llbracket G, A \vdash \{\text{Normal } P\} e \succ \{\lambda \text{Val}:v.. \lambda s..$
 $\text{abupd} (\text{raise-if } (\neg G, s \vdash v \text{ fits } T) \ \text{ClassCast}) \ .; Q \leftarrow \text{Val } v\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} \text{Cast } T \ e \succ \{Q\}$
- | *Inst*: $\llbracket G, A \vdash \{\text{Normal } P\} e \succ \{\lambda \text{Val}:v.. \lambda s..$
 $Q \leftarrow \text{Val} (\text{Bool} (v \neq \text{Null} \wedge G, s \vdash v \text{ fits } \text{RefT } T))\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} e \text{InstOf } T \succ \{Q\}$
- | *Lit*: $G, A \vdash \{\text{Normal} (P \leftarrow \text{Val } v)\} \text{Lit } v \succ \{P\}$
- | *UnOp*: $\llbracket G, A \vdash \{\text{Normal } P\} e \succ \{\lambda \text{Val}:v.. Q \leftarrow \text{Val} (\text{eval-unop } \text{unop } v)\} \rrbracket$
 \implies
 $G, A \vdash \{\text{Normal } P\} \text{UnOp } \text{unop } e \succ \{Q\}$
- | *BinOp*:
 $\llbracket G, A \vdash \{\text{Normal } P\} e1 \succ \{Q\};$
 $\forall v1. G, A \vdash \{Q \leftarrow \text{Val } v1\}$
 $(\text{if need-second-arg binop } v1 \text{ then } (\text{In1l } e2) \text{ else } (\text{In1r Skip})) \succ$
 $\{\lambda \text{Val}:v2.. R \leftarrow \text{Val} (\text{eval-binop } \text{binop } v1 \ v2)\} \rrbracket$
 \implies
 $G, A \vdash \{\text{Normal } P\} \text{BinOp } \text{binop } e1 \ e2 \succ \{R\}$
- | *Super*: $G, A \vdash \{\text{Normal} (\lambda s.. P \leftarrow \text{Val} (\text{val-this } s))\} \text{Super} \succ \{P\}$
- | *Acc*: $\llbracket G, A \vdash \{\text{Normal } P\} va = \succ \{\lambda \text{Var}:(v,f).. Q \leftarrow \text{Val } v\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} \text{Acc } va \succ \{Q\}$
- | *Ass*: $\llbracket G, A \vdash \{\text{Normal } P\} va = \succ \{Q\};$
 $\forall vf. G, A \vdash \{Q \leftarrow \text{Var } vf\} e \succ \{\lambda \text{Val}:v.. \text{assign} (\text{snd } vf) \ v \ .; R\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} va := e \succ \{R\}$
- | *Cond*: $\llbracket G, A \vdash \{\text{Normal } P\} e0 \succ \{P'\};$
 $\forall b. G, A \vdash \{P' \leftarrow = b\} (\text{if } b \text{ then } e1 \text{ else } e2) \succ \{Q\} \rrbracket \implies$
 $G, A \vdash \{\text{Normal } P\} e0 \ ? \ e1 : e2 \succ \{Q\}$
- | *Call*:
 $\llbracket G, A \vdash \{\text{Normal } P\} e \succ \{Q\}; \forall a. G, A \vdash \{Q \leftarrow \text{Val } a\} \text{args} = \succ \{R \ a\};$

- $\forall a \text{ vs } \text{invC } \text{declC } l. G, A \vdash \{(R \text{ a} \leftarrow \text{Vals } \text{vs} \wedge .$
 $(\lambda s. \text{declC} = \text{invocation-declclass } G \text{ mode } (\text{store } s) \text{ a } \text{statT } (\downarrow \text{name} = \text{mn}, \text{parTs} = \text{pTs})) \wedge$
 $\text{invC} = \text{invocation-class } \text{mode } (\text{store } s) \text{ a } \text{statT } \wedge$
 $l = \text{locals } (\text{store } s)) \};$
 $\text{init-lvars } G \text{ declC } (\downarrow \text{name} = \text{mn}, \text{parTs} = \text{pTs}) \text{ mode } a \text{ vs} \wedge .$
 $(\lambda s. \text{normal } s \longrightarrow G \vdash \text{mode} \rightarrow \text{invC} \preceq \text{statT})\}$
 $\text{Methd } \text{declC } (\downarrow \text{name} = \text{mn}, \text{parTs} = \text{pTs}) \multimap \{\text{set-lvars } l \text{ .}; S\} \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} \{\text{accC}, \text{statT}, \text{mode}\} e \cdot \text{mn}(\{\text{pTs}\} \text{args}) \multimap \{S\}$
- $| \text{Methd}: \llbracket G, A \cup \{\{P\} \text{Methd} \multimap \{Q\} \mid \text{ms}\} \vdash \{\{P\} \text{body } G \multimap \{Q\} \mid \text{ms}\} \rrbracket \Longrightarrow$
 $G, A \vdash \{\{P\} \text{Methd} \multimap \{Q\} \mid \text{ms}\}$
- $| \text{Body}: \llbracket G, A \vdash \{\text{Normal } P\} \text{.Init } D. \{Q\};$
 $G, A \vdash \{Q\} \text{.c. } \{\lambda s. \text{abupd } (\text{absorb } \text{Ret}) \text{ .}; R \leftarrow (\text{In1 } (\text{the } (\text{locals } s \text{ Result})))\} \rrbracket$
 \Longrightarrow
 $G, A \vdash \{\text{Normal } P\} \text{Body } D \text{ c} \multimap \{R\}$
- expression lists
- $| \text{Nil}: G, A \vdash \{\text{Normal } (P \leftarrow \text{Vals } [])\} \llbracket \multimap \{P\} \rrbracket$
- $| \text{Cons}: \llbracket G, A \vdash \{\text{Normal } P\} e \multimap \{Q\};$
 $\forall v. G, A \vdash \{Q \leftarrow \text{Val } v\} \text{es} \multimap \{\lambda \text{Vals} : \text{vs}. R \leftarrow \text{Vals } (v \# \text{vs})\} \rrbracket \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} e \# \text{es} \multimap \{R\}$
- statements
- $| \text{Skip}: G, A \vdash \{\text{Normal } (P \leftarrow \diamond)\} \text{.Skip. } \{P\}$
- $| \text{Expr}: \llbracket G, A \vdash \{\text{Normal } P\} e \multimap \{Q \leftarrow \diamond\} \rrbracket \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} \text{.Expr } e. \{Q\}$
- $| \text{Lab}: \llbracket G, A \vdash \{\text{Normal } P\} \text{.c. } \{\text{abupd } (\text{absorb } l) \text{ .}; Q\} \rrbracket \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} \text{.l. } c. \{Q\}$
- $| \text{Comp}: \llbracket G, A \vdash \{\text{Normal } P\} \text{.c1. } \{Q\};$
 $G, A \vdash \{Q\} \text{.c2. } \{R\} \rrbracket \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} \text{.c1;;c2. } \{R\}$
- $| \text{If}: \llbracket G, A \vdash \{\text{Normal } P\} e \multimap \{P'\};$
 $\forall b. G, A \vdash \{P' \leftarrow b\} \text{.(if } b \text{ then } c1 \text{ else } c2). \{Q\} \rrbracket \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} \text{.If}(e) \text{ } c1 \text{ Else } c2. \{Q\}$
- $| \text{Loop}: \llbracket G, A \vdash \{P\} e \multimap \{P'\};$
 $G, A \vdash \{\text{Normal } (P' \leftarrow \text{True})\} \text{.c. } \{\text{abupd } (\text{absorb } (\text{Cont } l)) \text{ .}; P\} \rrbracket \Longrightarrow$
 $G, A \vdash \{P\} \text{.l. } \text{While}(e) \text{ } c. \{(P' \leftarrow \text{False}) \downarrow = \diamond\}$
- $| \text{Jmp}: G, A \vdash \{\text{Normal } (\text{abupd } (\lambda a. (\text{Some } (\text{Jump } j))) \text{ .}; P \leftarrow \diamond)\} \text{.Jmp } j. \{P\}$
- $| \text{Throw}: \llbracket G, A \vdash \{\text{Normal } P\} e \multimap \{\lambda \text{Val} : a. \text{abupd } (\text{throw } a) \text{ .}; Q \leftarrow \diamond\} \rrbracket \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} \text{.Throw } e. \{Q\}$
- $| \text{Try}: \llbracket G, A \vdash \{\text{Normal } P\} \text{.c1. } \{S \text{XAlloc } G \text{ } Q\};$
 $G, A \vdash \{Q \wedge . (\lambda s. G, s \vdash \text{catch } C) \text{ .}; \text{new-xcpt-var } \text{vn}\} \text{.c2. } \{R\};$
 $(Q \wedge . (\lambda s. \neg G, s \vdash \text{catch } C)) \Rightarrow R \rrbracket \Longrightarrow$
 $G, A \vdash \{\text{Normal } P\} \text{.Try } c1 \text{ Catch}(C \text{ } \text{vn}) \text{ } c2. \{R\}$
- $| \text{Fin}: \llbracket G, A \vdash \{\text{Normal } P\} \text{.c1. } \{Q\};$
 $\forall x. G, A \vdash \{Q \wedge . (\lambda s. x = \text{fst } s) \text{ .}; \text{abupd } (\lambda x. \text{None})\} \rrbracket$

$$.c2. \{abupd (abrupt\text{-if } (x \neq \text{None}) x) .; R\} \Longrightarrow \\ G, A \vdash \{Normal P\} .c1 \text{ Finally } c2. \{R\}$$

$$| \text{ Done: } G, A \vdash \{Normal (P \leftarrow \diamond \wedge \text{ initd } C)\} .Init C. \{P\}$$

$$| \text{ Init: } \llbracket \text{the (class } G C) = c; \\ G, A \vdash \{Normal ((P \wedge \text{ Not } \circ \text{ initd } C) ; \text{ supd (init-class-obj } G C))\} \\ \text{.(if } C = \text{Object then Skip else Init (super } c)\text{). } \{Q\}; \\ \forall l. G, A \vdash \{Q \wedge (\lambda s. l = \text{locals (store } s)) ; \text{ set-lvars empty}\} \\ \text{.init } c. \{set\text{-lvars } l ; R\} \rrbracket \Longrightarrow \\ G, A \vdash \{Normal (P \wedge \text{ Not } \circ \text{ initd } C)\} .Init C. \{R\}$$

— Some dummy rules for the intermediate terms *Callee*, *InsInitE*, *InsInitV*, *FinA* only used by the smallstep semantics.

$$| \text{ InsInitV: } G, A \vdash \{Normal P\} \text{ InsInitV } c v \multimap \{Q\} \\ | \text{ InsInitE: } G, A \vdash \{Normal P\} \text{ InsInitE } c e \multimap \{Q\} \\ | \text{ Callee: } G, A \vdash \{Normal P\} \text{ Callee } l e \multimap \{Q\} \\ | \text{ FinA: } G, A \vdash \{Normal P\} .FinA a c. \{Q\}$$

definition

$$\text{adapt-pre} :: 'a \text{ assn} \Rightarrow 'a \text{ assn} \Rightarrow 'a \text{ assn} \Rightarrow 'a \text{ assn} \\ \text{where adapt-pre } P Q Q' = (\lambda Y s Z. \forall Y' s'. \exists Z'. P Y s Z' \wedge (Q Y' s' Z' \longrightarrow Q' Y' s' Z'))$$

rules derived by induction

$$\text{lemma cut-valid: } \llbracket G, A' \Vdash ts; G, A \Vdash A' \rrbracket \Longrightarrow G, A \Vdash ts \\ \langle \text{proof} \rangle$$

lemma *ax-thin* [rule-format (no-asm)]:

$$G, (A' :: 'a \text{ triple set}) \Vdash (ts :: 'a \text{ triple set}) \Longrightarrow \forall A. A' \subseteq A \longrightarrow G, A \Vdash ts \\ \langle \text{proof} \rangle$$

$$\text{lemma ax-thin-insert: } G, (A :: 'a \text{ triple set}) \Vdash (t :: 'a \text{ triple}) \Longrightarrow G, \text{insert } x A \Vdash t \\ \langle \text{proof} \rangle$$

lemma *subset-mtriples-iff*:

$$ts \subseteq \{\{P\} mb \multimap \{Q\} \mid ms\} = (\exists ms'. ms' \subseteq ms \wedge ts = \{\{P\} mb \multimap \{Q\} \mid ms'\}) \\ \langle \text{proof} \rangle$$

lemma *weaken*:

$$G, (A :: 'a \text{ triple set}) \Vdash (ts' :: 'a \text{ triple set}) \Longrightarrow !ts. ts \subseteq ts' \longrightarrow G, A \Vdash ts \\ \langle \text{proof} \rangle$$

rules derived from conseq

In the following rules we often have to give some type annotations like: $G, A \vdash \{P\} t \multimap \{Q\}$. Given only the term above without annotations, Isabelle would infer a more general type were we could have different types of auxiliary variables in the assumption set (A) and in the triple itself (P and Q). But *ax-derivs.Methd* enforces the same type in the inductive definition of the derivation. So we have to restrict the types to be able to apply the rules.

$$\text{lemma conseq12: } \llbracket G, (A :: 'a \text{ triple set}) \Vdash \{P' :: 'a \text{ assn}\} t \multimap \{Q'\}; \\ \forall Y s Z. P Y s Z \longrightarrow (\forall Y' s'. (\forall Y Z'. P' Y s Z' \longrightarrow Q' Y' s' Z')) \longrightarrow \rrbracket$$

$$\begin{aligned} & \llbracket Q \ Y' \ s' \ Z \rrbracket \\ \implies & G, A \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q\} \\ \langle \text{proof} \rangle & \end{aligned}$$

lemma *conseq12'*: $\llbracket G, (A :: 'a \text{ triple set}) \vdash \{P' :: 'a \text{ assn}\} \ t \succ \{Q'\}; \forall s \ Y' \ s'.$
 $(\forall Y \ Z. P' \ Y \ s \ Z \longrightarrow Q' \ Y' \ s' \ Z) \longrightarrow$
 $(\forall Y \ Z. P \ Y \ s \ Z \longrightarrow Q \ Y' \ s' \ Z) \rrbracket$
 $\implies G, A \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q\}$
 $\langle \text{proof} \rangle$

lemma *conseq12-from-conseq12'*: $\llbracket G, (A :: 'a \text{ triple set}) \vdash \{P' :: 'a \text{ assn}\} \ t \succ \{Q'\};$
 $\forall Y \ s \ Z. P \ Y \ s \ Z \longrightarrow (\forall Y' \ s'. (\forall Y \ Z'. P' \ Y \ s \ Z' \longrightarrow Q' \ Y' \ s' \ Z') \longrightarrow$
 $Q \ Y' \ s' \ Z) \rrbracket$
 $\implies G, A \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q\}$
 $\langle \text{proof} \rangle$

lemma *conseq1*: $\llbracket G, (A :: 'a \text{ triple set}) \vdash \{P' :: 'a \text{ assn}\} \ t \succ \{Q\}; P \Rightarrow P' \rrbracket$
 $\implies G, A \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q\}$
 $\langle \text{proof} \rangle$

lemma *conseq2*: $\llbracket G, (A :: 'a \text{ triple set}) \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q'\}; Q' \Rightarrow Q \rrbracket$
 $\implies G, A \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q\}$
 $\langle \text{proof} \rangle$

lemma *ax-escape*:
 $\llbracket \forall Y \ s \ Z. P \ Y \ s \ Z$
 $\longrightarrow G, (A :: 'a \text{ triple set}) \vdash \{\lambda Y' \ s' \ (Z' :: 'a). (Y', s') = (Y, s)\}$
 $\xrightarrow{t \succ}$
 $\{\lambda Y \ s \ Z'. Q \ Y \ s \ Z\}$
 $\rrbracket \implies G, A \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q :: 'a \text{ assn}\}$
 $\langle \text{proof} \rangle$

lemma *ax-constant*: $\llbracket C \implies G, (A :: 'a \text{ triple set}) \vdash \{P :: 'a \text{ assn}\} \ t \succ \{Q\} \rrbracket$
 $\implies G, A \vdash \{\lambda Y \ s \ Z. C \wedge P \ Y \ s \ Z\} \ t \succ \{Q\}$
 $\langle \text{proof} \rangle$

lemma *ax-impossible [intro]*:
 $G, (A :: 'a \text{ triple set}) \vdash \{\lambda Y \ s \ Z. \text{False}\} \ t \succ \{Q :: 'a \text{ assn}\}$
 $\langle \text{proof} \rangle$

lemma *ax-nochange-lemma*: $\llbracket P \ Y \ s; \text{All} \ (op = w) \rrbracket \implies P \ w \ s$
 $\langle \text{proof} \rangle$

lemma *ax-nochange*:
 $G, (A :: (\text{res} \times \text{state}) \text{ triple set}) \vdash \{\lambda Y \ s \ Z. (Y, s) = Z\} \ t \succ \{\lambda Y \ s \ Z. (Y, s) = Z\}$
 $\implies G, A \vdash \{P :: (\text{res} \times \text{state}) \text{ assn}\} \ t \succ \{P\}$
 $\langle \text{proof} \rangle$

lemma ax-trivial: $G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} \text{ t> } \{\lambda Y s Z. \text{True}\}$
 <proof>

lemma ax-disj:

$\llbracket G, (A::'a \text{ triple set}) \vdash \{P1::'a \text{ assn}\} \text{ t> } \{Q1\}; G, A \vdash \{P2::'a \text{ assn}\} \text{ t> } \{Q2\} \rrbracket$
 $\implies G, A \vdash \{\lambda Y s Z. P1 Y s Z \vee P2 Y s Z\} \text{ t> } \{\lambda Y s Z. Q1 Y s Z \vee Q2 Y s Z\}$
 <proof>

lemma ax-supd-shuffle:

$(\exists Q. G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} .c1. \{Q\} \wedge G, A \vdash \{Q ;. f\} .c2. \{R\}) =$
 $(\exists Q'. G, A \vdash \{P\} .c1. \{f ;. Q'\} \wedge G, A \vdash \{Q'\} .c2. \{R\})$
 <proof>

lemma ax-cases:

$\llbracket G, (A::'a \text{ triple set}) \vdash \{P \wedge. C\} \text{ t> } \{Q::'a \text{ assn}\};$
 $G, A \vdash \{P \wedge. \text{Not} \circ C\} \text{ t> } \{Q\} \rrbracket \implies G, A \vdash \{P\} \text{ t> } \{Q\}$
 <proof>

lemma ax-adapt: $G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} \text{ t> } \{Q\}$
 $\implies G, A \vdash \{\text{adapt-pre } P Q Q'\} \text{ t> } \{Q'\}$
 <proof>

lemma adapt-pre-adapts: $G, (A::'a \text{ triple set}) \models \{P::'a \text{ assn}\} \text{ t> } \{Q\}$
 $\longrightarrow G, A \models \{\text{adapt-pre } P Q Q'\} \text{ t> } \{Q'\}$
 <proof>

lemma adapt-pre-weakest:

$\forall G (A::'a \text{ triple set}) t. G, A \models \{P\} \text{ t> } \{Q\} \longrightarrow G, A \models \{P'\} \text{ t> } \{Q'\} \implies$
 $P' \Rightarrow \text{adapt-pre } P Q (Q'::'a \text{ assn})$
 <proof>

lemma peek-and-forget1-Normal:

$G, (A::'a \text{ triple set}) \vdash \{\text{Normal } P\} \text{ t> } \{Q::'a \text{ assn}\}$
 $\implies G, A \vdash \{\text{Normal } (P \wedge. p)\} \text{ t> } \{Q\}$
 <proof>

lemma peek-and-forget1:

$G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} \text{ t> } \{Q\}$
 $\implies G, A \vdash \{P \wedge. p\} \text{ t> } \{Q\}$
 <proof>

lemmas ax-NormalD = peek-and-forget1 [of - - - - normal]

lemma peek-and-forget2:

$$G, (A :: 'a \text{ triple set}) \vdash \{P :: 'a \text{ assn}\} t \succ \{Q \wedge p\}$$

$$\implies G, A \vdash \{P\} t \succ \{Q\}$$

<proof>

lemma ax-subst-Val-allI:

$$\forall v. G, (A :: 'a \text{ triple set}) \vdash \{(P' \quad v) \leftarrow \text{Val } v\} t \succ \{(Q \ v) :: 'a \text{ assn}\}$$

$$\implies \forall v. G, A \vdash \{(\lambda w. P' (\text{the-In1 } w)) \leftarrow \text{Val } v\} t \succ \{Q \ v\}$$

<proof>

lemma ax-subst-Var-allI:

$$\forall v. G, (A :: 'a \text{ triple set}) \vdash \{(P' \quad v) \leftarrow \text{Var } v\} t \succ \{(Q \ v) :: 'a \text{ assn}\}$$

$$\implies \forall v. G, A \vdash \{(\lambda w. P' (\text{the-In2 } w)) \leftarrow \text{Var } v\} t \succ \{Q \ v\}$$

<proof>

lemma ax-subst-Vals-allI:

$$(\forall v. G, (A :: 'a \text{ triple set}) \vdash \{(P' \quad v) \leftarrow \text{Vals } v\} t \succ \{(Q \ v) :: 'a \text{ assn}\})$$

$$\implies \forall v. G, A \vdash \{(\lambda w. P' (\text{the-In3 } w)) \leftarrow \text{Vals } v\} t \succ \{Q \ v\}$$

<proof>

alternative axioms

lemma ax-Lit2:

$$G, (A :: 'a \text{ triple set}) \vdash \{\text{Normal } P :: 'a \text{ assn}\} \text{Lit } v \succ \{\text{Normal } (P \downarrow = \text{Val } v)\}$$

<proof>

lemma ax-Lit2-test-complete:

$$G, (A :: 'a \text{ triple set}) \vdash \{\text{Normal } (P \leftarrow \text{Val } v) :: 'a \text{ assn}\} \text{Lit } v \succ \{P\}$$

<proof>

lemma ax-LVar2: $G, (A :: 'a \text{ triple set}) \vdash \{\text{Normal } P :: 'a \text{ assn}\} \text{LVar } vn \succ \{\text{Normal } (\lambda s. P \downarrow = \text{Var } (\text{lvar } vn \ s))\}$

<proof>

lemma ax-Super2: $G, (A :: 'a \text{ triple set}) \vdash$

$$\{\text{Normal } P :: 'a \text{ assn}\} \text{Super} \succ \{\text{Normal } (\lambda s. P \downarrow = \text{Val } (\text{val-this } s))\}$$

<proof>

lemma ax-Nil2:

$$G, (A :: 'a \text{ triple set}) \vdash \{\text{Normal } P :: 'a \text{ assn}\} [] \succ \{\text{Normal } (P \downarrow = \text{Vals } [])\}$$

<proof>

misc derived structural rules

lemma ax-finite-mtriples-lemma: $[F \subseteq ms; \text{finite } ms; \forall (C, sig) \in ms.$

$$G, (A :: 'a \text{ triple set}) \vdash \{\text{Normal } (P \ C \ sig) :: 'a \text{ assn}\} \text{mb } C \ sig \succ \{Q \ C \ sig\} \implies$$

$$G, A \vdash \{\{P\} \text{mb} \succ \{Q\} \mid F\}$$

<proof>

lemmas ax-finite-mtriples = ax-finite-mtriples-lemma [OF subset-refl]

lemma ax-derivs-insertD:

$$G, (A :: 'a \text{ triple set}) \vdash \text{insert } (t :: 'a \text{ triple}) \ ts \implies G, A \vdash t \wedge G, A \vdash ts$$

$\langle \text{proof} \rangle$

lemma *ax-methods-spec*:

$\llbracket G, (A::'a \text{ triple set}) \vdash \text{split } f \text{ ' } ms; (C, sig) \in ms \rrbracket \implies G, A \vdash ((f \ C \ sig)::'a \ \text{triple})$
 $\langle \text{proof} \rangle$

lemma *ax-finite-pointwise-lemma* [rule-format]: $\llbracket F \subseteq ms; \text{finite } ms \rrbracket \implies$

$((\forall (C, sig) \in F. G, (A::'a \ \text{triple set}) \vdash (f \ C \ sig)::'a \ \text{triple})) \longrightarrow (\forall (C, sig) \in ms. G, A \vdash (g \ C \ sig)::'a \ \text{triple})) \longrightarrow$
 $G, A \vdash \text{split } f \text{ ' } F \longrightarrow G, A \vdash \text{split } g \text{ ' } F$

$\langle \text{proof} \rangle$

lemmas *ax-finite-pointwise* = *ax-finite-pointwise-lemma* [OF subset-refl]

lemma *ax-no-hazard*:

$G, (A::'a \ \text{triple set}) \vdash \{P \ \wedge. \ \text{type-ok } G \ t\} \ t \succ \{Q::'a \ \text{assn}\} \implies G, A \vdash \{P\} \ t \succ \{Q\}$
 $\langle \text{proof} \rangle$

lemma *ax-free-wt*:

$(\exists T \ L \ C. (\text{prg} = G, \text{cls} = C, \text{lcl} = L) \vdash t::T)$
 $\longrightarrow G, (A::'a \ \text{triple set}) \vdash \{\text{Normal } P\} \ t \succ \{Q::'a \ \text{assn}\} \implies$
 $G, A \vdash \{\text{Normal } P\} \ t \succ \{Q\}$

$\langle \text{proof} \rangle$

$\langle \text{ML} \rangle$

declare *ax-Abrupts* [intro!]

lemmas *ax-Normal-cases* = *ax-cases* [of - - - normal]

lemma *ax-Skip* [intro!]: $G, (A::'a \ \text{triple set}) \vdash \{P \leftarrow \diamond\} \ .\text{Skip}. \{P::'a \ \text{assn}\}$

$\langle \text{proof} \rangle$

lemmas *ax-SkipI* = *ax-Skip* [THEN conseq1]

derived rules for methd call

lemma *ax-Call-known-DynT*:

$\llbracket G \vdash \text{IntVir} \rightarrow C \preceq \text{statT};$
 $\forall a \ \text{vs } l. G, A \vdash \{(R \ a \leftarrow \text{Vals } \text{vs} \ \wedge. (\lambda s. l = \text{locals } (\text{store } s)) \ ;$
 $\text{init-lvars } G \ C \ (\text{name} = mn, \text{parTs} = pTs) \ \text{IntVir } a \ \text{vs})\}$
 $\text{Methd } C \ (\text{name} = mn, \text{parTs} = pTs) \ \dashv \succ \{\text{set-lvars } l \ ; \ S\};$
 $\forall a. G, A \vdash \{Q \leftarrow \text{Val } a\} \ \text{args} \dashv \succ$
 $\{R \ a \ \wedge. (\lambda s. C = \text{obj-class } (\text{the } (\text{heap } (\text{store } s) \ (\text{the-Addr } a))) \ \wedge$
 $C = \text{invocation-declclass}$
 $G \ \text{IntVir } (\text{store } s) \ a \ \text{statT } (\text{name} = mn, \text{parTs} = pTs) \ \};$
 $G, (A::'a \ \text{triple set}) \vdash \{\text{Normal } P\} \ e \dashv \succ \{Q::'a \ \text{assn}\}$
 $\implies G, A \vdash \{\text{Normal } P\} \ \{\text{acc } C, \text{statT}, \text{IntVir}\} e \cdot mn(\{pTs\} \ \text{args}) \dashv \succ \{S\}$

$\langle \text{proof} \rangle$

lemma *ax-Call-Static*:

$\llbracket \forall a \ \text{vs } l. G, A \vdash \{R \ a \leftarrow \text{Vals } \text{vs} \ \wedge. (\lambda s. l = \text{locals } (\text{store } s)) \ ;$
 $\text{init-lvars } G \ C \ (\text{name} = mn, \text{parTs} = pTs) \ \text{Static any-Addr } \text{vs}\}$
 $\text{Methd } C \ (\text{name} = mn, \text{parTs} = pTs) \ \dashv \succ \{\text{set-lvars } l \ ; \ S\};$
 $G, A \vdash \{\text{Normal } P\} \ e \dashv \succ \{Q\};$

$$\begin{aligned} & \forall a. G, (A::'a \text{ triple set}) \vdash \{Q \leftarrow \text{Val } a\} \text{ args} \doteq \succ \{(R::\text{val} \Rightarrow 'a \text{ assn}) \ a \\ & \wedge. (\lambda s. C = \text{invocation-declclass} \\ & \quad G \text{ Static } (\text{store } s) \ a \ \text{statT } (\downarrow \text{name=mn, parTs=pTs}))\} \\ \llbracket & \implies G, A \vdash \{\text{Normal } P\} \{accC, \text{statT}, \text{Static}\} \cdot \text{mn}(\{pTs\} \text{args}) \succ \{S\} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ax-Method1*:

$$\begin{aligned} & \llbracket G, A \cup \{\{P\} \text{ Methd} \succ \{Q\} \mid ms\} \vdash \{\{P\} \text{ body } G \succ \{Q\} \mid ms\}; (C, sig) \in ms \rrbracket \implies \\ & \quad G, A \vdash \{\text{Normal } (P \ C \ sig)\} \text{ Methd } C \ sig \succ \{Q \ C \ sig\} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ax-MethodN*:

$$\begin{aligned} & G, \text{insert}(\{\text{Normal } P\} \text{ Methd } C \ sig \succ \{Q\}) \ A \vdash \\ & \quad \{\text{Normal } P\} \ \text{body } G \ C \ sig \succ \{Q\} \implies \\ & \quad G, A \vdash \{\text{Normal } P\} \ \text{Methd } C \ sig \succ \{Q\} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ax-StatRef*:

$$\begin{aligned} & G, (A::'a \text{ triple set}) \vdash \{\text{Normal } (P \leftarrow \text{Val } \text{Null})\} \ \text{StatRef } rt \succ \{P::'a \ \text{assn}\} \\ & \langle \text{proof} \rangle \end{aligned}$$

rules derived from Init and Done

lemma *ax-InitS*: $\llbracket \text{the } (\text{class } G \ C) = c; C \neq \text{Object};$

$$\begin{aligned} & \forall l. G, A \vdash \{Q \wedge. (\lambda s. l = \text{locals } (\text{store } s)) \ ; \ \text{set-lvars empty}\} \\ & \quad \cdot \text{init } c. \ \{\text{set-lvars } l \ ; \ R\}; \\ & \quad G, A \vdash \{\text{Normal } ((P \wedge. \text{Not} \circ \text{initd } C) \ ; \ \text{supd } (\text{init-class-obj } G \ C))\} \\ & \quad \cdot \text{Init } (\text{super } c). \ \{Q\} \rrbracket \implies \\ & \quad G, (A::'a \ \text{triple set}) \vdash \{\text{Normal } (P \wedge. \text{Not} \circ \text{initd } C)\} \ \cdot \text{Init } C. \ \{R::'a \ \text{assn}\} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ax-Init-Skip-lemma*:

$$\begin{aligned} & \forall l. G, (A::'a \ \text{triple set}) \vdash \{P \leftarrow \diamond \wedge. (\lambda s. l = \text{locals } (\text{store } s)) \ ; \ \text{set-lvars } l'\} \\ & \quad \cdot \text{Skip}. \ \{\text{set-lvars } l \ ; \ P\}::'a \ \text{assn}\} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ax-triv-InitS*: $\llbracket \text{the } (\text{class } G \ C) = c; \text{init } c = \text{Skip}; C \neq \text{Object};$

$$\begin{aligned} & P \leftarrow \diamond \implies (\text{supd } (\text{init-class-obj } G \ C) \ ; \ P); \\ & \quad G, A \vdash \{\text{Normal } (P \wedge. \text{initd } C)\} \ \cdot \text{Init } (\text{super } c). \ \{(P \wedge. \text{initd } C) \leftarrow \diamond\} \rrbracket \implies \\ & \quad G, (A::'a \ \text{triple set}) \vdash \{\text{Normal } P \leftarrow \diamond\} \ \cdot \text{Init } C. \ \{(P \wedge. \text{initd } C)::'a \ \text{assn}\} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ax-Init-Object*: $wf\text{-prog } G \implies G, (A::'a \ \text{triple set}) \vdash$

$$\begin{aligned} & \{\text{Normal } ((\text{supd } (\text{init-class-obj } G \ \text{Object}) \ ; \ P \leftarrow \diamond) \wedge. \text{Not} \circ \text{initd } \text{Object})\} \\ & \quad \cdot \text{Init } \text{Object}. \ \{(P \wedge. \text{initd } \text{Object})::'a \ \text{assn}\} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *ax-triv-Init-Object*: $\llbracket wf\text{-prog } G;$

$$\begin{aligned} & (P::'a \ \text{assn}) \implies (\text{supd } (\text{init-class-obj } G \ \text{Object}) \ ; \ P) \rrbracket \implies \\ & \quad G, (A::'a \ \text{triple set}) \vdash \{\text{Normal } P \leftarrow \diamond\} \ \cdot \text{Init } \text{Object}. \ \{P \wedge. \text{initd } \text{Object}\} \\ & \langle \text{proof} \rangle \end{aligned}$$

introduction rules for Alloc and SXAlloc**lemma** *ax-SXAlloc-Normal*:
$$G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} \text{ .c. } \{Normal\} Q\}$$

$$\implies G, A \vdash \{P\} \text{ .c. } \{SXAlloc\} G\} Q\}$$

<proof>

lemma *ax-Alloc*:
$$G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} \text{ t>}$$

$$\{Normal\} (\lambda Y (x, s) Z. (\forall a. \text{new-Addr} (\text{heap } s) = \text{Some } a \longrightarrow$$

$$Q (\text{Val} (\text{Addr } a)) (\text{Norm} (\text{init-obj } G (\text{CInst } C) (\text{Heap } a) s)) Z)) \wedge.$$

$$\text{heap-free} (\text{Suc} (\text{Suc } 0))\}$$

$$\implies G, A \vdash \{P\} \text{ t> } \{Alloc\} G (\text{CInst } C) Q\}$$

<proof>

lemma *ax-Alloc-Arr*:
$$G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} \text{ t>}$$

$$\{\lambda \text{Val}:i:. Normal\} (\lambda Y (x, s) Z. \neg \text{the-Intg } i < 0 \wedge$$

$$(\forall a. \text{new-Addr} (\text{heap } s) = \text{Some } a \longrightarrow$$

$$Q (\text{Val} (\text{Addr } a)) (\text{Norm} (\text{init-obj } G (\text{Arr } T (\text{the-Intg } i)) (\text{Heap } a) s)) Z)) \wedge.$$

$$\text{heap-free} (\text{Suc} (\text{Suc } 0))\}$$

$$\implies$$

$$G, A \vdash \{P\} \text{ t> } \{\lambda \text{Val}:i:. \text{abupd} (\text{check-neg } i) .; Alloc\} G (\text{Arr } T (\text{the-Intg } i)) Q\}$$

<proof>

lemma *ax-SXAlloc-catch-SXcpt*:
$$\llbracket G, (A::'a \text{ triple set}) \vdash \{P::'a \text{ assn}\} \text{ t>}$$

$$\{(\lambda Y (x, s) Z. x = \text{Some} (\text{Xcpt} (\text{Std } xn)) \wedge$$

$$(\forall a. \text{new-Addr} (\text{heap } s) = \text{Some } a \longrightarrow$$

$$Q Y (\text{Some} (\text{Xcpt} (\text{Loc } a)), \text{init-obj } G (\text{CInst} (\text{SXcpt } xn)) (\text{Heap } a) s) Z))$$

$$\wedge. \text{heap-free} (\text{Suc} (\text{Suc } 0))\} \rrbracket$$

$$\implies$$

$$G, A \vdash \{P\} \text{ t> } \{SXAlloc\} G (\lambda Y s Z. Q Y s Z \wedge G, s \vdash \text{catch } \text{SXcpt } xn)\}$$

<proof>

end

Chapter 23

AxSound

62 Soundness proof for Axiomatic semantics of Java expressions and statements

theory *AxSound* imports *AxSem* begin

validity

definition

triple-valid2 :: *prog* \Rightarrow *nat* \Rightarrow 'a *triple* \Rightarrow *bool* (-|=:-[61,0, 58] 57)

where

$$G \models n :: t =$$

$$(\text{case } t \text{ of } \{P\} t \succ \{Q\} \Rightarrow$$

$$\forall Y s Z. P Y s Z \longrightarrow (\forall L. s :: \preceq(G, L)$$

$$\longrightarrow (\forall T C A. (\text{normal } s \longrightarrow ((\text{prg} = G, \text{cls} = C, \text{lcl} = L) \vdash t :: T \wedge$$

$$(\text{prg} = G, \text{cls} = C, \text{lcl} = L) \vdash \text{dom} (\text{locals } (\text{store } s)) \gg t \gg A)) \longrightarrow$$

$$(\forall Y' s'. G \vdash s - t \succ - n \rightarrow (Y', s') \longrightarrow Q Y' s' Z \wedge s' :: \preceq(G, L))))))$$

This definition differs from the ordinary *triple-valid-def* manly in the conclusion: We also ensures conformance of the result state. So we don't have to apply the type soundness lemma all the time during induction. This definition is only introduced for the soundness proof of the axiomatic semantics, in the end we will conclude to the ordinary definition.

definition

ax-valids2 :: *prog* \Rightarrow 'a *triples* \Rightarrow 'a *triples* \Rightarrow *bool* (-,|=:- [61,58,58] 57)

where $G, A \models :: ts = (\forall n. (\forall t \in A. G \models n :: t) \longrightarrow (\forall t \in ts. G \models n :: t))$

lemma *triple-valid2-def2*: $G \models n :: \{P\} t \succ \{Q\} =$

$$(\forall Y s Z. P Y s Z \longrightarrow (\forall Y' s'. G \vdash s - t \succ - n \rightarrow (Y', s') \longrightarrow$$

$$(\forall L. s :: \preceq(G, L) \longrightarrow (\forall T C A. (\text{normal } s \longrightarrow ((\text{prg} = G, \text{cls} = C, \text{lcl} = L) \vdash t :: T \wedge$$

$$(\text{prg} = G, \text{cls} = C, \text{lcl} = L) \vdash \text{dom} (\text{locals } (\text{store } s)) \gg t \gg A)) \longrightarrow$$

$$Q Y' s' Z \wedge s' :: \preceq(G, L))))))$$

<proof>

lemma *triple-valid2-eq* [rule-format (no-asm)]:

wf-prog $G \implies \text{triple-valid2 } G = \text{triple-valid } G$

<proof>

lemma *ax-valids2-eq*: *wf-prog* $G \implies G, A \models :: ts = G, A \models ts$

<proof>

lemma *triple-valid2-Suc* [rule-format (no-asm)]: $G \models \text{Suc } n :: t \longrightarrow G \models n :: t$

<proof>

lemma *Methd-triple-valid2-0*: $G \models 0 :: \{\text{Normal } P\} \text{Methd } C \text{ sig} \succ \{Q\}$

<proof>

lemma *Methd-triple-valid2-SucI*:

$$[[G \models n :: \{\text{Normal } P\} \text{body } G \text{ } C \text{ sig} \succ \{Q\}]]$$

$$\implies G \models \text{Suc } n :: \{\text{Normal } P\} \text{Methd } C \text{ sig} \succ \{Q\}$$

<proof>

lemma *triples-valid2-Suc*:

$\text{Ball } ts (\text{triple-valid2 } G (\text{Suc } n)) \implies \text{Ball } ts (\text{triple-valid2 } G n)$

\langle proof \rangle

lemma $G \models n: \text{insert } t \ A = (G \models n:t \wedge G \models n:A)$

\langle proof \rangle

soundness

lemma *Method-sound*:

assumes *recursive*: $G, A \cup \{\{P\} \text{ Methd} \rightarrow \{Q\} \mid ms\} \models \{\{P\} \text{ body } G \rightarrow \{Q\} \mid ms\}$

shows $G, A \models \{\{P\} \text{ Methd} \rightarrow \{Q\} \mid ms\}$

\langle proof \rangle

lemma *valids2-inductI*: $\forall s \ t \ n \ Y' \ s'. G \vdash s \rightarrow t \rightarrow n \rightarrow (Y', s') \rightarrow t = c \rightarrow$

Ball A (*triple-valid2* $G \ n$) $\rightarrow (\forall Y \ Z. P \ Y \ s \ Z \rightarrow$

$(\forall L. s :: \preceq(G, L) \rightarrow$

$(\forall T \ C \ A. (\text{normal } s \rightarrow ((\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash t :: T) \wedge$

$(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom} (\text{locals} (\text{store } s)) \gg t \gg A) \rightarrow$

$Q \ Y' \ s' \ Z \wedge s' :: \preceq(G, L))) \Rightarrow$

$G, A \models \{\{P\} \ c \rightarrow \{Q\}\}$

\langle proof \rangle

lemma *da-good-approx-evalnE* [*consumes 4*]:

assumes *evaln*: $G \vdash s0 \rightarrow t \rightarrow n \rightarrow (v, s1)$

and *wt*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash t :: T$

and *da*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom} (\text{locals} (\text{store } s0)) \gg t \gg A$

and *wf*: *wf-prog* G

and *elim*: $\llbracket \text{normal } s1 \Rightarrow \text{nrm } A \subseteq \text{dom} (\text{locals} (\text{store } s1));$

$\wedge l. \llbracket \text{abrupt } s1 = \text{Some} (\text{Jump} (\text{Break } l)); \text{normal } s0 \rrbracket$

$\Rightarrow \text{brk } A \ l \subseteq \text{dom} (\text{locals} (\text{store } s1));$

$\llbracket \text{abrupt } s1 = \text{Some} (\text{Jump } \text{Ret}); \text{normal } s0 \rrbracket$

$\Rightarrow \text{Result} \in \text{dom} (\text{locals} (\text{store } s1))$

$\rrbracket \Rightarrow P$

shows P

\langle proof \rangle

lemma *validI*:

assumes $I: \bigwedge n \ s0 \ L \ \text{acc} \ C \ T \ C \ v \ s1 \ Y \ Z.$

$\llbracket \forall t \in A. G \models n :: t; s0 :: \preceq(G, L);$

$\text{normal } s0 \Rightarrow (\text{prg}=G, \text{cls}=\text{acc} \ C, \text{lcl}=L) \vdash t :: T;$

$\text{normal } s0 \Rightarrow (\text{prg}=G, \text{cls}=\text{acc} \ C, \text{lcl}=L) \vdash \text{dom} (\text{locals} (\text{store } s0)) \gg t \gg C;$

$G \vdash s0 \rightarrow t \rightarrow n \rightarrow (v, s1); P \ Y \ s0 \ Z \rrbracket \Rightarrow Q \ v \ s1 \ Z \wedge s1 :: \preceq(G, L)$

shows $G, A \models \{\{P\} \ t \rightarrow \{Q\}\}$

\langle proof \rangle

declare $\llbracket \text{simproc } \text{add}: \text{wt-expr } \text{wt-var } \text{wt-exprs } \text{wt-stmt} \rrbracket$

lemma *valid-stmtI*:

assumes $I: \bigwedge n \ s0 \ L \ \text{acc} \ C \ C \ s1 \ Y \ Z.$

$\llbracket \forall t \in A. G \models n :: t; s0 :: \preceq(G, L);$

$\text{normal } s0 \Rightarrow (\text{prg}=G, \text{cls}=\text{acc} \ C, \text{lcl}=L) \vdash c :: \surd;$

$\text{normal } s0 \Rightarrow (\text{prg}=G, \text{cls}=\text{acc} \ C, \text{lcl}=L) \vdash \text{dom} (\text{locals} (\text{store } s0)) \gg \langle c \rangle_s \gg C;$

$G \vdash s0 \rightarrow c \rightarrow n \rightarrow s1; P \ Y \ s0 \ Z \rrbracket \Rightarrow Q \ \diamond s1 \ Z \wedge s1 :: \preceq(G, L)$

shows $G, A \models :: \{ \{P\} \langle c \rangle_s \succ \{Q\} \}$
 ⟨proof⟩

lemma *valid-stmt-NormalI*:

assumes $I: \bigwedge n \ s0 \ L \ accC \ C \ s1 \ Y \ Z.$

$\llbracket \forall t \in A. G \models n :: t; s0 :: \preceq(G, L); \text{normal } s0; (\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash c :: \surd;$

$(\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash \text{dom } (\text{locals } (\text{store } s0)) \gg \langle c \rangle_s \gg C;$

$G \vdash s0 \ -c-n \rightarrow s1; (\text{Normal } P) \ Y \ s0 \ Z \rrbracket \implies Q \ \diamond \ s1 \ Z \ \wedge \ s1 :: \preceq(G, L)$

shows $G, A \models :: \{ \{ \text{Normal } P \} \langle c \rangle_s \succ \{Q\} \}$
 ⟨proof⟩

lemma *valid-var-NormalI*:

assumes $I: \bigwedge n \ s0 \ L \ accC \ T \ C \ \text{vf} \ s1 \ Y \ Z.$

$\llbracket \forall t \in A. G \models n :: t; s0 :: \preceq(G, L); \text{normal } s0;$

$(\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash t :: T;$

$(\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash \text{dom } (\text{locals } (\text{store } s0)) \gg \langle t \rangle_v \gg C;$

$G \vdash s0 \ -t \succ \text{vf} - n \rightarrow s1; (\text{Normal } P) \ Y \ s0 \ Z \rrbracket$

$\implies Q \ (\text{In}2 \ \text{vf}) \ s1 \ Z \ \wedge \ s1 :: \preceq(G, L)$

shows $G, A \models :: \{ \{ \text{Normal } P \} \langle t \rangle_v \succ \{Q\} \}$
 ⟨proof⟩

lemma *valid-expr-NormalI*:

assumes $I: \bigwedge n \ s0 \ L \ accC \ T \ C \ v \ s1 \ Y \ Z.$

$\llbracket \forall t \in A. G \models n :: t; s0 :: \preceq(G, L); \text{normal } s0;$

$(\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash t :: -T;$

$(\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash \text{dom } (\text{locals } (\text{store } s0)) \gg \langle t \rangle_e \gg C;$

$G \vdash s0 \ -t \succ v - n \rightarrow s1; (\text{Normal } P) \ Y \ s0 \ Z \rrbracket$

$\implies Q \ (\text{In}1 \ v) \ s1 \ Z \ \wedge \ s1 :: \preceq(G, L)$

shows $G, A \models :: \{ \{ \text{Normal } P \} \langle t \rangle_e \succ \{Q\} \}$
 ⟨proof⟩

lemma *valid-expr-list-NormalI*:

assumes $I: \bigwedge n \ s0 \ L \ accC \ T \ C \ \text{vs} \ s1 \ Y \ Z.$

$\llbracket \forall t \in A. G \models n :: t; s0 :: \preceq(G, L); \text{normal } s0;$

$(\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash t :: \doteq T;$

$(\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash \text{dom } (\text{locals } (\text{store } s0)) \gg \langle t \rangle_l \gg C;$

$G \vdash s0 \ -t \doteq \text{vs} - n \rightarrow s1; (\text{Normal } P) \ Y \ s0 \ Z \rrbracket$

$\implies Q \ (\text{In}3 \ \text{vs}) \ s1 \ Z \ \wedge \ s1 :: \preceq(G, L)$

shows $G, A \models :: \{ \{ \text{Normal } P \} \langle t \rangle_l \succ \{Q\} \}$
 ⟨proof⟩

lemma *validE* [consumes 5]:

assumes *valid*: $G, A \models :: \{ \{P\} \ t \succ \{Q\} \}$

and $P: P \ Y \ s0 \ Z$

and *valid-A*: $\forall t \in A. G \models n :: t$

and *conf*: $s0 :: \preceq(G, L)$

and *eval*: $G \vdash s0 \ -t \succ -n \rightarrow (v, s1)$

and *wt*: $\text{normal } s0 \implies (\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash t :: T$

and *da*: $\text{normal } s0 \implies (\text{prg} = G, \text{cls} = \text{acc}C, \text{lcl} = L) \vdash \text{dom } (\text{locals } (\text{store } s0)) \gg t \gg C$

and *elim*: $\llbracket Q \ v \ s1 \ Z; s1 :: \preceq(G, L) \rrbracket \implies \text{concl}$

shows *concl*

⟨proof⟩

lemma *all-empty*: $(!x. P) = P$

\langle proof \rangle

corollary *evaln-type-sound*:

assumes *evaln*: $G \vdash s0 \text{ -t>-n} \rightarrow (v, s1)$ **and**

wt: $(\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash t :: T$ **and**

da: $(\text{prg}=G, \text{cls}=\text{acc}C, \text{lcl}=L) \vdash \text{dom} (\text{locals} (\text{store } s0)) \gg t \gg A$ **and**

conf-s0: $s0 :: \preceq (G, L)$ **and**

wf: *wf-prog* G

shows $s1 :: \preceq (G, L) \wedge (\text{normal } s1 \rightarrow G, L, \text{store } s1 \vdash t \gg v :: \preceq T) \wedge$

$(\text{error-free } s0 = \text{error-free } s1)$

\langle proof \rangle

corollary *dom-locals-evaln-mono-elim* [*consumes 1*]:

assumes

evaln: $G \vdash s0 \text{ -t>-n} \rightarrow (v, s1)$ **and**

hyps: $\llbracket \text{dom} (\text{locals} (\text{store } s0)) \subseteq \text{dom} (\text{locals} (\text{store } s1)) \rrbracket$;

$\wedge \llbracket v = \text{In2 } vv; \text{normal } s1 \rrbracket$

$\implies \text{dom} (\text{locals} (\text{store } s))$

$\subseteq \text{dom} (\text{locals} (\text{store} ((\text{snd } vv) \text{ val } s))) \rrbracket \implies P$

shows P

\langle proof \rangle

lemma *evaln-no-abrupt*:

$\llbracket \bigwedge s s'. \llbracket G \vdash s \text{ -t>-n} \rightarrow (w, s') \rrbracket; \text{normal } s' \rrbracket \implies \text{normal } s$

\langle proof \rangle

declare *inj-term-simps* [*simp*]

lemma *ax-sound2*:

assumes *wf*: *wf-prog* G

and *deriv*: $G, A \vdash ts$

shows $G, A \Vdash ts$

\langle proof \rangle

declare *inj-term-simps* [*simp del*]

theorem *ax-sound*:

wf-prog $G \implies G, (A :: 'a \text{ triple set}) \vdash (ts :: 'a \text{ triple set}) \implies G, A \Vdash ts$

\langle proof \rangle

lemma *sound-valid2-lemma*:

$\llbracket \forall v n. \text{Ball } A (\text{triple-valid2 } G n) \rightarrow P v n; \text{Ball } A (\text{triple-valid2 } G n) \rrbracket$

$\implies P v n$

\langle proof \rangle

end

Chapter 24

AxCompl

63 Completeness proof for Axiomatic semantics of Java expressions and statements

theory *AxCompl* **imports** *AxSem* **begin**

design issues:

- proof structured by Most General Formulas (-j; Thomas Kleymann)

set of not yet initialized classes

definition

nyinitcls :: *prog* \Rightarrow *state* \Rightarrow *qname set*
where *nyinitcls* *G s* = {*C*. *is-class* *G C* \wedge \neg *initd* *C s*}

lemma *nyinitcls-subset-class*: *nyinitcls* *G s* \subseteq {*C*. *is-class* *G C*}
 <proof>

lemmas *finite-nyinitcls* [*simp*] =
finite-is-class [*THEN nyinitcls-subset-class* [*THEN finite-subset*]]

lemma *card-nyinitcls-bound*: *card* (*nyinitcls* *G s*) \leq *card* {*C*. *is-class* *G C*}
 <proof>

lemma *nyinitcls-set-locals-cong* [*simp*]:
nyinitcls *G* (*x*, *set-locals* *l s*) = *nyinitcls* *G* (*x*, *s*)
 <proof>

lemma *nyinitcls-abrupt-cong* [*simp*]: *nyinitcls* *G* (*f x*, *y*) = *nyinitcls* *G* (*x*, *y*)
 <proof>

lemma *nyinitcls-abupd-cong* [*simp*]:!!*s*. *nyinitcls* *G* (*abupd* *f s*) = *nyinitcls* *G s*
 <proof>

lemma *card-nyinitcls-abrupt-congE* [*elim!*]:
card (*nyinitcls* *G* (*x*, *s*)) \leq *n* \Longrightarrow *card* (*nyinitcls* *G* (*y*, *s*)) \leq *n*
 <proof>

lemma *nyinitcls-new-xcpt-var* [*simp*]:
nyinitcls *G* (*new-xcpt-var* *vn s*) = *nyinitcls* *G s*
 <proof>

lemma *nyinitcls-init-lvars* [*simp*]:
nyinitcls *G* ((*init-lvars* *G C sig mode a' pvs*) *s*) = *nyinitcls* *G s*
 <proof>

lemma *nyinitcls-emptyD*: \llbracket *nyinitcls* *G s* = {}; *is-class* *G C* $\rrbracket \Longrightarrow$ *initd* *C s*
 <proof>

lemma *card-Suc-lemma*:

$\llbracket \text{card} (\text{insert } a \ A) \leq \text{Suc } n; a \notin A; \text{finite } A \rrbracket \implies \text{card } A \leq n$
 ⟨proof⟩

lemma *nyinitcls-le-SucD*:

$\llbracket \text{card} (\text{nyinitcls } G \ (x,s)) \leq \text{Suc } n; \neg \text{inited } C \ (\text{globs } s); \text{class } G \ C = \text{Some } y \rrbracket \implies$
 $\text{card} (\text{nyinitcls } G \ (x, \text{init-class-obj } G \ C \ s)) \leq n$
 ⟨proof⟩

lemma *inited-gext'*: $\llbracket s \leq |s'; \text{inited } C \ (\text{globs } s) \rrbracket \implies \text{inited } C \ (\text{globs } s')$

⟨proof⟩

lemma *nyinitcls-gext*: $\text{snd } s \leq | \text{snd } s' \implies \text{nyinitcls } G \ s' \subseteq \text{nyinitcls } G \ s$

⟨proof⟩

lemma *card-nyinitcls-gext*:

$\llbracket \text{snd } s \leq | \text{snd } s'; \text{card} (\text{nyinitcls } G \ s) \leq n \rrbracket \implies \text{card} (\text{nyinitcls } G \ s') \leq n$
 ⟨proof⟩

init-le

definition

init-le :: *prog* \Rightarrow *nat* \Rightarrow *state* \Rightarrow *bool* (+*init*≤- [51,51] 50)
 where $G \vdash \text{init} \leq n = (\lambda s. \text{card} (\text{nyinitcls } G \ s) \leq n)$

lemma *init-le-def2* [*simp*]: $(G \vdash \text{init} \leq n) \ s = (\text{card} (\text{nyinitcls } G \ s) \leq n)$

⟨proof⟩

lemma *All-init-leD*:

$\forall n::\text{nat}. G, (A::'a \ \text{triple set}) \vdash \{P \ \wedge. \ G \vdash \text{init} \leq n\} \ t \succ \ \{Q::'a \ \text{assn}\}$
 $\implies G, A \vdash \{P\} \ t \succ \ \{Q\}$

⟨proof⟩

Most General Triples and Formulas

definition

remember-init-state :: *state assn* (\doteq)
 where $\doteq \equiv \lambda Y \ s \ Z. \ s = Z$

lemma *remember-init-state-def2* [*simp*]: $\doteq \ Y = \text{op} =$

⟨proof⟩

definition

MGF :: [*state assn*, *term*, *prog*] \Rightarrow *state triple* ($\{-\} \dashv \rightarrow \{-\}$)[3,65,3]62)
 where $\{P\} \ t \succ \ \{G \rightarrow\} = \{P\} \ t \succ \ \{\lambda Y \ s' \ s. \ G \vdash s \dashv \rightarrow (Y, s')\}$

definition

MGFn :: [*nat*, *term*, *prog*] \Rightarrow *state triple* ($\{=: \} \dashv \rightarrow \{-\}$)[3,65,3]62)
 where $\{=: n\} \ t \succ \ \{G \rightarrow\} = \{\doteq \ \wedge. \ G \vdash \text{init} \leq n\} \ t \succ \ \{G \rightarrow\}$

lemma *MGF-valid: wf-prog* $G \implies G, \{ \} \models \{ \dot{=} \} t \succ \{ G \rightarrow \}$
 ⟨proof⟩

lemma *MGF-res-eq-lemma [simp]*:
 $(\forall Y' Y s. Y = Y' \wedge P s \longrightarrow Q s) = (\forall s. P s \longrightarrow Q s)$
 ⟨proof⟩

lemma *MGFn-def2*:
 $G, A \vdash \{ =:n \} t \succ \{ G \rightarrow \} = G, A \vdash \{ \dot{=} \wedge. G \vdash \text{init} \leq n \}$
 $t \succ \{ \lambda Y s' s. G \vdash s - t \succ \rightarrow (Y, s') \}$
 ⟨proof⟩

lemma *MGF-MGFn-iff*:
 $G, (A::\text{state triple set}) \vdash \{ \dot{=} \} t \succ \{ G \rightarrow \} = (\forall n. G, A \vdash \{ =:n \} t \succ \{ G \rightarrow \})$
 ⟨proof⟩

lemma *MGFnD*:
 $G, (A::\text{state triple set}) \vdash \{ =:n \} t \succ \{ G \rightarrow \} \implies$
 $G, A \vdash \{ (\lambda Y' s' s. s' = s \quad \wedge P s) \wedge. G \vdash \text{init} \leq n \}$
 $t \succ \{ (\lambda Y' s' s. G \vdash s - t \succ \rightarrow (Y', s') \wedge P s) \wedge. G \vdash \text{init} \leq n \}$
 ⟨proof⟩

lemmas $MGFnD' = MGFnD$ [of - - - $\lambda x. \text{True}$]

To derive the most general formula, we can always assume a normal state in the precondition, since abrupt cases can be handled uniformly by the abrupt rule.

lemma *MGFNormalI*: $G, A \vdash \{ \text{Normal} \dot{=} \} t \succ \{ G \rightarrow \} \implies$
 $G, (A::\text{state triple set}) \vdash \{ \dot{=}::\text{state assn} \} t \succ \{ G \rightarrow \}$
 ⟨proof⟩

lemma *MGFNormalD*:
 $G, (A::\text{state triple set}) \vdash \{ \dot{=} \} t \succ \{ G \rightarrow \} \implies G, A \vdash \{ \text{Normal} \dot{=} \} t \succ \{ G \rightarrow \}$
 ⟨proof⟩

Additionally to *MGFNormalI*, we also expand the definition of the most general formula here

lemma *MGFn-NormalI*:
 $G, (A::\text{state triple set}) \vdash \{ \text{Normal}((\lambda Y' s' s. s' = s \wedge \text{normal } s) \wedge. G \vdash \text{init} \leq n) \} t \succ$
 $\{ \lambda Y s' s. G \vdash s - t \succ \rightarrow (Y, s') \} \implies G, A \vdash \{ =:n \} t \succ \{ G \rightarrow \}$
 ⟨proof⟩

To derive the most general formula, we can restrict ourselves to welltyped terms, since all others can be uniformly handled by the hazard rule.

lemma *MGFn-free-wt*:
 $(\exists T L C. (\text{prg} = G, \text{cls} = C, \text{lcl} = L) \vdash t::T)$
 $\longrightarrow G, (A::\text{state triple set}) \vdash \{ =:n \} t \succ \{ G \rightarrow \}$
 $\implies G, A \vdash \{ =:n \} t \succ \{ G \rightarrow \}$
 ⟨proof⟩

To derive the most general formula, we can restrict ourselves to welltyped terms and assume that the state in the precondition conforms to the environment. All type violations can be uniformly handled by the hazard rule.

lemma *MGFn-free-wt-NormalConformI*:

$$\begin{aligned}
& (\forall T L C . (\downarrow \text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash t :: T \\
& \quad \longrightarrow G, (A :: \text{state triple set}) \\
& \quad \vdash \{ \text{Normal}((\lambda Y' s' s . s'=s \wedge \text{normal } s) \wedge . G \vdash \text{init} \leq n) \wedge . (\lambda s . s :: \preceq(G, L)) \} \\
& \quad t \succ \\
& \quad \{ \lambda Y s' s . G \vdash s - t \succ \rightarrow (Y, s') \} \\
& \implies G, A \vdash \{ =:n \} t \succ \{ G \rightarrow \} \\
& \langle \text{proof} \rangle
\end{aligned}$$

To derive the most general formula, we can restrict ourselves to welltyped terms and assume that the state in the precondition conforms to the environment and that the term is definitely assigned with respect to this state. All type violations can be uniformly handled by the hazard rule.

lemma *MGFn-free-wt-da-NormalConformI*:

$$\begin{aligned}
& (\forall T L C B . (\downarrow \text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash t :: T \\
& \quad \longrightarrow G, (A :: \text{state triple set}) \\
& \quad \vdash \{ \text{Normal}((\lambda Y' s' s . s'=s \wedge \text{normal } s) \wedge . G \vdash \text{init} \leq n) \wedge . (\lambda s . s :: \preceq(G, L)) \\
& \quad \quad \wedge . (\lambda s . (\downarrow \text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash \text{dom } (\text{locals } (\text{store } s)) \gg t \gg B) \} \\
& \quad t \succ \\
& \quad \{ \lambda Y s' s . G \vdash s - t \succ \rightarrow (Y, s') \} \\
& \implies G, A \vdash \{ =:n \} t \succ \{ G \rightarrow \} \\
& \langle \text{proof} \rangle
\end{aligned}$$

main lemmas

lemma *MGFn-Init*:

assumes *mgf-hyp*: $\forall m . \text{Suc } m \leq n \longrightarrow (\forall t . G, A \vdash \{ =:m \} t \succ \{ G \rightarrow \})$
shows $G, (A :: \text{state triple set}) \vdash \{ =:n \} \langle \text{Init } C \rangle_s \succ \{ G \rightarrow \}$
 $\langle \text{proof} \rangle$

lemmas *MGFn-InitD = MGFn-Init [THEN MGFnD, THEN ax-NormalD]*

lemma *MGFn-Call*:

assumes *mgf-methds*:
 $\forall C \text{ sig} . G, (A :: \text{state triple set}) \vdash \{ =:n \} \langle (\text{Methd } C \text{ sig}) \rangle_e \succ \{ G \rightarrow \}$
and *mgf-e*: $G, A \vdash \{ =:n \} \langle e \rangle_e \succ \{ G \rightarrow \}$
and *mgf-ps*: $G, A \vdash \{ =:n \} \langle ps \rangle_t \succ \{ G \rightarrow \}$
and *wf*: *wf-prog* G
shows $G, A \vdash \{ =:n \} \langle \{ \text{acc } C, \text{stat } T, \text{mode} \} \cdot \text{mn}(\{ pTs' \} ps) \rangle_e \succ \{ G \rightarrow \}$
 $\langle \text{proof} \rangle$

lemma *eval-expression-no-jump'*:

assumes *eval*: $G \vdash s0 - e - \succ v \rightarrow s1$
and *no-jmp*: $\text{abrupt } s0 \neq \text{Some } (\text{Jump } j)$
and *wt*: $(\downarrow \text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash e :: -T$
and *wf*: *wf-prog* G
shows $\text{abrupt } s1 \neq \text{Some } (\text{Jump } j)$
 $\langle \text{proof} \rangle$

To derive the most general formula for the loop statement, we need to come up with a proper loop invariant, which intuitively states that we are currently inside the evaluation of the loop. To define such an invariant, we unroll the loop in iterated evaluations of the expression and evaluations of the loop body.

definition

unroll :: *prog* \Rightarrow *label* \Rightarrow *expr* \Rightarrow *stmt* \Rightarrow (*state* \times *state*) *set* **where**
unroll $G \ l \ e \ c = \{ (s, t) . \exists v \ s1 \ s2 .$
 $G \vdash s - e - \succ v \rightarrow s1 \wedge \text{the-Bool } v \wedge \text{normal } s1 \wedge$
 $G \vdash s1 - c \rightarrow s2 \wedge t = (\text{abupd } (\text{absorb } (\text{Cont } l)) \ s2) \}$

lemma *unroll-while*:

assumes *unroll*: $(s, t) \in (\text{unroll } G \text{ l e c})^*$
and *eval-e*: $G \vdash t - e \rightarrow v \rightarrow s'$
and *normal-termination*: $\text{normal } s' \longrightarrow \neg \text{the-Bool } v$
and *wt*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash e :: -T$
and *wf*: *wf-prog* G
shows $G \vdash s - l \cdot \text{While}(e) \ c \rightarrow s'$

<proof>

lemma *MGFn-Loop*:

assumes *mgf-e*: $G, (A :: \text{state triple set}) \vdash \{=:n\} \langle e \rangle_e \succ \{G \rightarrow\}$
and *mgf-c*: $G, A \vdash \{=:n\} \langle c \rangle_s \succ \{G \rightarrow\}$
and *wf*: *wf-prog* G
shows $G, A \vdash \{=:n\} \langle l \cdot \text{While}(e) \ c \rangle_s \succ \{G \rightarrow\}$

<proof>

lemma *MGFn-FVar*:

fixes $A :: \text{state triple set}$
assumes *mgf-init*: $G, A \vdash \{=:n\} \langle \text{Init statDeclC} \rangle_s \succ \{G \rightarrow\}$
and *mgf-e*: $G, A \vdash \{=:n\} \langle e \rangle_e \succ \{G \rightarrow\}$
and *wf*: *wf-prog* G
shows $G, A \vdash \{=:n\} \langle \{\text{accC}, \text{statDeclC}, \text{stat}\} e..fn \rangle_v \succ \{G \rightarrow\}$

<proof>

lemma *MGFn-Fin*:

assumes *wf*: *wf-prog* G
and *mgf-c1*: $G, A \vdash \{=:n\} \langle c1 \rangle_s \succ \{G \rightarrow\}$
and *mgf-c2*: $G, A \vdash \{=:n\} \langle c2 \rangle_s \succ \{G \rightarrow\}$
shows $G, (A :: \text{state triple set}) \vdash \{=:n\} \langle c1 \text{ Finally } c2 \rangle_s \succ \{G \rightarrow\}$

<proof>

lemma *Body-no-break*:

assumes *eval-init*: $G \vdash \text{Norm } s0 - \text{Init } D \rightarrow s1$
and *eval-c*: $G \vdash s1 - c \rightarrow s2$
and *jmpOk*: $\text{jumpNestingOkS } \{\text{Ret}\} \ c$
and *wt-c*: $(\text{prg}=G, \text{cls}=C, \text{lcl}=L) \vdash c :: \checkmark$
and *clsD*: $\text{class } G \ D = \text{Some } d$
and *wf*: *wf-prog* G
shows $\forall l. \text{abrupt } s2 \neq \text{Some } (\text{Jump } (\text{Break } l)) \wedge$
 $\text{abrupt } s2 \neq \text{Some } (\text{Jump } (\text{Cont } l))$

<proof>

lemma *MGFn-Body*:

assumes *wf*: *wf-prog* G
and *mgf-init*: $G, A \vdash \{=:n\} \langle \text{Init } D \rangle_s \succ \{G \rightarrow\}$
and *mgf-c*: $G, A \vdash \{=:n\} \langle c \rangle_s \succ \{G \rightarrow\}$
shows $G, (A :: \text{state triple set}) \vdash \{=:n\} \langle \text{Body } D \ c \rangle_e \succ \{G \rightarrow\}$

<proof>

lemma *MGFn-lemma*:

assumes *mgf-methods*:

$$\bigwedge n. \forall C \text{ sig}. G, (A::\text{state triple set}) \vdash \{=:n\} \langle \text{Methd } C \text{ sig} \rangle_e \succ \{G \rightarrow\}$$

and *wf*: *wf-prog* G

shows $\bigwedge t. G, A \vdash \{=:n\} t \succ \{G \rightarrow\}$

<proof>

lemma *MGF-asm*:

$$\llbracket \forall C \text{ sig}. \text{is-methd } G \ C \ \text{sig} \longrightarrow G, A \vdash \{=\} \text{In1l } (\text{Methd } C \ \text{sig}) \succ \{G \rightarrow\}; \text{wf-prog } G \rrbracket$$

$$\implies G, (A::\text{state triple set}) \vdash \{=\} t \succ \{G \rightarrow\}$$

<proof>

nested version

lemma *nesting-lemma'* [*rule-format (no-asm)*]:

assumes *ax-derivs-asm*: $\bigwedge A \ ts. \ ts \subseteq A \implies P \ A \ ts$

and *MGF-nested-Methd*: $\bigwedge A \ pn. \forall b \in \text{bdy } pn. P \ (\text{insert } (\text{mgf-call } pn) \ A) \ \{\text{mgf } b\}$
 $\implies P \ A \ \{\text{mgf-call } pn\}$

and *MGF-asm*: $\bigwedge A \ t. \forall pn \in U. P \ A \ \{\text{mgf-call } pn\} \implies P \ A \ \{\text{mgf } t\}$

and *finU*: *finite* U

and *uA*: $uA = \text{mgf-call}' U$

shows $\forall A. A \subseteq uA \longrightarrow n \leq \text{card } uA \longrightarrow \text{card } A = \text{card } uA - n$
 $\longrightarrow (\forall t. P \ A \ \{\text{mgf } t\})$

<proof>

lemma *nesting-lemma* [*rule-format (no-asm)*]:

assumes *ax-derivs-asm*: $\bigwedge A \ ts. \ ts \subseteq A \implies P \ A \ ts$

and *MGF-nested-Methd*: $\bigwedge A \ pn. \forall b \in \text{bdy } pn. P \ (\text{insert } (\text{mgf } (f \ pn)) \ A) \ \{\text{mgf } b\}$
 $\implies P \ A \ \{\text{mgf } (f \ pn)\}$

and *MGF-asm*: $\bigwedge A \ t. \forall pn \in U. P \ A \ \{\text{mgf } (f \ pn)\} \implies P \ A \ \{\text{mgf } t\}$

and *finU*: *finite* U

shows $P \ \{\} \ \{\text{mgf } t\}$

<proof>

lemma *MGF-nested-Methd*: \llbracket

$$G, \text{insert } (\{\text{Normal } \doteq\} \langle \text{Methd } C \ \text{sig} \rangle_e \succ \{G \rightarrow\}) \ A$$

$$\vdash \{\text{Normal } \doteq\} \langle \text{body } G \ C \ \text{sig} \rangle_e \succ \{G \rightarrow\}$$

$$\rrbracket \implies G, A \vdash \{\text{Normal } \doteq\} \langle \text{Methd } C \ \text{sig} \rangle_e \succ \{G \rightarrow\}$$

<proof>

lemma *MGF-deriv*: *wf-prog* $G \implies G, (\{\}::\text{state triple set}) \vdash \{=\} t \succ \{G \rightarrow\}$

<proof>

simultaneous version

lemma *MGF-simult-Methd-lemma*: *finite* $ms \implies$

$$G, A \cup (\lambda(C, \text{sig}). \{\text{Normal } \doteq\} \langle \text{Methd } C \ \text{sig} \rangle_e \succ \{G \rightarrow\}) \ 'ms$$

$$\vdash (\lambda(C, \text{sig}). \{\text{Normal } \doteq\} \langle \text{body } G \ C \ \text{sig} \rangle_e \succ \{G \rightarrow\}) \ 'ms \implies$$

$$G, A \vdash (\lambda(C, \text{sig}). \{\text{Normal } \doteq\} \langle \text{Methd } C \ \text{sig} \rangle_e \succ \{G \rightarrow\}) \ 'ms$$

<proof>

lemma *MGF-simult-Methd*: *wf-prog* $G \implies$

$$G, (\{\}::\text{state triple set}) \vdash (\lambda(C, \text{sig}). \{\text{Normal } \doteq\} \langle \text{Methd } C \ \text{sig} \rangle_e \succ \{G \rightarrow\})$$

‘ *Collect (split (is-methd G))*
 ⟨proof⟩

corollaries

lemma *eval-to-evaln*: $\llbracket G \vdash s \rightarrow t \gg \rightarrow (Y', s'); \text{type-ok } G \ t \ s; \text{wf-prog } G \rrbracket$
 $\implies \exists n. G \vdash s \rightarrow t \gg \rightarrow n \rightarrow (Y', s')$
 ⟨proof⟩

lemma *MGF-complete*:

assumes *valid*: $G, \{ \} \models \{ P \} \ t \gg \{ Q \}$
and *mgf*: $G, (\{ \} :: \text{state triple set}) \vdash \{ \doteq \} \ t \gg \{ G \rightarrow \}$
and *wf*: *wf-prog* G
shows $G, (\{ \} :: \text{state triple set}) \vdash \{ P :: \text{state assn} \} \ t \gg \{ Q \}$
 ⟨proof⟩

theorem *ax-complete*:

assumes *wf*: *wf-prog* G
and *valid*: $G, \{ \} \models \{ P :: \text{state assn} \} \ t \gg \{ Q \}$
shows $G, (\{ \} :: \text{state triple set}) \vdash \{ P \} \ t \gg \{ Q \}$
 ⟨proof⟩

end

Chapter 25

AxExample

64 Example of a proof based on the Bali axiomatic semantics

```
theory AxExample
imports AxSem Example
begin
```

definition

```
arr-inv :: st ⇒ bool where
arr-inv = (λs. ∃ obj a T el. globs s (Stat Base) = Some obj ∧
          values obj (Inl (arr, Base)) = Some (Addr a) ∧
          heap s a = Some (tag=Arr T 2, values=el))
```

lemma arr-inv-new-obj:

```
∧ a. [arr-inv s; new-Addr (heap s)=Some a] ⇒ arr-inv (gupd(Inl a→x) s)
⟨proof⟩
```

lemma arr-inv-set-locals [simp]: arr-inv (set-locals l s) = arr-inv s

⟨proof⟩

lemma arr-inv-gupd-Stat [simp]:

```
Base ≠ C ⇒ arr-inv (gupd(Stat C→obj) s) = arr-inv s
⟨proof⟩
```

lemma ax-inv-lupd [simp]: arr-inv (lupd(x→y) s) = arr-inv s

⟨proof⟩

```
declare split-if-asm [split del]
```

```
declare lvar-def [simp]
```

⟨ML⟩

theorem ax-test: tprg,({::'a triple set})⊢

```
{Normal (λY s Z::'a. heap-free four s ∧ ¬initd Base s ∧ ¬ initd Ext s)}
.test [Class Base].
{λY s Z. abrupt s = Some (Xcpt (Std IndOutBound))}
⟨proof⟩
```

lemma Loop-Xcpt-benchmark:

```
Q = (λY (x,s) Z. x ≠ None → the-Bool (the (locals s i))) ⇒
  G,({::'a triple set})⊢{Normal (λY s Z::'a. True)}
  .lab1· While(Lit (Bool True)) (If(Acc (LVar i)) (Throw (Acc (LVar xcpt))) Else
    (Expr (Ass (LVar i) (Acc (LVar j)))). {Q}
⟨proof⟩
```

end