Jive Data and Store Model

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Abstract

This document presents the formalization of an object-oriented data and store model in Isabelle/HOL. This model is being used in the **J**ava **I**nteractive **V**erification **E**nvironment, Jive.

Contents

1 Introduction

JIVE [MPH00, Jiv] is a verification system that is being developed at the University of Kaiserslautern and at the ETH Zürich. It is an interactive special-purpose theorem prover for the verification of object-oriented programs on the basis of a partial-correctness Hoare-style programming logic. JIVE operates on JAVA-KE [PHGR05], a desugared subset of sequential Java which contains all important features of object-oriented languages (subtyping, exceptions, static and dynamic method invocation, etc.). JIVE is written in Java and currently has a size of about 40,000 lines of code.

JIVE is able to operate on completely unannotated programs, allowing the user to dynamically add specifications. It is also possible to preliminarily annotate programs with invariants, pre- and postconditions using the specification language JML [LBR99]. In practice, a mixture of both techniques is employed, in which the user extends and refines the pre-annotated specifications during the verification process. The program to be verified, together with the specifications, is translated to Hoare sequents. Program and pre-annotated specifications are translated during startup, while the dynamically added specifications are translated whenever they are entered by the user. Hoare sequents have the shape $\mathcal{A} \rhd \{ \mathbf{P} \}\ \mathtt{pp}\ \{ \mathbf{Q} \}$ and express that for all states S that fulfill $\mathbf{P}$, if the execution of the program part $\mathtt{pp}$ terminates, the state that is reached when pp has been evaluated in S must fulfill $\mathbf{Q}$. The so-called assumptions $\mathcal{A}$ are used to prove recursive methods.

JIVE's logic contains so-called Hoare rules and axioms. The rules consist of one or more Hoare sequents that represent the assumptions of the rule, and a Hoare sequent which is the conclusion of the rule. Axioms consist of only one Hoare sequent; they do not have assumptions. Therefore, axioms represent the known facts of the Hoare logic.

To prove a program specification, the user directly works on the program source code. Proofs can be performed in backward direction and in forward direction. In backward direction, an initial open proof goal is reduced to new, smaller open subgoals by applying a rule. This process is repeated for the smaller subgoals until eventually each open subgoal can be closed by the application of an axiom. If all open subgoals are proven by axioms, the initial goal is proven as well.

In forward direction, the axioms can be used to establish known facts about the statements of a given program. The rules are then used to produce new facts from these already known facts. This way, facts can be constructed for parts of the program.

A large number of the rules and axioms of the Hoare logic is related to the structure of the program part that is currently being examined. Besides these, the logic also contains rules that manipulate the pre- or postcondition of the examined subgoal without affecting the current program part selection. A prominent member of this kind of rules is the rule of consequence[1]:

$$\frac{\mathbf{PP} \Rightarrow \mathbf{P} \qquad \mathcal{A} \rhd \{ \mathbf{P} \}\ \mathtt{pp}\ \{ \mathbf{Q} \} \qquad \mathbf{Q} \Rightarrow \mathbf{QQ}}{\mathcal{A} \rhd \{ \mathbf{PP} \}\ \mathtt{pp}\ \{ \mathbf{QQ} \}}$$

It plays a special role in the Hoare logic because it additionally requires implications between stronger and weaker conditions to be proven. If a JIVE proof contains an application of the rule of consequence, the implication is attached to the proof tree node that documents this rule application; these attachments are called lemmas. JIVE sends these lemmas to an associated

[1] In JIVE, the rule of consequence is part of a larger rule which serves several purposes at once. Since we want to focus on the rule of consequence, we left out the parts that are irrelevant in this context.

general purpose theorem prover where the user is required to prove them. Currently, JIVE supports ISABELLE/HOL as associated prover. It is required that all lemmas that are attached to any node of a proof tree are proven before the initial goal of the proof tree is accepted as being proven.

In order to prove these logical predicates, ISABELLE/HOL needs a data and store model of JAVA-KE. This model acts as an interface between JIVE and ISABELLE/HOL.

The first paper-and-pencil formalization of the data and store model was given in Arnd Poetzsch-Heffter's habilitation thesis [PH97, Sect. 3.1.2]. The first machine-supported formalization was performed in PVS by Peter Müller, by translating the axioms given in [PH97] to axioms in PVS. The formalization presented in this report extends the PVS formalization. The axioms have been replaced by conservative extensions and proven lemmas, thus there is no longer any possibility to accidentally introduce unsoundness.

Some changes were made to the PVS theories during the conversion. Some were caused due to the differences in the tools ISABELLE/HOL and PVS, but some are more conceptional. Here is a list of the major changes.

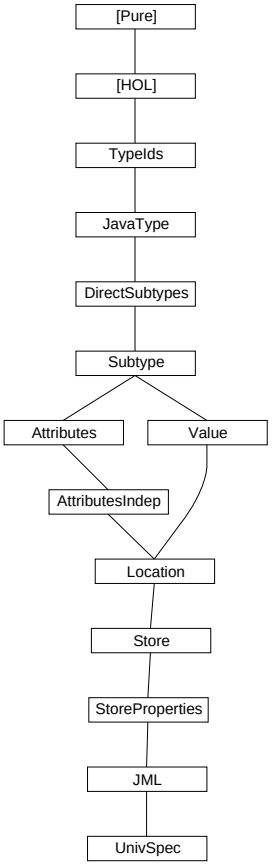
- In PVS, function arguments were sometimes restricted to subtypes. In ISABELLE/HOL, unintended usage of functions is left unspecified.
- In PVS, the program-independent theories were parameterized by the datatypes that were generated for the program to be verified. In ISABELLE/HOL, we just build on the generated theories. This makes the whole setting easier. The drawback is that we have to run the theories for each program we want to verify. But the proof scripts are designed in a way that they will work if the basic program-dependent theories are generated in the proper way. Since we can create an image of a proof session before starting actual verification we do not run into time problems either.
- The subtype relation is based on the direct subtype relation between classes and interfaces. We prove that subtyping forms a partial order. In the PVS version subtyping was expressed by axioms that described the subtype relation for the types appearing in the Java program to be verified.

Besides these changes we also added new concepts to the model. We can now deal with static fields and arrays. This way, the model supports programming languages that are much richer than JAVA-KE to allow for future extensions of JIVE.

Please note that although the typographic conventions in Isabelle suggest that constructors start with a capital letter while types do not, we kept the capitalization as it was before (which means that types start with a capital letter while constructors usually do not) to keep the naming more uniform across the various JIVE-related publications.

The theories presented in this report require the use of ISABELLE 2005. The proofs of lemmas are skipped in the presentation to keep it compact. The full proofs can be found in the original ISABELLE theories.

2 Theory Dependencies



The theories "TypeIds", "DirectSubtypes", "Attributes" and "UnivSpec" are program-dependent and are generated by the Jive tool. The program-dependent theories presented in this report are just examples and act as placeholders. The theories are stored in four different directories:

Isabelle:
- JavaType.thy
- Subtype.thy
- Value.thy
- JML.thy

Isabelle_Store:
- AttributesIndep.thy
- Location.thy
- Store.thy
- StoreProperties.thy

Isa_⟨Prog⟩:
- TypeIds.thy
- DirectSubtypes.thy
- UnivSpec.thy

Isa_⟨Prog⟩_Store:
- Attributes.thy

In this naming convention, the suffix "_Store" denotes those theories that depend on the actual realization of the Store. They have been separated in order to allow for easy exchanging of the Store realization. The midfix "⟨Prog⟩" denotes the name of the program for which the program-dependent theories have been generated. This way, different program-dependent theories can reside side-by-side without conflicts.

These four directories have to be added to the ML path before loading UnivSpec. This can be done in a setup theory with the following command (here applied to a program called `Counter`):

```
ML {*
add_path "<PATH_TO_THEORIES>/Isabelle";
add_path "<PATH_TO_THEORIES>/Isabelle_Store";
add_path "<PATH_TO_THEORIES>/Isa_Counter";
add_path "<PATH_TO_THEORIES>/Isa_Counter_Store";
*}
```

This way, one can select the program-dependent theories for the program that currently is to be proven.

3 The Example Program

The program-dependent theories are generated for the following example program:

```
    interface Counter {

        public int incr();

        public int reset();
    }

class CounterImpl implements Counter {
    protected int value;

    public int incr()
    {
        int dummy;
        res = this.value;
        res = (int) res + 1;
        this.value = res;
    }

    public int reset()
    {
        int dummy;
        this.value=0;
        res = (int) 0;
    }
}

class UndoCounter extends CounterImpl {
    private int save;
```

```
    public int incr()
    {
        int dummy;
        res = this.value;
        this.save = res;
        res = res + 1;
        this.value = res;
    }

    public int un_do()
    {
        int res2;
        res = this.save;
        res2 = this.value;
        this.value = res;
        this.save  = res2;
    }
}
```

4 TypeIds

theory *TypeIds* **imports** *Main* **begin**

This theory contains the program specific names of abstract and concrete classes and interfaces. It has to be generated for each program we want to verify. The following classes are an example taken from the program given in Sect. 3. They are complemented by the classes that are known to exist in each Java program implicitly, namely `Object`, `Exception`, `ClassCastException` and `NullPointerException`. The example program does not contain any abstract classes, but since we cannot formalize datatypes without constructors, we have to insert a dummy class which we call `Dummy`.

The datatype CTypeId must contain a constructor called `Object` because subsequent proofs in the Subtype theory rely on it.

datatype *CTypeId* = *CounterImpl* | *UndoCounter*
| *Object* | *Exception* | *ClassCastException* | *NullPointerException*
— The last line contains the classes that exist in every program by default.
datatype *ITypeId* = *Counter*
datatype *ATypeId* = *Dummy*
— we cannot have an empty type.

Why do we need different datatypes for the different type identifiers? Because we want to be able to distinguish the different identifier kinds. This has a practical reason: If we formalize objects as "ObjectId × TypeId" and if we quantify over all objects, we get a lot of objects that do not exist, namely all objects that bear an interface type identifier or abstract class identifier. This is not very helpful. Therefore, we separate the three identifier kinds from each other.

end

5 Java-Type

theory *JavaType* **imports** *TypeIds* **begin**

This theory formalizes the types that appear in a Java program. Note that the types defined by the classes and interfaces are formalized via their identifiers. This way, this theory is program-independent.

We only want to formalize one-dimensional arrays. Therefore, we describe the types that can be used as element types of arrays. This excludes the `null` type and array types themselves. This way, we get a finite number of types in our type hierarchy, and the subtype relations can be given explicitly (see Sec. 6). If desired, this can be extended in the future by using Javatype as argument type of the *ArrT* type constructor. This will yield infinitely many types.

datatype *Arraytype* = *BoolAT* | *IntgAT* | *ShortAT* | *ByteAT*
| *CClassAT CTypeId* | *AClassAT ATypeId*
| *InterfaceAT ITypeId*

datatype *Javatype* = *BoolT* | *IntgT* | *ShortT* | *ByteT* | *NullT* | *ArrT Arraytype*
| *CClassT CTypeId* | *AClassT ATypeId*
| *InterfaceT ITypeId*

We need a function that widens *Arraytype* to *Javatype*.

constdefs
at2jt :: *Arraytype* ⇒ *Javatype*
at2jt at == *case at of*
BoolAT ⇒ *BoolT*
| *IntgAT* ⇒ *IntgT*
| *ShortAT* ⇒ *ShortT*
| *ByteAT* ⇒ *ByteT*
| *CClassAT CTypeId* ⇒ *CClassT CTypeId*
| *AClassAT ATypeId* ⇒ *AClassT ATypeId*
| *InterfaceAT ITypeId* ⇒ *InterfaceT ITypeId*

We define two predicates that separate the primitive types and the class types.

consts
isprimitive:: *Javatype* ⇒ *bool*
isclass:: *Javatype* ⇒ *bool*

primrec
isprimitive BoolT = *True*
isprimitive IntgT = *True*
isprimitive ShortT = *True*
isprimitive ByteT = *True*
isprimitive NullT = *False*
isprimitive (*ArrT T*) = *False*
isprimitive (*CClassT c*) = *False*
isprimitive (*AClassT c*) = *False*
isprimitive (*InterfaceT i*) = *False*

primrec
isclass BoolT = *False*
isclass IntgT = *False*
isclass ShortT = *False*
isclass ByteT = *False*
isclass NullT = *False*
isclass (*ArrT T*) = *False*
isclass (*CClassT c*) = *True*

isclass (*AClassT c*) = *True*
isclass (*InterfaceT i*) = *False*

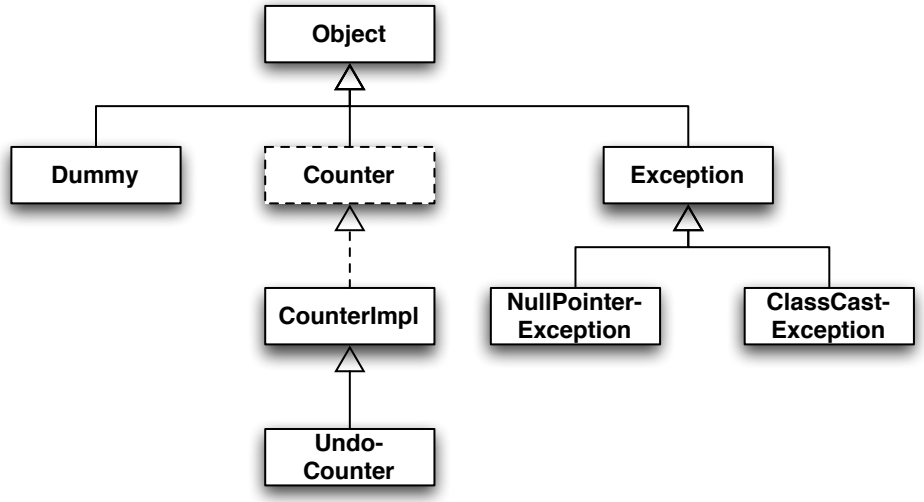
end

6 The Direct Subtype Relation of Java Types

theory *DirectSubtypes* **imports** *JavaType* **begin**

In this theory, we formalize the direct subtype relations of the Java types (as defined in Sec. 4) that appear in the program to be verified. Thus, this theory has to be generated for each program.

We have the following type hierarchy:



We need to describe all direct subtype relations of this type hierarchy. As you can see in the picture, all unnecessary direct subtype relations can be ignored, e.g. the subclass relation between CounterImpl and Object, because it is added transitively by the widening relation of types (see Sec. 7.2).

We have to specify the direct subtype relation between

- each "leaf" class or interface and its subtype `NullT`
- each "root" class or interface and its supertype `Object`
- each two types that are direct subtypes as specified in the code by `extends` or `implements`
- each array type of a primitive type and its subtype `NullT`
- each array type of a primitive type and its supertype `Object`
- each array type of a "leaf" class or interface and its subtype `NullT`
- the array type `Object[]` and its supertype `Object`

- two array types if their element types are in a subtype hierarchy

consts
direct-subtype :: (*Javatype* ∗ *Javatype*) *set*

defs
direct-subtype-def: *direct-subtype* ==
{ (*NullT*, *AClassT Dummy*),
(*NullT*, *CClassT UndoCounter*),
(*NullT*, *CClassT NullPointerException*),
(*NullT*, *CClassT ClassCastException*),

(*AClassT Dummy*, *CClassT Object*),
(*InterfaceT Counter*, *CClassT Object*),
(*CClassT Exception*, *CClassT Object*),

(*CClassT UndoCounter*, *CClassT CounterImpl*),
(*CClassT CounterImpl*, *InterfaceT Counter*),
(*CClassT NullPointerException*, *CClassT Exception*),
(*CClassT ClassCastException*, *CClassT Exception*),

(*NullT*, *ArrT BoolAT*),
(*NullT*, *ArrT IntgAT*),
(*NullT*, *ArrT ShortAT*),
(*NullT*, *ArrT ByteAT*),
(*ArrT BoolAT*, *CClassT Object*),
(*ArrT IntgAT*, *CClassT Object*),
(*ArrT ShortAT*, *CClassT Object*),
(*ArrT ByteAT*, *CClassT Object*),

(*NullT*, *ArrT* (*AClassAT Dummy*)),
(*NullT*, *ArrT* (*CClassAT UndoCounter*)),
(*NullT*, *ArrT* (*CClassAT NullPointerException*)),
(*NullT*, *ArrT* (*CClassAT ClassCastException*)),

(*ArrT* (*CClassAT Object*), *CClassT Object*),

(*ArrT* (*AClassAT Dummy*), *ArrT* (*CClassAT Object*)),
(*ArrT* (*CClassAT CounterImpl*), *ArrT* (*InterfaceAT Counter*)),
(*ArrT* (*InterfaceAT Counter*), *ArrT* (*CClassAT Object*)),
(*ArrT* (*CClassAT Exception*), *ArrT* (*CClassAT Object*)),
(*ArrT* (*CClassAT UndoCounter*), *ArrT* (*CClassAT CounterImpl*)),
(*ArrT* (*CClassAT NullPointerException*), *ArrT* (*CClassAT Exception*)),
(*ArrT* (*CClassAT ClassCastException*), *ArrT* (*CClassAT Exception*))
}

This lemma is used later in the Simplifier.

lemma *direct-subtype*:
(*NullT*, *AClassT Dummy*) ∈ *direct-subtype*
(*NullT*, *CClassT UndoCounter*) ∈ *direct-subtype*
(*NullT*, *CClassT NullPointerException*) ∈ *direct-subtype*
(*NullT*, *CClassT ClassCastException*) ∈ *direct-subtype*

(*AClassT Dummy*, *CClassT Object*) ∈ *direct-subtype*

(*InterfaceT Counter*, *CClassT Object*) ∈ *direct-subtype*
(*CClassT Exception*, *CClassT Object*) ∈ *direct-subtype*

(*CClassT UndoCounter*, *CClassT CounterImpl*) ∈ *direct-subtype*
(*CClassT CounterImpl*, *InterfaceT Counter*) ∈ *direct-subtype*
(*CClassT NullPointerException*, *CClassT Exception*) ∈ *direct-subtype*
(*CClassT ClassCastException*, *CClassT Exception*) ∈ *direct-subtype*

(*NullT*, *ArrT BoolAT*) ∈ *direct-subtype*
(*NullT*, *ArrT IntgAT*) ∈ *direct-subtype*
(*NullT*, *ArrT ShortAT*) ∈ *direct-subtype*
(*NullT*, *ArrT ByteAT*) ∈ *direct-subtype*
(*ArrT BoolAT*, *CClassT Object*) ∈ *direct-subtype*
(*ArrT IntgAT*, *CClassT Object*) ∈ *direct-subtype*
(*ArrT ShortAT*, *CClassT Object*) ∈ *direct-subtype*
(*ArrT ByteAT*, *CClassT Object*) ∈ *direct-subtype*

(*NullT*, *ArrT* (*AClassAT Dummy*)) ∈ *direct-subtype*
(*NullT*, *ArrT* (*CClassAT UndoCounter*)) ∈ *direct-subtype*
(*NullT*, *ArrT* (*CClassAT NullPointerException*)) ∈ *direct-subtype*
(*NullT*, *ArrT* (*CClassAT ClassCastException*)) ∈ *direct-subtype*

(*ArrT* (*CClassAT Object*), *CClassT Object*) ∈ *direct-subtype*

(*ArrT* (*AClassAT Dummy*), *ArrT* (*CClassAT Object*)) ∈ *direct-subtype*
(*ArrT* (*CClassAT CounterImpl*), *ArrT* (*InterfaceAT Counter*)) ∈ *direct-subtype*
(*ArrT* (*InterfaceAT Counter*), *ArrT* (*CClassAT Object*)) ∈ *direct-subtype*
(*ArrT* (*CClassAT Exception*), *ArrT* (*CClassAT Object*)) ∈ *direct-subtype*
(*ArrT* (*CClassAT UndoCounter*), *ArrT* (*CClassAT CounterImpl*)) ∈ *direct-subtype*
(*ArrT* (*CClassAT NullPointerException*), *ArrT* (*CClassAT Exception*)) ∈ *direct-subtype*
(*ArrT* (*CClassAT ClassCastException*), *ArrT* (*CClassAT Exception*)) ∈ *direct-subtype*
by (*simp-all add*: *direct-subtype-def*)

end

7 Widening the Direct Subtype Relation

theory *Subtype* **imports** *DirectSubtypes* **begin**

In this theory, we define the widening subtype relation of types and prove that it is a partial order.

7.1 Auxiliary lemmas

These general lemmas are not especially related to Jive. They capture some useful properties of general relations.

lemma *distinct-rtrancl-into-trancl*:
assumes *neq-x-y*: $x \neq y$
assumes *x-y-rtrancl*: $(x,y) \in r^*$
shows $(x,y) \in r^+$
using *x-y-rtrancl neq-x-y*

proof (*induct*)
assume $x{\neq}x$ **thus** $(x,\ x) \in r^+$ **by** *simp*
next
fix *y z*
assume *x-y-rtrancl*: $(x,\ y) \in r^*$
assume *y-z-r*: $(y,\ z) \in r$
assume $x \neq y \Longrightarrow (x,\ y) \in r^+$
assume $x \neq z$
from *x-y-rtrancl*
show $(x,\ z) \in r^+$
proof (*cases*)
assume $x{=}y$
with *y-z-r* **have** $(x,z) \in r$ **by** *simp*
thus $(x,z) \in\ r^+$**..**
next
fix *w*
assume $(x,\ w) \in r^*$
moreover assume $(w,\ y) \in r$
ultimately have $(x,y) \in r^+$
by (*rule rtrancl-into-trancl1*)
from *this y-z-r*
show $(x,\ z) \in r^+$**..**
qed
qed

lemma *acyclic-imp-antisym-rtrancl*: *acyclic r* $\Longrightarrow$ *antisym* (r^*)
proof (*clarsimp simp only*: *acyclic-def antisym-def*)
fix *x y*
assume *acyclic*: $\forall\, x.\ (x,\ x) \notin r^+$
assume *x-y*: $(x,\ y) \in r^*$
assume *y-x*: $(y,\ x) \in r^*$
show $x{=}y$
proof (*cases* $x{=}y$)
case *True* **thus** *?thesis* **.**
next
case *False*
from *False x-y* **have** $(x,\ y) \in r^+$
by (*rule distinct-rtrancl-into-trancl*)
also
from *False y-x* **have** $(y,\ x) \in r^+$
by (*fastsimp intro*: *distinct-rtrancl-into-trancl*)
finally have $(x,x) \in r^+$**.**
with *acyclic* **show** *?thesis* **by** *simp*
qed
qed

lemma *acyclic-trancl-rtrancl*:
assumes *acyclic*: *acyclic r*
shows $(x,y) \in r^+ = ((x,y) \in r^* \wedge x{\neq}y)$
proof
assume *x-y-trancl*: $(x,y) \in r^+$
show $(x,y) \in r^* \wedge x{\neq}y$
proof
from *x-y-trancl* **show** $(x,y) \in r^*$**..**

next
from *x-y-trancl acyclic* **show** $x \neq y$ **by** (*auto simp add*: *acyclic-def*)
qed
next
assume $(x,y) \in r^* \wedge x \neq y$
thus $(x,y) \in r^+$
by (*auto intro*: *distinct-rtrancl-into-trancl*)
qed

7.2 The Widening (Subtype) Relation of Javatypes

In this section we widen the direct subtype relations specified in Sec. 6. It is done by a calculation of the transitive closure of the direct subtype relation.

This is the concrete syntax that expresses the subtype relations between all types.

syntax
@*direct-subtype* :: *Javatype* ⇒ *Javatype* ⇒ *bool* (- ≺1 - [71,71] 70)
@*widen* :: *Javatype* ⇒ *Javatype* ⇒ *bool* (- ≼ - [71,71] 70)
@*widen-strict* :: *Javatype* ⇒ *Javatype* ⇒ *bool* (- ≺ - [71,71] 70)

translations
$A \prec 1\ B == (A,B) \in$ *direct-subtype*
— direct subtype relation
$A \preccurlyeq B == (A,B) \in$ *direct-subtype**
— reflexive transitive closure of direct subtype relation
$A \prec B == (A,B) \in$ *direct-subtype*$^+$
— transitive closure of direct subtype relation

7.3 The Subtype Relation as Partial Order

We prove the axioms required for partial orders, i.e. reflexivity, transitivity and antisymmetry, for the widened subtype relation. The direct subtype relation has been defined in Sec. 6. The reflexivity lemma is added to the Simplifier and to the Classical reasoner (via the attribute iff), and the transitivity and antisymmetry lemmas are made known as transitivity rules (via the attribute trans). This way, these lemmas will be automatically used in subsequent proofs.

lemma *acyclic-direct-subtype*: *acyclic direct-subtype*
proof (*clarsimp simp add*: *acyclic-def*)
fix *x* **show** $x \prec x \Longrightarrow$ *False*
by (*cases x*) (*fastsimp elim*: *tranclE simp add*: *direct-subtype-def*)+

qed

lemma *antisym-rtrancl-direct-subtype*: *antisym* (*direct-subtype**)
using *acyclic-direct-subtype* **by** (*rule acyclic-imp-antisym-rtrancl*)

lemma *widen-strict-to-widen*: $C \prec D = (C \preccurlyeq D \wedge C \neq D)$
using *acyclic-direct-subtype* **by** (*rule acyclic-trancl-rtrancl*)

The widening relation on Javatype is reflexive.

lemma *widen-refl* [*iff*]: $X \preccurlyeq X$ **..**

The widening relation on Javatype is transitive.

lemma *widen-trans* [*trans*] :
assumes *a-b*: $a \preceq b$
shows $\bigwedge c.\ b \preceq c \Longrightarrow a \preceq c$
by (*insert a-b*, *rule rtrancl-trans*)

The widening relation on Javatype is antisymmetric.

lemma *widen-antisym* [*trans*]:
assumes *a-b*: $a \preceq b$
assumes *b-c*: $b \preceq a$
shows $a = b$
using *a-b b-c antisym-rtrancl-direct-subtype*
by (*unfold antisym-def*) *blast*

7.4 Javatype Ordering Properties

We can show that *Javatype* is in the type class *ord*, which does not require to prove any axioms.

instance *Javatype*:: *ord* **..**

The type class *ord* allows us to overwrite the two comparison operators $<$ and $\leq$. These are the two comparison operators on *Javatype* that we want to use subsequently.

defs (**overloaded**)
le-Javatype-def: $A \leq B \equiv A \preceq B$
less-Javatype-def: $A < B \equiv A \leq B \wedge A \neq (B::Javatype)$

We can also prove that *Javatype* is in the type class *order*. For this we have to prove reflexivity, transitivity, antisymmetry and that $<$ and $\leq$ are defined in such a way that $(x < y) = (x \leq y \wedge x \neq y)$ holds. This proof can easily be achieved by using the lemmas proved above and the definition of *less-Javatype-def*.

instance *Javatype*:: *order*
proof
fix *x y z*:: *Javatype*
{
show $x \leq x$
by (*simp add*: *le-Javatype-def*)
next
assume $x \leq y$ $y \leq z$
then show $x \leq z$
by (*unfold le-Javatype-def*) (*rule rtrancl-trans*)
next
assume $x \leq y$ $y \leq x$
then show $x = y$
apply (*unfold le-Javatype-def*)
apply (*rule widen-antisym*)
apply *assumption* +
done
next
show $(x < y) = (x \leq y \wedge x \neq y)$
by (*simp add*: *less-Javatype-def*)
}
qed

7.5 Enhancing the Simplifier

lemmas *subtype-defs* = *le-Javatype-def less-Javatype-def*
direct-subtype-def

lemmas *subtype-ok-simps* = *subtype-defs*
lemmas *subtype-wrong-elims* = *rtranclE*

During verification we will often have to solve the goal that one type widens to the other. So we equip the simplifier with a special solver-tactic.

lemma *widen-asm*: $(a::Javatype) \leq b \Longrightarrow a \leq b$
by *simp*

lemmas *direct-subtype-widened* = *direct-subtype*[*THEN r-into-rtrancl*]

ML ⟪
local
val widen-asm = *thm widen-asm*;
val widen-lemmas = *thms direct-subtype-widened*;
val ss = (*simpset-of* (*theory Transitive-Closure*));
val widen-tac = *rtac widen-asm*
THEN' simp-tac (*simpset*() *addsimps* [*thm le-Javatype-def*])
THEN' Method.insert-tac widen-lemmas THEN' simp-tac ss;
in
fun widenSolver prems = *widen-tac*
end
⟫

In this solver-tactic, we first try the trivial resolution with *widen-asm* to check if the actual subgaol really is a request to solve a subtyping problem. If so, we unfold the comparison operator, insert the direct subtype relations and call the simplifier.

ML ⟪
change-simpset (*fn ss => ss addSolver* (*mk-solver widenSolver widenSolver*));
⟫

7.6 Properties of the Subtype Relation

The class *Object* has to be the root of the class hierarchy, i.e. it is supertype of each concrete class, abstract class, interface and array type. The proof scripts should run on every correctly generated type hierarchy.

lemma *Object-root*: *CClassT C* ≤ *CClassT Object*
by (*cases C*, *simp-all*)

lemma *Object-root-abs*: *AClassT C* ≤ *CClassT Object*
by (*cases C*, *simp-all*)

lemma *Object-root-int*: *InterfaceT C* ≤ *CClassT Object*
by (*cases C*, *simp-all*)

lemma *Object-root-array*: *ArrT C* ≤ *CClassT Object*
proof (*cases C*)
fix *x*
assume *c*: *C* = *CClassAT x*

```
    show ArrT C ≤ CClassT Object
      using c by (cases x, simp-all)
  next
    fix x
    assume c: C = AClassAT x
    show ArrT C ≤ CClassT Object
      using c by (cases x, simp-all)
  next
    fix x
    assume c: C = InterfaceAT x
    show ArrT C ≤ CClassT Object
      using c by (cases x, simp-all)
  next
    assume c: C = BoolAT
    show ArrT C ≤ CClassT Object
      using c by simp
  next
    assume c: C = IntgAT
    show ArrT C ≤ CClassT Object
      using c by simp
  next
    assume c: C = ShortAT
    show ArrT C ≤ CClassT Object
      using c by simp
  next
    assume c: C = ByteAT
    show ArrT C ≤ CClassT Object
      using c by simp
qed
```

If another type is (non-strict) supertype of Object, then it must be the type Object itself.

```
lemma Object-rootD:
  assumes p: CClassT Object ≤ c
  shows CClassT Object = c
  using p
  apply (cases c)
  apply (fastsimp elim: subtype-wrong-elims simp add: subtype-defs) +
  — In this lemma, we only get contradictory cases except for Object itself.
done
```

The type NullT has to be the leaf of each branch of the class hierarchy, i.e. it is subtype of each type.

```
lemma NullT-leaf [simp]: NullT ≤ CClassT C
  by (cases C, simp-all)

lemma NullT-leaf-abs [simp]: NullT ≤ AClassT C
  by (cases C, simp-all)

lemma NullT-leaf-int [simp]: NullT ≤ InterfaceT C
  by (cases C, simp-all)

lemma NullT-leaf-array: NullT ≤ ArrT C
  proof (cases C)
    fix x
```

```
    assume c: C = CClassAT x
    show NullT ≤ ArrT C
      using c by (cases x, simp-all)
  next
    fix x
    assume c: C = AClassAT x
    show NullT ≤ ArrT C
      using c by (cases x, simp-all)
  next
    fix x
    assume c: C = InterfaceAT x
    show NullT ≤ ArrT C
      using c by (cases x, simp-all)
  next
    assume c: C = BoolAT
    show NullT ≤ ArrT C
      using c by simp
  next
    assume c: C = IntgAT
    show NullT ≤ ArrT C
      using c by simp
  next
    assume c: C = ShortAT
    show NullT ≤ ArrT C
      using c by simp
  next
    assume c: C = ByteAT
    show NullT ≤ ArrT C
      using c by simp
qed

end
```

8 Attributes

theory *Attributes* **imports** *Subtype* **begin**

This theory has to be generated as well for each program under verification. It defines the attributes of the classes and various functions on them.

```
datatype AttId = CounterImpl'value | UndoCounter'save
  | Dummy'dummy | Counter'dummy
```

The last two entries are only added to demonstrate what is to happen with attributes of abstract classes and interfaces.

It would be nice if attribute names were generated in a way that keeps them short, so that the proof state does not get unreadable because of fancy long names. The generation of attribute names that is performed by the Jive tool should only add the definition class if necessary, i.e. if there would be a name clash otherwise. For the example above, the class names are not necessary. One must be careful, though, not to generate names that might clash with names of free variables that are used subsequently.

The domain type of an attribute is the definition class (or interface) of the attribute.

constdefs *dtype*:: *AttId* ⇒ *Javatype*
dtype f ≡ (*case f of*
CounterImpl'value ⇒ *CClassT CounterImpl*
| *UndoCounter'save* ⇒ *CClassT UndoCounter*
| *Dummy'dummy* ⇒ *AClassT Dummy*
| *Counter'dummy* ⇒ *InterfaceT Counter*)

lemma *dtype-simps* [*simp*]:
dtype CounterImpl'value = *CClassT CounterImpl*
dtype UndoCounter'save = *CClassT UndoCounter*
dtype Dummy'dummy = *AClassT Dummy*
dtype Counter'dummy = *InterfaceT Counter*
by (*simp-all add*: *dtype-def dtype-def dtype-def*)

For convenience, we add some functions that directly apply the selectors of the datatype *Javatype*.

constdefs *cDTypeId* :: *AttId* ⇒ *CTypeId*
cDTypeId f ≡ (*case f of*
CounterImpl'value ⇒ *CounterImpl*
| *UndoCounter'save* ⇒ *UndoCounter*
| *Dummy'dummy* ⇒ *arbitrary*
| *Counter'dummy* ⇒ *arbitrary*)

constdefs *aDTypeId*:: *AttId* ⇒ *ATypeId*
aDTypeId f ≡ (*case f of*
CounterImpl'value ⇒ *arbitrary*
| *UndoCounter'save* ⇒ *arbitrary*
| *Dummy'dummy* ⇒ *Dummy*
| *Counter'dummy* ⇒ *arbitrary*)

constdefs *iDTypeId*:: *AttId* ⇒ *ITypeId*
iDTypeId f ≡ (*case f of*
CounterImpl'value ⇒ *arbitrary*
| *UndoCounter'save* ⇒ *arbitrary*
| *Dummy'dummy* ⇒ *arbitrary*
| *Counter'dummy* ⇒ *Counter*)

lemma *DTypeId-simps* [*simp*]:
cDTypeId CounterImpl'value = *CounterImpl*
cDTypeId UndoCounter'save = *UndoCounter*
aDTypeId Dummy'dummy = *Dummy*
iDTypeId Counter'dummy = *Counter*
by (*simp-all add*: *cDTypeId-def aDTypeId-def iDTypeId-def*)

The range type of an attribute is the type of the value stored in that attribute.

constdefs *rtype*:: *AttId* ⇒ *Javatype*
rtype f ≡ (*case f of*
CounterImpl'value ⇒ *IntgT*
| *UndoCounter'save* ⇒ *IntgT*
| *Dummy'dummy* ⇒ *NullT*
| *Counter'dummy* ⇒ *NullT*)

lemma *rtype-simps* [*simp*]:
rtype CounterImpl'value = IntgT
rtype UndoCounter'save = IntgT
rtype Dummy'dummy = NullT
rtype Counter'dummy = NullT
by (*simp-all add*: *rtype-def rtype-def rtype-def*)

With the datatype *CAttId* we describe the possible locations in memory for instance fields. We rule out the impossible combinations of class names and field names. For example, a *CounterImpl* cannot have a *save* field. A store model which provides locations for all possible combinations of the Cartesian product of class name and field name works out fine as well, because we cannot express modification of such "wrong" locations in a Java program. So we can only prove useful properties about reasonable combinations. The only drawback in such a model is that we cannot prove a property like *not-treach-ref-impl-not-reach* in theory StoreProperties. If the store provides locations for every combination of class name and field name, we cannot rule out reachability of certain pointer chains that go through "wrong" locations. That is why we decided to introduce the new type *CAttId*.

While *AttId* describes which fields are declared in which classes and interfaces, *CAttId* describes which objects of which classes may contain which fields at run-time. Thus, *CAttId* makes the inheritance of fields visible in the formalization.

There is only one such datatype because only objects of concrete classes can be created at run-time, thus only instance fields of concrete classes can occupy memory.

datatype *CAttId = CounterImpl'CounterImpl'value | UndoCounter'CounterImpl'value*
| UndoCounter'UndoCounter'save
| CounterImpl'Counter'dummy | UndoCounter'Counter'dummy

Function *catt* builds a *CAttId* from a class name and a field name. In case of the illegal combinations we just return *arbitrary*. We can also filter out static fields in *catt*.

constdefs *catt*:: *CTypeId ⇒ AttId ⇒ CAttId*
catt C f ≡
(case C of
CounterImpl ⇒ (case f of
CounterImpl'value ⇒ CounterImpl'CounterImpl'value
| UndoCounter'save ⇒ arbitrary
| Dummy'dummy ⇒ arbitrary
| Counter'dummy ⇒ CounterImpl'Counter'dummy)
| UndoCounter ⇒ (case f of
CounterImpl'value ⇒ UndoCounter'CounterImpl'value
| UndoCounter'save ⇒ UndoCounter'UndoCounter'save
| Dummy'dummy ⇒ arbitrary
| Counter'dummy ⇒ UndoCounter'Counter'dummy)
| Object ⇒ arbitrary
| Exception ⇒ arbitrary
| ClassCastException ⇒ arbitrary
| NullPointerException ⇒ arbitrary
)

lemma *catt-simps* [*simp*]:
catt CounterImpl CounterImpl'value = CounterImpl'CounterImpl'value
catt UndoCounter CounterImpl'value = UndoCounter'CounterImpl'value

catt UndoCounter UndoCounter'save = UndoCounter'UndoCounter'save
catt CounterImpl Counter'dummy = CounterImpl'Counter'dummy
catt UndoCounter Counter'dummy = UndoCounter'Counter'dummy
by (*simp-all add*: *catt-def*)

Selection of the class name of the type of the object in which the field lives. The field can only be located in a concrete class.

constdefs *cls*:: *CAttId* ⇒ *CTypeId*
cls cf ≡ (*case cf of*
CounterImpl'CounterImpl'value ⇒ *CounterImpl*
| *UndoCounter'CounterImpl'value* ⇒ *UndoCounter*
| *UndoCounter'UndoCounter'save* ⇒ *UndoCounter*
| *CounterImpl'Counter'dummy* ⇒ *CounterImpl*
| *UndoCounter'Counter'dummy* ⇒ *UndoCounter*
)

lemma *cls-simps* [*simp*]:
cls CounterImpl'CounterImpl'value = CounterImpl
cls UndoCounter'CounterImpl'value = UndoCounter
cls UndoCounter'UndoCounter'save = UndoCounter
cls CounterImpl'Counter'dummy = CounterImpl
cls UndoCounter'Counter'dummy = UndoCounter
by (*simp-all add*: *cls-def*)

Selection of the field name.

constdefs *att*:: *CAttId* ⇒ *AttId*
att cf ≡ (*case cf of*
CounterImpl'CounterImpl'value ⇒ *CounterImpl'value*
| *UndoCounter'CounterImpl'value* ⇒ *CounterImpl'value*
| *UndoCounter'UndoCounter'save* ⇒ *UndoCounter'save*
| *CounterImpl'Counter'dummy* ⇒ *Counter'dummy*
| *UndoCounter'Counter'dummy* ⇒ *Counter'dummy*
)

lemma *att-simps* [*simp*]:
att CounterImpl'CounterImpl'value = CounterImpl'value
att UndoCounter'CounterImpl'value = CounterImpl'value
att UndoCounter'UndoCounter'save = UndoCounter'save
att CounterImpl'Counter'dummy = Counter'dummy
att UndoCounter'Counter'dummy = Counter'dummy
by (*simp-all add*: *att-def*)

end

9 Program-Independent Lemmas on Attributes

theory *AttributesIndep* **imports** *Attributes* **begin**

The following lemmas validate the functions defined in the Attributes theory. They also aid in subsequent proving tasks. Since they are program-independent, it is of no use to add them to the generation process of Attributes.thy. Therefore, they have been extracted to this theory.

lemma *cls-catt* [*simp*]:

CClassT c ≤ *dtype f* ⟹ *cls* (*catt c f*) = *c*
apply (*case-tac c*)
apply (*case-tac* [!] *f*)
apply *simp-all*
— solves all goals where *CClassT c* ≤ *dtype f*
apply (*fastsimp elim*: *subtype-wrong-elims simp add*: *subtype-defs*)+
— solves all the rest where ¬ *CClassT c* ≤ *dtype f* can be derived
done

lemma *att-catt* [*simp*]:
CClassT c ≤ *dtype f* ⟹ *att* (*catt c f*) = *f*
apply (*case-tac c*)
apply (*case-tac* [!] *f*)
apply *simp-all*
— solves all goals where *CClassT c* ≤ *dtype f*
apply (*fastsimp elim*: *subtype-wrong-elims simp add*: *subtype-defs*)+
— solves all the rest where ¬ *CClassT c* ≤ *dtype f* can be derived
done

The following lemmas are just a demonstration of simplification.

lemma *rtype-att-catt*:
CClassT c ≤ *dtype f* ⟹ *rtype* (*att* (*catt c f*)) = *rtype f*
by *simp*

lemma *widen-cls-dtype-att* [*simp*,*intro*]:
(*CClassT* (*cls cf*) ≤ *dtype* (*att cf*))
by (*cases cf*, *simp-all*)

end

10 Value

theory *Value* **imports** *Subtype* **begin**

This theory contains our model of the values in the store. The store is untyped, therefore all types that exist in Java are wrapped into one type *Value*.

In a first approach, the primitive Java types supported in this formalization are mapped to similar Isabelle types. Later, we will have proper formalizations of the Java types in Isabelle, which will then be used here.

types *JavaInt* = *int*
types *JavaShort* = *int*
types *JavaByte* = *int*
types *JavaBoolean* = *bool*

The objects of each class are identified by a unique ID. We use elements of type *nat* here, but in general it is sufficient to use an infinite type with a successor function and a comparison predicate.

types *ObjectId* = *nat*

The definition of the datatype *Value*. Values can be of the Java types boolean, int, short and byte. Additionally, they can be an object reference, an array reference or the value null.

datatype *Value* = *boolV JavaBoolean*
| *intgV JavaInt*
| *shortV JavaShort*
| *byteV JavaByte*
| *objV CTypeId ObjectId* — typed object reference
| *arrV Arraytype ObjectId* — typed array reference
| *nullV*

Arrays are modeled as references just like objects. So they can be viewed as special kinds of objects, like in Java.

10.1 Discriminator Functions

To test values, we define the following discriminator functions.

consts *isBoolV* :: *Value* ⇒ *bool*
isIntgV :: *Value* ⇒ *bool*
isShortV :: *Value* ⇒ *bool*
isByteV :: *Value* ⇒ *bool*
isRefV :: *Value* ⇒ *bool*
isObjV :: *Value* ⇒ *bool*
isArrV :: *Value* ⇒ *bool*
isNullV :: *Value* ⇒ *bool*

defs *isBoolV-def*:
isBoolV v ≡ (*case v of*
boolV b ⇒ *True*
| *intgV i* ⇒ *False*
| *shortV s* ⇒ *False*
| *byteV by* ⇒ *False*
| *objV C a* ⇒ *False*
| *arrV T a* ⇒ *False*
| *nullV* ⇒ *False*)

lemma *isBoolV-simps* [*simp*]:
isBoolV (*boolV b*) = *True*
isBoolV (*intgV i*) = *False*
isBoolV (*shortV s*) = *False*
isBoolV (*byteV by*) = *False*
isBoolV (*objV C a*) = *False*
isBoolV (*arrV T a*) = *False*
isBoolV (*nullV*) = *False*
by (*simp-all add*: *isBoolV-def*)

defs *isIntgV-def*:
isIntgV v ≡ (*case v of*
boolV b ⇒ *False*
| *intgV i* ⇒ *True*
| *shortV s* ⇒ *False*
| *byteV by* ⇒ *False*
| *objV C a* ⇒ *False*
| *arrV T a* ⇒ *False*
| *nullV* ⇒ *False*)

lemma *isIntgV-simps* [*simp*]:
isIntgV (*boolV b*) = *False*
isIntgV (*intgV i*) = *True*
isIntgV (*shortV s*) = *False*
isIntgV (*byteV by*) = *False*
isIntgV (*objV C a*) = *False*
isIntgV (*arrV T a*) = *False*
isIntgV (*nullV*) = *False*
by (*simp-all add*: *isIntgV-def*)

defs *isShortV-def*:
isShortV v ≡ (*case v of*
boolV b ⇒ *False*
| *intgV i* ⇒ *False*
| *shortV s* ⇒ *True*
| *byteV by* ⇒ *False*
| *objV C a* ⇒ *False*
| *arrV T a* ⇒ *False*
| *nullV* ⇒ *False*)

lemma *isShortV-simps* [*simp*]:
isShortV (*boolV b*) = *False*
isShortV (*intgV i*) = *False*
isShortV (*shortV s*) = *True*
isShortV (*byteV by*) = *False*
isShortV (*objV C a*) = *False*
isShortV (*arrV T a*) = *False*
isShortV (*nullV*) = *False*
by (*simp-all add*: *isShortV-def*)

defs *isByteV-def*:
isByteV v ≡ (*case v of*
boolV b ⇒ *False*
| *intgV i* ⇒ *False*
| *shortV s* ⇒ *False*
| *byteV by* ⇒ *True*
| *objV C a* ⇒ *False*
| *arrV T a* ⇒ *False*
| *nullV* ⇒ *False*)

lemma *isByteV-simps* [*simp*]:
isByteV (*boolV b*) = *False*
isByteV (*intgV i*) = *False*
isByteV (*shortV s*) = *False*
isByteV (*byteV by*) = *True*
isByteV (*objV C a*) = *False*
isByteV (*arrV T a*) = *False*
isByteV (*nullV*) = *False*
by (*simp-all add*: *isByteV-def*)

defs *isRefV-def*:

isRefV v ≡ (*case v of*
boolV b ⇒ *False*
| *intgV i* ⇒ *False*
| *shortV s* ⇒ *False*
| *byteV by* ⇒ *False*
| *objV C a* ⇒ *True*
| *arrV T a* ⇒ *True*
| *nullV* ⇒ *True*)

lemma *isRefV-simps* [*simp*]:
isRefV (*boolV b*) = *False*
isRefV (*intgV i*) = *False*
isRefV (*shortV s*) = *False*
isRefV (*byteV by*) = *False*
isRefV (*objV C a*) = *True*
isRefV (*arrV T a*) = *True*
isRefV (*nullV*) = *True*
by (*simp-all add*: *isRefV-def*)

defs *isObjV-def*:
isObjV v ≡ (*case v of*
boolV b ⇒ *False*
| *intgV i* ⇒ *False*
| *shortV s* ⇒ *False*
| *byteV by* ⇒ *False*
| *objV C a* ⇒ *True*
| *arrV T a* ⇒ *False*
| *nullV* ⇒ *False*)

lemma *isObjV-simps* [*simp*]:
isObjV (*boolV b*) = *False*
isObjV (*intgV i*) = *False*
isObjV (*shortV s*) = *False*
isObjV (*byteV by*) = *False*
isObjV (*objV c a*) = *True*
isObjV (*arrV T a*) = *False*
isObjV nullV = *False*
by (*simp-all add*: *isObjV-def*)

defs *isArrV-def*:
isArrV v ≡ (*case v of*
boolV b ⇒ *False*
| *intgV i* ⇒ *False*
| *shortV s* ⇒ *False*
| *byteV by* ⇒ *False*
| *objV C a* ⇒ *False*
| *arrV T a* ⇒ *True*
| *nullV* ⇒ *False*)

lemma *isArrV-simps* [*simp*]:
isArrV (*boolV b*) = *False*
isArrV (*intgV i*) = *False*

isArrV (*shortV s*) = *False*
isArrV (*byteV by*) = *False*
isArrV (*objV c a*) = *False*
isArrV (*arrV T a*) = *True*
isArrV nullV = *False*
by (*simp-all add*: *isArrV-def*)

defs *isNullV-def*:
isNullV v ≡ (*case v of*
boolV b ⇒ *False*
| *intgV i* ⇒ *False*
| *shortV s* ⇒ *False*
| *byteV by* ⇒ *False*
| *objV C a* ⇒ *False*
| *arrV T a* ⇒ *False*
| *nullV* ⇒ *True*)

lemma *isNullV-simps* [*simp*]:
isNullV (*boolV b*) = *False*
isNullV (*intgV i*) = *False*
isNullV (*shortV s*) = *False*
isNullV (*byteV by*) = *False*
isNullV (*objV c a*) = *False*
isNullV (*arrV T a*) = *False*
isNullV nullV = *True*
by (*simp-all add*: *isNullV-def*)

10.2 Selector Functions

consts
aI :: *Value* ⇒ *JavaInt*
aB :: *Value* ⇒ *JavaBoolean*
aSh :: *Value* ⇒ *JavaShort*
aBy :: *Value* ⇒ *JavaByte*
tid :: *Value* ⇒ *CTypeId*
oid :: *Value* ⇒ *ObjectId*
jt :: *Value* ⇒ *Javatype*
aid :: *Value* ⇒ *ObjectId*

defs *aI-def*:
aI v ≡ *case v of*
boolV b ⇒ *arbitrary*
| *intgV i* ⇒ *i*
| *shortV sh* ⇒ *arbitrary*
| *byteV by* ⇒ *arbitrary*
| *objV C a* ⇒ *arbitrary*
| *arrV T a* ⇒ *arbitrary*
| *nullV* ⇒ *arbitrary*
lemma *aI-simps* [*simp*]:
aI (*intgV i*) = *i*
by (*simp add*: *aI-def*)

defs *aB-def*:
aB v ≡ *case v of*
boolV b ⇒ *b*
| *intgV i* ⇒ *arbitrary*
| *shortV sh* ⇒ *arbitrary*
| *byteV by* ⇒ *arbitrary*
| *objV C a* ⇒ *arbitrary*
| *arrV T a* ⇒ *arbitrary*
| *nullV* ⇒ *arbitrary*
lemma *aB-simps* [*simp*]:
aB (*boolV b*) = *b*
by (*simp add*: *aB-def*)

defs *aSh-def*:
aSh v ≡ *case v of*
boolV b ⇒ *arbitrary*
| *intgV i* ⇒ *arbitrary*
| *shortV sh* ⇒ *sh*
| *byteV by* ⇒ *arbitrary*
| *objV C a* ⇒ *arbitrary*
| *arrV T a* ⇒ *arbitrary*
| *nullV* ⇒ *arbitrary*
lemma *aSh-simps* [*simp*]:
aSh (*shortV sh*) = *sh*
by (*simp add*: *aSh-def*)

defs *aBy-def*:
aBy v ≡ *case v of*
boolV b ⇒ *arbitrary*
| *intgV i* ⇒ *arbitrary*
| *shortV s* ⇒ *arbitrary*
| *byteV by* ⇒ *by*
| *objV C a* ⇒ *arbitrary*
| *arrV T a* ⇒ *arbitrary*
| *nullV* ⇒ *arbitrary*
lemma *aBy-simps* [*simp*]:
aBy (*byteV by*) = *by*
by (*simp add*: *aBy-def*)

defs *tid-def*:
tid v ≡ *case v of*
boolV b ⇒ *arbitrary*
| *intgV i* ⇒ *arbitrary*
| *shortV s* ⇒ *arbitrary*
| *byteV by* ⇒ *arbitrary*
| *objV C a* ⇒ *C*
| *arrV T a* ⇒ *arbitrary*
| *nullV* ⇒ *arbitrary*

lemma *tid-simps* [*simp*]:
tid (*objV C a*) = *C*

by (*simp add*: *tid-def*)

defs *oid-def*:
oid v ≡ *case v of*
boolV b ⇒ *arbitrary*
| *intgV i* ⇒ *arbitrary*
| *shortV s* ⇒ *arbitrary*
| *byteV by* ⇒ *arbitrary*
| *objV C a* ⇒ *a*
| *arrV T a* ⇒ *arbitrary*
| *nullV* ⇒ *arbitrary*

lemma *oid-simps* [*simp*]:
oid (*objV C a*) = *a*
by (*simp add*: *oid-def*)

defs *jt-def*:
jt v ≡ *case v of*
boolV b ⇒ *arbitrary*
| *intgV i* ⇒ *arbitrary*
| *shortV s* ⇒ *arbitrary*
| *byteV by* ⇒ *arbitrary*
| *objV C a* ⇒ *arbitrary*
| *arrV T a* ⇒ *at2jt T*
| *nullV* ⇒ *arbitrary*

lemma *jt-simps* [*simp*]:
jt (*arrV T a*) = *at2jt T*
by (*simp add*: *jt-def*)

defs *aid-def*:
aid v ≡ *case v of*
boolV b ⇒ *arbitrary*
| *intgV i* ⇒ *arbitrary*
| *shortV s* ⇒ *arbitrary*
| *byteV by* ⇒ *arbitrary*
| *objV C a* ⇒ *arbitrary*
| *arrV T a* ⇒ *a*
| *nullV* ⇒ *arbitrary*

lemma *aid-simps* [*simp*]:
aid (*arrV T a*) = *a*
by (*simp add*: *aid-def*)

10.3 Determining the Type of a Value

To determine the type of a value, we define the function *typeof*. This function is often written as τ in theoretical texts, therefore we add the appropriate syntax support.

constdefs *typeof* :: *Value* ⇒ *Javatype*

typeof v ≡ (*case v of*
boolV b ⇒ *BoolT*
| *intgV i* ⇒ *IntgT*
| *shortV sh* ⇒ *ShortT*
| *byteV by* ⇒ *ByteT*
| *objV C a* ⇒ *CClassT C*
| *arrV T a* ⇒ *ArrT T*
| *nullV* ⇒ *NullT*)

syntax
-tau :: *Value* ⇒ *Javatype* (*τ* -)

translations
τ v == *typeof v*

lemma *typeof-simps* [*simp*]:
(*τ* (*boolV b*)) = *BoolT*
(*τ* (*intgV i*)) = *IntgT*
(*τ* (*shortV sh*)) = *ShortT*
(*τ* (*byteV by*)) = *ByteT*
(*τ* (*objV c a*)) = *CClassT c*
(*τ* (*arrV t a*)) = *ArrT t*
(*τ* (*nullV*)) = *NullT*
by (*simp-all add*: *typeof-def*)

10.4 Default Initialization Values for Types

The function *init* yields the default initialization values for each type. For boolean, the default value is False, for the integral types, it is 0, and for the reference types, it is nullV.

constdefs *init* :: *Javatype* ⇒ *Value*
init T ≡ (*case T of*
BoolT ⇒ *boolV False*
| *IntgT* ⇒ *intgV 0*
| *ShortT* ⇒ *shortV 0*
| *ByteT* ⇒ *byteV 0*
| *NullT* ⇒ *nullV*
| *ArrT T* ⇒ *nullV*
| *CClassT C* ⇒ *nullV*
| *AClassT C* ⇒ *nullV*
| *InterfaceT I* ⇒ *nullV*)

lemma *init-simps* [*simp*]:
init BoolT = *boolV False*
init IntgT = *intgV 0*
init ShortT = *shortV 0*
init ByteT = *byteV 0*
init NullT = *nullV*
init (*ArrT T*) = *nullV*
init (*CClassT c*) = *nullV*
init (*AClassT a*) = *nullV*
init (*InterfaceT i*) = *nullV*
by (*simp-all add*: *init-def*)

lemma *typeof-init-widen* [*simp*,*intro*]: *typeof* (*init* T) $\leq$ T
proof (*cases* T)
  assume *c*: T = *BoolT*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** *simp*
next
  assume *c*: T = *IntgT*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** *simp*
next
  assume *c*: T = *ShortT*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** *simp*
next
  assume *c*: T = *ByteT*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** *simp*
next
  assume *c*: T = *NullT*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** *simp*
next
  fix *x*
  assume *c*: T = *CClassT* *x*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** (*cases* *x*, *simp-all*)
next
  fix *x*
  assume *c*: T = *AClassT* *x*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** (*cases* *x*, *simp-all*)
next
  fix *x*
  assume *c*: T = *InterfaceT* *x*
  show (τ (*init* T)) $\leq$ T
    using *c* **by** (*cases* *x*, *simp-all*)
next
  fix *x*
  assume *c*: T = *ArrT* *x*
  show (τ (*init* T)) $\leq$ T
    using *c*
  proof (*cases* *x*)
    fix *y*
    assume *c2*: *x* = *CClassAT* *y*
    show (τ (*init* T)) $\leq$ T
      using *c c2* **by** (*cases* *y*, *simp-all*)
  next
    fix *y*
    assume *c2*: *x* = *AClassAT* *y*
    show (τ (*init* T)) $\leq$ T
      using *c c2* **by** (*cases* *y*, *simp-all*)
  next
    fix *y*
    assume *c2*: *x* = *InterfaceAT* *y*

```
    show (τ (init T)) ≤ T
      using c c2 by (cases y, simp-all)
  next
    assume c2: x = BoolAT
    show (τ (init T)) ≤ T
      using c c2 by simp
  next
    assume c2: x = IntgAT
    show (τ (init T)) ≤ T
      using c c2 by simp
  next
    assume c2: x = ShortAT
    show (τ (init T)) ≤ T
      using c c2 by simp
  next
    assume c2: x = ByteAT
    show (τ (init T)) ≤ T
      using c c2 by simp
  qed
qed

end
```

11 Location

theory *Location* **imports** *AttributesIndep Value* **begin**

A storage location can be a field of an object, a static field, the length of an array, or the contents of an array.

```
datatype Location = objLoc    CAttId ObjectId     — field in object
                  | staticLoc AttId               — static field in concrete class
                  | arrLenLoc Arraytype ObjectId  — length of an array
                  | arrLoc    Arraytype ObjectId nat — contents of an array
```

We only directly support one-dimensional arrays. Multidimensional arrays can be simulated by arrays of references to arrays.

The function *ltype* yields the content type of a location.

```
constdefs ltype:: Location ⇒ Javatype
ltype l ≡ (case l of
             objLoc cf a  ⇒ rtype (att cf)
           | staticLoc f    ⇒ rtype f
           | arrLenLoc T a  ⇒ IntgT
           | arrLoc T a i ⇒ at2jt T)

lemma ltype-simps [simp]:
ltype (objLoc cf a)  = rtype (att cf)
ltype (staticLoc f)    = rtype f
ltype (arrLenLoc T a)  = IntgT
ltype (arrLoc T a i) = at2jt T
  by (simp-all add: ltype-def)
```

Discriminator functions to test whether a location denotes an array length or whether it denotes a static object. Currently, the discriminator functions for object and array locations are not specified. They can be added if they are needed.

constdefs *isArrLenLoc*:: *Location* ⇒ *bool*
isArrLenLoc l ≡ (*case l of*
objLoc cf a ⇒ *False*
| *staticLoc f* ⇒ *False*
| *arrLenLoc T a* ⇒ *True*
| *arrLoc T a i* ⇒ *False*)

lemma *isArrLenLoc-simps* [*simp*]:
isArrLenLoc (*objLoc cf a*) = *False*
isArrLenLoc (*staticLoc f*) = *False*
isArrLenLoc (*arrLenLoc T a*) = *True*
isArrLenLoc (*arrLoc T a i*) = *False*
by (*simp-all add*: *isArrLenLoc-def*)

constdefs *isStaticLoc*:: *Location* ⇒ *bool*
isStaticLoc l ≡ (*case l of*
objLoc cff a ⇒ *False*
| *staticLoc f* ⇒ *True*
| *arrLenLoc T a* ⇒ *False*
| *arrLoc T a i* ⇒ *False*)
lemma *isStaticLoc-simps* [*simp*]:
isStaticLoc (*objLoc cf a*) = *False*
isStaticLoc (*staticLoc f*) = *True*
isStaticLoc (*arrLenLoc T a*) = *False*
isStaticLoc (*arrLoc T a i*) = *False*
by (*simp-all add*: *isStaticLoc-def*)

The function *ref* yields the object or array containing the location that is passed as argument (see the function *obj* in [PH97, p. 43 f.]). Note that for static locations the result is *nullV* since static locations are not associated to any object.

constdefs *ref*:: *Location* ⇒ *Value*
ref l ≡ (*case l of*
objLoc cf a ⇒ *objV* (*cls cf*) *a*
| *staticLoc f* ⇒ *nullV*
| *arrLenLoc T a* ⇒ *arrV T a*
| *arrLoc T a i* ⇒ *arrV T a*)

lemma *ref-simps* [*simp*]:
ref (*objLoc cf a*) = *objV* (*cls cf*) *a*
ref (*staticLoc f*) = *nullV*
ref (*arrLenLoc T a*) = *arrV T a*
ref (*arrLoc T a i*) = *arrV T a*
by (*simp-all add*: *ref-def*)

The function *loc* denotes the subscription of an object reference with an attribute.

consts *loc*:: *Value* ⇒ *AttId* ⇒ *Location* (-..- [*80*,*80*] *80*)
primrec
loc (*objV c a*) *f* = *objLoc* (*catt c f*) *a*

Note that we only define subscription properly for object references. For all other values we do

not provide any defining equation, so they will internally be mapped to *arbitrary*.

The length of an array can be selected with the function *arr-len*.

consts *arr-len*:: *Value* ⇒ *Location*
primrec
arr-len (*arrV T a*) = *arrLenLoc T a*

Arrays can be indexed by the function *arr-loc*.

consts *arr-loc*:: *Value* ⇒ *nat* ⇒ *Location* (-.[-] [*80*,*80*] *80*)
primrec
arr-loc (*arrV T a*) *i* = *arrLoc T a i*

The functions *loc*, *arr-len* and *arr-loc* define the interface between the basic store model (based on locations) and the programming language Java. Instance field access `obj.x` is modelled as *obj..x* or *loc obj x* (without the syntactic sugar), array length `a.length` with *arr-len a*, array indexing `a[i]` with *a*.[*i*] or *arr-loc a i*. The accessing of a static field `C.f` can be expressed by the location itself *staticLoc C'f*. Of course one can build more infrastructure to make access to instance fields and static fields more uniform. We could for example define a function *static* which indicates whether a field is static or not and based on that create an *objLoc* location or a *staticLoc* location. But this will only complicate the actual proofs and we can already easily perform the distinction whether a field is static or not in the Jive-frontend and therefore keep the verification simpler.

lemma *ref-loc* [*simp*]: ⟦*isObjV r*; *typeof r* ≤ *dtype f*⟧ ⟹ *ref* (*r..f*) = *r*
apply (*case-tac r*)
apply (*tactic* ⟪ *ALLGOALS* (*case-tac f*) ⟫)
apply (*simp-all*)
done

lemma *obj-arr-loc* [*simp*]: *isArrV r* ⟹ *ref* (*r*.[*i*]) = *r*
by (*cases r*) *simp-all*

lemma *obj-arr-len* [*simp*]: *isArrV r* ⟹ *ref* (*arr-len r*) = *r*
by (*cases r*) *simp-all*

end

12 Store

theory *Store* **imports** *Location* **begin**

12.1 New

The store provides a uniform interface to allocate new objects and new arrays. The constructors of this datatype distinguish both cases.

datatype *New* = *new-instance CTypeId* — New object, can only be of a concrete class type
| *new-array Arraytype nat* — New array with given size

The discriminator *isNewArr* can be used to distinguish both kinds of newly created elements.

constdefs *isNewArr* :: *New* ⇒ *bool*

```
isNewArr t ≡ (case t of
                new-instance C ⇒ False
              | new-array T l ⇒ True)

lemma isNewArr-simps [simp]:
isNewArr (new-instance C) = False
isNewArr (new-array T l)  = True
  by (simp-all add: isNewArr-def)
```

The function *typeofNew* yields the type of the newly created element.

```
constdefs typeofNew :: New ⇒ Javatype
typeofNew n ≡ (case n of
                 new-instance C ⇒ CClassT C
               | new-array T l  ⇒ ArrT T)

lemma typeofNew-simps:
typeofNew (new-instance C) = CClassT C
typeofNew (new-array T l)  = ArrT T
  by (simp-all add: typeofNew-def)
```

12.2 The Definition of the Store

In our store model, all objects[2] of all classes exist at all times, but only those objects that have already been allocated are alive. Objects cannot be deallocated, thus an object that once gained the aliveness status cannot lose it later on.

To model the store, we need two functions that give us fresh object Id's for the allocation of new objects (function *newOID*) and arrays (function *newAID*) as well as a function that maps locations to their contents (function *vals*).

```
record StoreImpl = newOID :: CTypeId ⇒ ObjectId
                   newAID :: Arraytype ⇒ ObjectId
                   vals   :: Location ⇒ Value
```

The function *aliveImpl* determines for a given value whether it is alive in a given store.

```
constdefs aliveImpl::Value ⇒ StoreImpl ⇒ bool
aliveImpl x s ≡ (case x of
                   boolV b  ⇒ True
                 | intgV i  ⇒ True
                 | shortV s ⇒ True
                 | byteV by ⇒ True
                 | objV C a ⇒ (a < newOID s C)
                 | arrV T a ⇒ (a < newAID s T)
                 | nullV    ⇒ True)
```

The store itself is defined as new type. The store ensures and maintains the following properties: All stored values are alive; for all locations whose values are not alive, the store yields the location type's init value; and all stored values are of the correct type (i.e. of the type of the location they are stored in).

```
typedef Store = {s. (∀ l. aliveImpl (vals s l) s) ∧
                    (∀ l. ¬ aliveImpl (ref l) s ⟶ vals s l = init (ltype l)) ∧
```

[2] In the following, the term "objects" includes arrays. This keeps the explanations compact.

```
                (∀ l. typeof (vals s l) ≤ ltype l)}
  by (rule exI [where ?x=(| newOID = (λC. 0),
                            newAID = (λT. 0),
                            vals = (λl. init (ltype l)) |)])
(auto simp add: aliveImpl-def init-def NullT-leaf-array split: Javatype.splits)
```

One might also model the Store as axiomatic type class and prove that the type StoreImpl belongs to this type class. This way, a clearer separation between the axiomatic description of the store and its properties on the one hand and the realization that has been chosen in this formalization on the other hand could be achieved. Additionally, it would be easier to make use of different store implementations that might have different additional features. This separation remains to be performed as future work.

12.3 The Store Interface

The Store interface consists of five functions: *access* to read the value that is stored at a location; *alive* to test whether a value is alive in the store; *alloc* to allocate a new element in the store; *new* to read the value of a newly allocated element; *update* to change the value that is stored at a location.

```
consts access:: Store ⇒ Location ⇒ Value  (-@@- [71,71] 70)
       alive:: Value ⇒ Store ⇒ bool
       alloc:: Store ⇒ New ⇒ Store
       new:: Store ⇒ New ⇒ Value
       update:: Store ⇒ Location ⇒ Value ⇒ Store

nonterminals
  smodifybinds smodifybind
syntax
  -smodifybind :: ['a, 'a]      ⇒ smodifybind ((2- :=/ -))
          :: smodifybind ⇒ smodifybinds     (-)
          :: CTypeId ⇒ smodifybind          (-)
  -smodifybinds:: [smodifybind, smodifybinds] => smodifybinds (-,/ -)
  -sModify  :: ['a, smodifybinds] ⇒ 'a       (-/⟨(-)⟩ [900,0] 900)
translations
  -sModify s (-smodifybinds b bs)  == -sModify (-sModify s b) bs
  s⟨x:=y⟩                           == update s x y
  s⟨c⟩                             == alloc s c
```

With this syntactic setup we can write chains of (array) updates and allocations like in the following term $s\langle$*new-instance Node*, $x :=$ *y*, $z :=$ *intgV 3*, *new-array IntgAT 3*, $a.[i] :=$ *intgV 4*, $k :=$ *boolV True*$\rangle$.

In the following, the definitions of the five store interface functions and some lemmas about them are given.

```
defs alive-def:
alive x s ≡ aliveImpl x (Rep-Store s)

lemma alive-trivial-simps [simp,intro]:
alive (boolV b) s
alive (intgV i) s
alive (shortV sh) s
alive (byteV by) s
```

```
alive nullV  s
  by (simp-all add: alive-def aliveImpl-def)

defs access-def:
access s l ≡ vals (Rep-Store s) l

defs update-def:
update s l v ≡ if alive (ref l) s ∧ alive v s ∧ typeof v ≤ ltype l
               then Abs-Store ((Rep-Store s)(|vals:=(vals (Rep-Store s))(l:=v)|))
               else s

defs alloc-def:
alloc s t ≡
  (case t of
     new-instance C
      ⇒ Abs-Store
          ((Rep-Store s)(|newOID := λ D. if C=D
                           then Suc (newOID (Rep-Store s) C)
                           else newOID (Rep-Store s) D|))
   | new-array T l
      ⇒ Abs-Store
          ((Rep-Store s)(|newAID := λ S. if T=S
                           then Suc (newAID (Rep-Store s) T)
                           else newAID (Rep-Store s) S,
                         vals :=  (vals (Rep-Store s))
                                  (arrLenLoc T (newAID (Rep-Store s) T)
                                    := intgV (int l))|)))

defs new-def:
new s t ≡ (case t of
             new-instance C ⇒ objV C (newOID (Rep-Store s) C)
           | new-array T l  ⇒ arrV T (newAID (Rep-Store s) T))
```

The predicate *wts* tests whether the store is well-typed.

```
constdefs
wts :: Store ⇒ bool
wts OS ≡ ∀ (l::Location) . (typeof (OS@@l)) ≤ (ltype l)
```

12.4 Derived Properties of the Store

In this subsection, a number of lemmas formalize various properties of the Store. Especially the 13 axioms are proven that must hold for a modelling of a Store (see [PH97, p. 45]). They are labeled with Store1 to Store13.

```
lemma alive-init [simp,intro]: alive (init T) s
  by (cases T) (simp-all add: alive-def aliveImpl-def)

lemma alive-loc [simp]:
  ⟦isObjV x; typeof x ≤ dtype f⟧ ⟹ alive (ref (x..f)) s = alive x s
  by (cases x) (simp-all)

lemma alive-arr-loc [simp]:
  isArrV x ⟹ alive (ref (x.[i])) s = alive x s
  by (cases x) (simp-all)
```

lemma *alive-arr-len* [*simp*]:
isArrV x $\Longrightarrow$ *alive* (*ref* (*arr-len x*)) *s* = *alive x s*
by (*cases x*) (*simp-all*)

lemma *ref-arr-len-new* [*simp*]:
ref (*arr-len* (*new s* (*new-array T n*))) = *new s* (*new-array T n*)
by (*simp add*: *new-def*)

lemma *ref-arr-loc-new* [*simp*]:
ref ((*new s* (*new-array T n*)).[*i*]) = *new s* (*new-array T n*)
by (*simp add*: *new-def*)

lemma *ref-loc-new* [*simp*]: *CClassT C* $\leq$ *dtype f*
$\Longrightarrow$ *ref* ((*new s* (*new-instance C*))..*f*) = *new s* (*new-instance C*)
by (*simp add*: *new-def*)

lemma *access-type-safe* [*simp*,*intro*]: *typeof* (*s*@@*l*) $\leq$ *ltype l*
proof −
have *Rep-Store s* $\in$ *Store*
by (*rule Rep-Store*)
thus *?thesis*
by (*auto simp add*: *access-def Store-def*)
qed

The store is well-typed by construction.

lemma *always-welltyped-store*: *wts OS*
by (*simp add*: *wts-def access-type-safe*)

Store8

lemma *alive-access* [*simp*,*intro*]: *alive* (*s*@@*l*) *s*
proof −
have *Rep-Store s* $\in$ *Store*
by (*rule Rep-Store*)
thus *?thesis*
by (*auto simp add*: *access-def Store-def alive-def aliveImpl-def*)
qed

Store3

lemma *access-unalive* [*simp*]:
assumes *unalive*: ¬ *alive* (*ref l*) *s*
shows *s*@@*l* = *init* (*ltype l*)
proof −
have *Rep-Store s* $\in$ *Store*
by (*rule Rep-Store*)
with *unalive* **show** *?thesis*
by (*simp add*: *access-def Store-def alive-def aliveImpl-def*)
qed

lemma *update-induct*:
assumes *skip*: *P s*
assumes *update*: ⟦*alive* (*ref l*) *s*; *alive v s*; *typeof v* $\leq$ *ltype l*⟧ $\Longrightarrow$

```
            P (Abs-Store ((Rep-Store s)(|vals:=(vals (Rep-Store s))(l:=v)|)))
  shows P (s⟨l:=v⟩)
  using update skip
  by (simp add: update-def)

lemma vals-update-in-Store:
  assumes alive-l: alive (ref l) s
  assumes alive-y: alive y s
  assumes type-conform: typeof y ≤ ltype l
  shows (Rep-Store s(|vals := (vals (Rep-Store s))(l := y)|)) ∈ Store
  (is ?s-upd ∈ Store)
proof −
  have s: Rep-Store s ∈ Store
    by (rule Rep-Store)
  have alloc-eq: newOID ?s-upd = newOID (Rep-Store s)
    by simp
  have ∀ l. aliveImpl (vals ?s-upd l) ?s-upd
  proof
    fix k
    show aliveImpl (vals ?s-upd k) ?s-upd
    proof (cases k=l)
      case True
      with alive-y show ?thesis
        by (simp add: alloc-eq alive-def aliveImpl-def split: Value.splits)
    next
      case False
      from s have ∀ l. aliveImpl (vals (Rep-Store s) l) (Rep-Store s)
        by (simp add: Store-def)
      with False show ?thesis
        by (simp add: aliveImpl-def split: Value.splits)
    qed
  qed
  moreover
  have ∀ l. ¬ aliveImpl (ref l) ?s-upd ⟶ vals ?s-upd l = init (ltype l)
  proof (intro allI impI)
    fix k
    assume unalive: ¬ aliveImpl (ref k) ?s-upd
    show vals ?s-upd k = init (ltype k)
    proof −
      from unalive alive-l
      have k≠l
        by (auto simp add: alive-def aliveImpl-def split: Value.splits)
      hence vals ?s-upd k = vals (Rep-Store s) k
        by simp
      moreover from unalive
      have ¬ aliveImpl (ref k) (Rep-Store s)
        by (simp add: aliveImpl-def split: Value.splits)
      ultimately show ?thesis
        using s by (simp add: Store-def)
    qed
  qed
  moreover
  have ∀ l. typeof (vals ?s-upd l) ≤ ltype l
  proof
```

```
    fix k show typeof (vals ?s-upd k) ≤ ltype k
    proof (cases k=l)
      case True
      with type-conform show ?thesis
        by simp
    next
      case False
      hence vals ?s-upd k = vals (Rep-Store s) k
        by simp
      with s show ?thesis
        by (simp add: Store-def)
    qed
  qed
  ultimately show ?thesis
    by (simp add: Store-def)
qed
```

Store6

```
lemma alive-update-invariant [simp]: alive x (s⟨l:=y⟩) = alive x s
proof (rule update-induct)
  show alive x s = alive x s..
next
  assume alive (ref l) s alive y s typeof y ≤ ltype l
  hence Rep-Store
        (Abs-Store (Rep-Store s(|vals := (vals (Rep-Store s))(l := y)|)))
       = Rep-Store s(|vals := (vals (Rep-Store s))(l := y)|)
    by (rule vals-update-in-Store [THEN Abs-Store-inverse])
  thus alive x
        (Abs-Store (Rep-Store s(|vals := (vals (Rep-Store s))(l := y)|))) =
       alive x s
    by (simp add: alive-def aliveImpl-def split: Value.split)
qed
```

Store1

```
lemma access-update-other [simp]:
  assumes neq-l-m: l ≠ m
  shows s⟨l:=x⟩@@m = s@@m
proof (rule update-induct)
  show s@@m = s@@m ..
next
  assume alive (ref l) s alive x s typeof x ≤ ltype l
  hence Rep-Store
        (Abs-Store (Rep-Store s(|vals := (vals (Rep-Store s))(l := x)|)))
       = Rep-Store s(|vals := (vals (Rep-Store s))(l := x)|)
    by (rule vals-update-in-Store [THEN Abs-Store-inverse])
  with neq-l-m
  show Abs-Store (Rep-Store s(|vals := (vals (Rep-Store s))(l := x)|))@@m = s@@m
    by (auto simp add: access-def)
qed
```

Store2

```
lemma update-access-same [simp]:
  assumes alive-l: alive (ref l) s
```

assumes *alive-x*: *alive x s*
assumes *widen-x-l*: *typeof x* ≤ *ltype l*
shows $s\langle l{:=}x\rangle @@ l = x$
proof −
from *alive-l alive-x widen-x-l*
have *Rep-Store*
(*Abs-Store* (*Rep-Store s*(|*vals* := (*vals* (*Rep-Store s*))(*l* := *x*)|)))
= *Rep-Store s*(|*vals* := (*vals* (*Rep-Store s*))(*l* := *x*)|)
by (*rule vals-update-in-Store* [*THEN Abs-Store-inverse*])
hence *Abs-Store* (*Rep-Store s*(|*vals* := (*vals* (*Rep-Store s*))(*l* := *x*)|))@@*l* = *x*
by (*simp add*: *access-def*)
with *alive-l alive-x widen-x-l*
show *?thesis*
by (*simp add*: *update-def*)
qed

Store4

lemma *update-unalive-val* [*simp*,*intro*]: ¬ *alive x s* ⟹ $s\langle l{:=}x\rangle = s$
by (*simp add*: *update-def*)

lemma *update-unalive-loc* [*simp*,*intro*]: ¬ *alive* (*ref l*) *s* ⟹ $s\langle l{:=}x\rangle = s$
by (*simp add*: *update-def*)

lemma *update-type-mismatch* [*simp*,*intro*]: ¬ *typeof x* ≤ *ltype l* ⟹ $s\langle l{:=}x\rangle = s$
by (*simp add*: *update-def*)

Store9

lemma *alive-primitive* [*simp*,*intro*]: *isprimitive* (*typeof x*) ⟹ *alive x s*
by (*cases x*) (*simp-all*)

Store10

lemma *new-unalive-old-Store* [*simp*]: ¬ *alive* (*new s t*) *s*
by (*cases t*) (*simp-all add*: *alive-def aliveImpl-def new-def*)

lemma *alloc-new-instance-in-Store*:
(*Rep-Store s*(|*newOID* := λ*D*. *if C* = *D*
then Suc (*newOID* (*Rep-Store s*) *C*)
else newOID (*Rep-Store s*) *D*|)) ∈ *Store*
(**is** *?s-alloc* ∈ *Store*)
proof −
have *s*: *Rep-Store s* ∈ *Store*
by (*rule Rep-Store*)
hence ∀ *l*. *aliveImpl* (*vals* (*Rep-Store s*) *l*) (*Rep-Store s*)
by (*simp add*: *Store-def*)
then
have ∀ *l*. *aliveImpl* (*vals ?s-alloc l*) *?s-alloc*
by (*auto intro*: *less-SucI simp add*: *aliveImpl-def split*: *Value.splits*)
moreover
have ∀ *l*. ¬ *aliveImpl* (*ref l*) *?s-alloc* ⟶ *vals ?s-alloc l* = *init* (*ltype l*)
proof (*intro allI impI*)
fix *l*
assume ¬ *aliveImpl* (*ref l*) *?s-alloc*
hence ¬ *aliveImpl* (*ref l*) (*Rep-Store s*)

```
    by (simp add: aliveImpl-def split: Value.splits split-if-asm)
  with s have vals (Rep-Store s) l = init (ltype l)
    by (simp add: Store-def)
  thus vals ?s-alloc l = init (ltype l)
    by simp
 qed
 moreover
 from s have ∀ l. typeof (vals ?s-alloc l) ≤ ltype l
  by (simp add: Store-def)
 ultimately
 show ?thesis
  by (simp add: Store-def)
qed

lemma alloc-new-array-in-Store:
(Rep-Store s (|newAID :=
                λS. if T = S
                    then Suc (newAID (Rep-Store s) T)
                    else newAID (Rep-Store s) S,
              vals := (vals (Rep-Store s))
                      (arrLenLoc T
                        (newAID (Rep-Store s) T) :=
                        intgV (int n))|)) ∈ Store
(is ?s-alloc ∈ Store)
proof −
 have s: Rep-Store s ∈ Store
  by (rule Rep-Store)
 have ∀ l. aliveImpl (vals ?s-alloc l) ?s-alloc
 proof
  fix l show aliveImpl (vals ?s-alloc l) ?s-alloc
  proof (cases l = arrLenLoc T (newAID (Rep-Store s) T))
   case True
   thus ?thesis
    by (simp add: aliveImpl-def split: Value.splits)
  next
   case False
   from s have ∀ l. aliveImpl (vals (Rep-Store s) l) (Rep-Store s)
    by (simp add: Store-def)
   with False show ?thesis
    by (auto intro: less-SucI simp add: aliveImpl-def split: Value.splits)
  qed
 qed
 moreover
 have ∀ l. ¬ aliveImpl (ref l) ?s-alloc ⟶ vals ?s-alloc l = init (ltype l)
 proof (intro allI impI)
  fix l
  assume unalive: ¬ aliveImpl (ref l) ?s-alloc
  show vals ?s-alloc l = init (ltype l)
  proof (cases l = arrLenLoc T (newAID (Rep-Store s) T))
   case True
   with unalive show ?thesis by (simp add: aliveImpl-def)
  next
   case False
   from unalive
```

```
    have ¬ aliveImpl (ref l) (Rep-Store s)
      by (simp add: aliveImpl-def split: Value.splits split-if-asm)
    with s have vals (Rep-Store s) l = init (ltype l)
      by (simp add: Store-def)
    with False show ?thesis
      by simp
  qed
 qed
 moreover
 from s have ∀ l. typeof (vals ?s-alloc l) ≤ ltype l
  by (simp add: Store-def)
 ultimately
 show ?thesis
  by (simp add: Store-def)
qed


lemma new-alive-alloc [simp,intro]: alive (new s t) (s⟨t⟩)
proof (cases t)
 case new-instance thus ?thesis
  by (simp add: alive-def aliveImpl-def new-def alloc-def
                alloc-new-instance-in-Store [THEN Abs-Store-inverse])
next
 case new-array thus ?thesis
  by (simp add: alive-def aliveImpl-def new-def alloc-def
                alloc-new-array-in-Store [THEN Abs-Store-inverse])
qed

lemma value-class-inhabitants:
(∀x. typeof x = CClassT typeId ⟶ P x) = (∀ a. P (objV typeId a))
 (is (∀ x. ?A x) = ?B)
proof
 assume ∀ x. ?A x thus ?B
  by simp
next
 assume B: ?B show ∀ x. ?A x
 proof
  fix x from B show ?A x
   by (cases x) auto
 qed
qed

lemma value-array-inhabitants:
(∀x. typeof x = ArrT typeId ⟶ P x) = (∀ a. P (arrV typeId a))
 (is (∀ x. ?A x) = ?B)
proof
 assume ∀ x. ?A x thus ?B
  by simp
next
 assume B: ?B show ∀ x. ?A x
 proof
  fix x from B show ?A x
   by (cases x) auto
 qed
```

qed

The following three lemmas are helper lemmas that are not related to the store theory. They might as well be stored in a separate helper theory.

lemma *le-Suc-eq*: $(\forall\, a.\ (a < Suc\ n) = (a < Suc\ m)) = (\forall\, a.\ (a < n) = (a < m))$
(**is** $(\forall\, a.\ ?A\ a) = (\forall\ a.\ ?B\ a)$)
proof
assume $\forall\, a.\ ?A\ a$ **thus** $\forall\ a.\ ?B\ a$
by *fastsimp*
next
assume B: $\forall\ a.\ ?B\ a$
show $\forall\, a.\ ?A\ a$
proof
fix a
from B **show** $?A\ a$
by (*cases a*) *simp-all*
qed
qed

lemma *all-le-eq-imp-eq*: $\bigwedge\ c{::}nat.\ (\forall\, a.\ (a < d) = (a < c)) \longrightarrow (d = c)$
proof (*induct d*)
case *0* **thus** *?case* **by** *fastsimp*
next
case (*Suc n c*)
thus *?case*
by (*cases c*) (*auto simp add*: *le-Suc-eq*)
qed

lemma *all-le-eq*: $(\forall\ a{::}nat.\ (a < d) = (a < c)) = (d = c)$
using *all-le-eq-imp-eq* **by** *auto*

Store11

lemma *typeof-new*: *typeof* (*new s t*) = *typeofNew t*
by (*cases t*) (*simp-all add*: *new-def typeofNew-def*)

Store12

lemma *new-eq*: (*new s1 t* = *new s2 t*) =
$(\forall\ x.$ *typeof x* = *typeofNew t* $\longrightarrow$ *alive x s1* = *alive x s2*)
by (*cases t*)
(*auto simp add*: *new-def typeofNew-def alive-def aliveImpl-def*
value-class-inhabitants value-array-inhabitants all-le-eq)

lemma *new-update* [*simp*]: *new* ($s\langle l{:=}x\rangle$) *t* = *new s t*
by (*simp add*: *new-eq*)

lemma *alive-alloc-propagation*:
assumes *alive-s*: *alive x s* **shows** *alive x* ($s\langle t\rangle$)
proof (*cases t*)
case *new-instance* **with** *alive-s* **show** *?thesis*
by (*cases x*)
(*simp-all add*: *alive-def aliveImpl-def alloc-def*
alloc-new-instance-in-Store [*THEN Abs-Store-inverse*])
next

```
  case new-array with alive-s show ?thesis
    by (cases x)
      (simp-all add: alive-def aliveImpl-def alloc-def
                     alloc-new-array-in-Store [THEN Abs-Store-inverse])
qed
```

Store7

```
lemma alive-alloc-exhaust: alive x (s⟨t⟩) = (alive x s ∨ (x = new s t))
proof
  assume alive-alloc: alive x (s⟨t⟩)
  show alive x s ∨ x = new s t
  proof (cases t)
    case (new-instance C)
    with alive-alloc show ?thesis
      by (cases x) (auto split: split-if-asm
                        simp add: alive-def new-def alloc-def aliveImpl-def
                            alloc-new-instance-in-Store [THEN Abs-Store-inverse])
  next
    case (new-array T l)
    with alive-alloc show ?thesis
      by (cases x) (auto split: split-if-asm
                        simp add: alive-def new-def alloc-def aliveImpl-def
                        alloc-new-array-in-Store [THEN Abs-Store-inverse])
  qed
next
  assume alive x s ∨ x = new s t
  then show alive x (s⟨t⟩)
  proof
    assume alive x s thus ?thesis by (rule alive-alloc-propagation)
  next
    assume new: x=new s t show ?thesis
    proof (cases t)
      case new-instance with new show ?thesis
        by (simp add: alive-def aliveImpl-def new-def alloc-def
                      alloc-new-instance-in-Store [THEN Abs-Store-inverse])
    next
      case new-array with new show ?thesis
        by (simp add: alive-def aliveImpl-def new-def alloc-def
                      alloc-new-array-in-Store [THEN Abs-Store-inverse])
    qed
  qed
qed

lemma alive-alloc-cases [consumes 1]:
  ⟦alive x (s⟨t⟩); alive x s ⟹ P; x=new s t ⟹ P⟧
   ⟹ P
  by (auto simp add: alive-alloc-exhaust)

lemma aliveImpl-vals-independent: aliveImpl x (s(|vals := z|)) = aliveImpl x s
  by (cases x) (simp-all add: aliveImpl-def)

lemma access-arr-len-new-alloc [simp]:
  s⟨new-array T l⟩@@arr-len (new s (new-array T l)) = intgV (int l)
  by (subst access-def)
```

```
    (simp add: new-def alloc-def alive-def
            alloc-new-array-in-Store [THEN Abs-Store-inverse] access-def)

lemma access-new [simp]:
  assumes ref-new: ref l = new s t
  assumes no-arr-len: isNewArr t ⟶ l ≠ arr-len (new s t)
  shows s⟨t⟩@@l = init (ltype l)
proof −
  from ref-new
  have ¬ alive (ref l) s
    by simp
  hence s@@l = init (ltype l)
    by simp
  moreover
  from ref-new
  have alive (ref l) (s⟨t⟩)
    by simp
  moreover
  from no-arr-len
  have vals (Rep-Store (s⟨t⟩)) l = s@@l
    by (cases t)
      (simp-all add: alloc-def new-def access-def
              alloc-new-instance-in-Store [THEN Abs-Store-inverse]
              alloc-new-array-in-Store [THEN Abs-Store-inverse] )
  ultimately show s⟨t⟩@@l = init (ltype l)
    by (subst access-def) (simp)
qed
```

Store5. We have to take into account that the length of an array is changed during allocation.

```
lemma access-alloc [simp]:
  assumes no-arr-len-new: isNewArr t ⟶ l ≠ arr-len (new s t)
  shows s⟨t⟩@@l = s@@l
proof −
  show ?thesis
  proof (cases alive (ref l) (s⟨t⟩))
    case True
    then
    have access-alloc-vals: s⟨t⟩@@l = vals (Rep-Store (s⟨t⟩)) l
      by (simp add: access-def alloc-def)
    from True show ?thesis
    proof (cases rule: alive-alloc-cases)
      assume alive-l-s: alive (ref l) s
      with new-unalive-old-Store
      have l-not-new: ref l ≠ new s t
        by fastsimp
      hence vals (Rep-Store (s⟨t⟩)) l = s@@l
        by (cases t)
          (auto simp add: alloc-def new-def access-def
                alloc-new-instance-in-Store [THEN Abs-Store-inverse]
                alloc-new-array-in-Store [THEN Abs-Store-inverse])
      with access-alloc-vals
      show ?thesis
        by simp
    next
```

```
    assume ref-new: ref l = new s t
    with no-arr-len-new
    have s⟨t⟩@@l = init (ltype l)
      by (simp add: access-new)
    moreover
    from ref-new have s@@l = init (ltype l)
      by simp
    ultimately
    show ?thesis by simp
  qed
 next
  case False
  hence s⟨t⟩@@l = init (ltype l)
    by (simp)
  moreover
  from False have ¬ alive (ref l) s
    by (auto simp add: alive-alloc-propagation)
  hence s@@l = init (ltype l)
    by simp
  ultimately show ?thesis by simp
 qed
qed
```

Store13

```
lemma Store-eqI:
 assumes eq-alive: ∀ x. alive x s1 = alive x s2
 assumes eq-access: ∀ l. s1@@l = s2@@l
 shows s1=s2
proof (cases s1=s2)
 case True thus ?thesis .
next
 case False note neq-s1-s2 = this
 show ?thesis
 proof (cases newOID (Rep-Store s1) = newOID (Rep-Store s2))
  case False
  have ∃ C. newOID (Rep-Store s1) C ≠ newOID (Rep-Store s2) C
  proof (rule ccontr)
   assume ¬ (∃ C. newOID (Rep-Store s1) C ≠ newOID (Rep-Store s2) C)
   then have newOID (Rep-Store s1) = newOID (Rep-Store s2)
     by (blast intro: ext)
   with False show False ..
  qed
  with eq-alive obtain C
   where newOID (Rep-Store s1) C ≠ newOID (Rep-Store s2) C
         ∀ a. alive (objV C a) s1 = alive (objV C a) s2 by auto
  then show ?thesis
   by (simp add: all-le-eq alive-def aliveImpl-def)
 next
  case True note eq-newOID = this
  show ?thesis
  proof (cases newAID (Rep-Store s1) = newAID (Rep-Store s2))
   case False
   have ∃ T. newAID (Rep-Store s1) T ≠ newAID (Rep-Store s2) T
   proof (rule ccontr)
```

```
      assume ¬ (∃ T. newAID (Rep-Store s1) T ≠ newAID (Rep-Store s2) T)
      then have newAID (Rep-Store s1) = newAID (Rep-Store s2)
        by (blast intro: ext)
      with False show False ..
    qed
    with eq-alive obtain T
      where newAID (Rep-Store s1) T ≠ newAID (Rep-Store s2) T
          ∀ a. alive (arrV T a) s1 = alive (arrV T a) s2 by auto
    then show ?thesis
      by (simp add: all-le-eq alive-def aliveImpl-def)
  next
    case True note eq-newAID = this
    show ?thesis
    proof (cases vals (Rep-Store s1) = vals (Rep-Store s2))
      case True
      with eq-newOID eq-newAID
      have (Rep-Store s1) = (Rep-Store s2)
        by (cases Rep-Store s1,cases Rep-Store s2) simp
      hence s1=s2
        by (simp add: Rep-Store-inject)
      with neq-s1-s2 show ?thesis
        by simp
    next
      case False
      have ∃ l. vals (Rep-Store s1) l ≠ vals (Rep-Store s2) l
      proof (rule ccontr)
        assume ¬ (∃ l. vals (Rep-Store s1) l ≠ vals (Rep-Store s2) l)
        hence vals (Rep-Store s1) = vals (Rep-Store s2)
          by (blast intro: ext)
        with False show False ..
      qed
      then obtain l
        where vals (Rep-Store s1) l ≠ vals (Rep-Store s2) l
        by auto
      with eq-access have False
        by (simp add: access-def)
      thus ?thesis ..
    qed
  qed
 qed
qed
```

Lemma 3.1 in [Poetzsch-Heffter97]. The proof of this lemma is quite an impressive demostration of readable Isar proofs since it closely follows the textual proof.

```
lemma comm:
  assumes neq-l-new: ref l ≠ new s t
  assumes neq-x-new: x ≠ new s t
  shows s⟨t⟩⟨l:=x⟩ = s⟨l:=x⟩⟨t⟩
proof (rule Store-eqI [rule-format])
  fix y
  show alive y (s⟨t⟩⟨l:=x⟩) = alive y (s⟨l:=x⟩⟨t⟩)
  proof −
    have alive y (s⟨t⟩⟨l:=x⟩) = alive y (s⟨t⟩)
      by (rule alive-update-invariant)
```

```
    also have ... = (alive y s ∨ (y = new s t))
      by (rule alive-alloc-exhaust)
    also have ... = (alive y (s⟨l:=x⟩) ∨ y = new s t)
      by (simp only: alive-update-invariant)
    also have ... = (alive y (s⟨l:=x⟩) ∨ y = new (s⟨l:=x⟩) t)
    proof −
      have new s t = new (s⟨l:=x⟩) t
        by simp
      thus ?thesis by simp
    qed
    also have ... = alive y (s⟨l:=x⟩⟨t⟩)
      by (simp add: alive-alloc-exhaust)
    finally show ?thesis .
  qed
next
  fix k
  show s⟨t⟩⟨l := x⟩@@k = s⟨l := x⟩⟨t⟩@@k
  proof (cases l=k)
    case False note neq-l-k = this
    show ?thesis
    proof (cases isNewArr t ⟶ k ≠ arr-len (new s t))
      case True
      from neq-l-k
      have  s⟨t⟩⟨l := x⟩@@k = s⟨t⟩@@k by simp
      also from True
      have ... = s@@k by simp
      also from neq-l-k
      have ... = s⟨l:=x⟩@@k by simp
      also from True
      have ... = s⟨l := x⟩⟨t⟩@@k  by simp
      finally show ?thesis .
    next
      case False
      then obtain T n where
        t: t=new-array T n and k: k=arr-len (new s (new-array T n))
        by (cases t) auto
      from k have k′: k=arr-len (new (s⟨l := x⟩) (new-array T n))
        by simp
      from neq-l-k
      have  s⟨t⟩⟨l := x⟩@@k = s⟨t⟩@@k by simp
      also from t k
      have ... = intgV (int n)
        by simp
      also from t k′
      have ... = s⟨l := x⟩⟨t⟩@@k
        by (simp del: new-update)
      finally show ?thesis .
    qed
  next
    case True note eq-l-k = this
    have lemma-3-1:
      ref l ≠ new s t ⟹ alive (ref l) (s⟨t⟩) = alive (ref l) s
      by (simp add: alive-alloc-exhaust)
    have lemma-3-2:
```

```
    x ≠ new s t ⟹ alive x (s⟨t⟩) = alive x s
    by (simp add: alive-alloc-exhaust)
  have lemma-3-3: s⟨l:=x,t⟩@@l = s⟨l:=x⟩@@l
  proof −
    from neq-l-new have ref l ≠ new (s⟨l:=x⟩) t
      by simp
    hence isNewArr t ⟶ l ≠ arr-len (new (s⟨l:=x⟩) t)
      by (cases t) auto
    thus ?thesis
      by (simp)
  qed
  show ?thesis
  proof (cases alive x s)
    case True note alive-x = this
    show ?thesis
    proof (cases alive (ref l) s)
      case True note alive-l = this
      show ?thesis
      proof (cases typeof x ≤ ltype l)
        case True
        with alive-l alive-x
        have s⟨l:=x⟩@@l = x
          by (rule update-access-same)
        moreover
        have s⟨t⟩⟨l:=x⟩@@l = x
        proof −
          from alive-l neq-l-new have alive (ref l) (s⟨t⟩)
            by (simp add: lemma-3-1)
          moreover
          from alive-x neq-x-new have alive x (s⟨t⟩)
            by (simp add: lemma-3-2)
          ultimately
          show s⟨t⟩⟨l:=x⟩@@l = x
            using True by (rule update-access-same)
        qed
        ultimately show ?thesis
          using eq-l-k lemma-3-3 by simp
      next
        case False
        thus ?thesis by simp
      qed
    next
      case False note not-alive-l = this
      from not-alive-l neq-l-new have ¬ alive (ref l) (s⟨t⟩)
        by (simp add: lemma-3-1)
      then have s⟨t⟩⟨l:=x⟩@@l = init (ltype l)
        by simp
      also from not-alive-l have ... = s⟨l:=x⟩@@l
        by simp
      also have ... = s⟨l:=x⟩⟨t⟩@@l
        by (simp add: lemma-3-3)
      finally show ?thesis by (simp add: eq-l-k)
    qed
  next
```

```
      case False note not-alive-x = this
      from not-alive-x neq-x-new have ¬ alive x (s⟨t⟩)
        by (simp add: lemma-3-2)
      then have s⟨t⟩⟨l:=x⟩@@l = s⟨t⟩@@l
        by (simp)
      also have ... = s@@l
      proof −
        from neq-l-new
        have isNewArr t ⟶ l ≠ arr-len (new s t)
          by (cases t) auto
        thus ?thesis
          by (simp)
      qed
      also from not-alive-x have ... = s⟨l:=x⟩@@l
        by (simp)
      also have ... = s⟨l:=x⟩⟨t⟩@@l
        by (simp add: lemma-3-3)
      finally show ?thesis by (simp add: eq-l-k)
    qed
  qed
qed


end
```

13 Store Properties

theory *StoreProperties* **imports** *Store* **begin**

This theory formalizes advanced concepts and properties of stores.

13.1 Reachability of a Location from a Reference

For a given store, the function *reachS* yields the set of all pairs (l, v) where l is a location that is reachable from the value v (which must be a reference) in the given store. The predicate *reach* decides whether a location is reachable from a value in a store.

```
inductive
  reach :: Store ⇒ Location ⇒ Value ⇒ bool
    (⊣ - reachable′-from - [91,91,91]90)
  for s :: Store
where
  Immediate: ref l ≠ nullV ⟹ s⊢ l reachable-from (ref l)
| Indirect: ⟦s⊢ l reachable-from (s@@k); ref k ≠ nullV⟧
            ⟹ s⊢ l reachable-from (ref k)
```

Note that we explicitly exclude *nullV* as legal reference for reachability. Keep in mind that static fields are not associated to any object, therefore *ref* yields *nullV* if invoked on static fields (see the definition of the function *ref*, Sect. 11). Reachability only describes the locations directly reachable from the object or array by following the pointers and should not include the static fields if we encounter a *nullV* reference in the pointer chain.

We formalize some properties of reachability. Especially, Lemma 3.2 as given in [PH97, p. 53] is proven.

lemma *unreachable-Null*:
assumes *reach*: *s⊢ l reachable-from x* **shows** *x≠nullV*
using *reach* **by** (*induct*) *auto*

corollary *unreachable-Null-simp* [*simp*]:
¬ *s⊢ l reachable-from nullV*
by (*iprover dest*: *unreachable-Null*)

corollary *unreachable-NullE* [*elim*]:
s⊢ l reachable-from nullV ⟹ *P*
by (*simp*)

lemma *reachObjLoc* [*simp*,*intro*]:
C=cls cf ⟹ *s⊢ objLoc cf a reachable-from objV C a*
by (*iprover intro*: *reach.Immediate* [*of objLoc cf a*,*simplified*])

lemma *reachArrLoc* [*simp*,*intro*]: *s⊢ arrLoc T a i reachable-from arrV T a*
by (*rule reach.Immediate* [*of arrLoc T a i*,*simplified*])

lemma *reachArrLen* [*simp*,*intro*]: *s⊢ arrLenLoc T a reachable-from arrV T a*
by (*rule reach.Immediate* [*of arrLenLoc T a*,*simplified*])

lemma *unreachStatic* [*simp*]: ¬ *s⊢ staticLoc f reachable-from x*
proof −
{
fix *y* **assume** *s⊢ y reachable-from x y=staticLoc f*
then have *False*
by *induct auto*
}
thus *?thesis*
by *auto*
qed

lemma *unreachStaticE* [*elim*]: *s⊢ staticLoc f reachable-from x* ⟹ *P*
by (*simp add*: *unreachStatic*)

lemma *reachable-from-ArrLoc-impl-Arr* [*simp*,*intro*]:
assumes *reach-loc*: *s⊢ l reachable-from* (*s@@arrLoc T a i*)
shows *s⊢ l reachable-from* (*arrV T a*)
using *reach.Indirect* [*OF reach-loc*]
by *simp*

lemma *reachable-from-ObjLoc-impl-Obj* [*simp*,*intro*]:
assumes *reach-loc*: *s⊢ l reachable-from* (*s@@objLoc cf a*)
assumes *C*: *C=cls cf*
shows *s⊢ l reachable-from* (*objV C a*)
using *C reach.Indirect* [*OF reach-loc*]
by *simp*

Lemma 3.2 (i)

lemma *reach-update* [*simp*]:

```
  assumes unreachable-l-x: ¬ s⊢ l reachable-from x
  shows s⟨l:=y⟩⊢ k reachable-from  x = s⊢ k reachable-from x
proof
  assume s⊢ k reachable-from x
  from this unreachable-l-x
  show s⟨l := y⟩⊢ k reachable-from x
  proof (induct)
    case (Immediate k)
    have ref k ≠ nullV by fact
    then show s⟨l := y⟩⊢ k reachable-from (ref k)
      by (rule reach.Immediate)
  next
    case (Indirect k m)
    have hyp: ¬ s⊢ l reachable-from (s@@m)
              ⟹ s⟨l:=y⟩ ⊢ k reachable-from (s@@m) by fact
    have ref m ≠ nullV and ¬ s⊢ l reachable-from (ref m) by fact+
    hence l≠m ¬ s⊢ l reachable-from (s@@m)
      by (auto intro: reach.intros)
    with hyp have s⟨l := y⟩ ⊢ k reachable-from (s⟨l := y⟩@@m)
      by simp
    then show s⟨l := y⟩⊢ k reachable-from (ref m)
      by (rule reach.Indirect) (rule Indirect.hyps)
  qed
next
  assume s⟨l := y⟩⊢ k reachable-from x
  from this unreachable-l-x
  show s⊢ k reachable-from x
  proof (induct)
    case (Immediate k)
    have ref k ≠ nullV by fact
    then show s ⊢ k reachable-from (ref k)
      by (rule reach.Immediate)
  next
    case (Indirect k m)
    with Indirect.hyps
    have hyp: ¬ s⊢ l reachable-from (s⟨l := y⟩@@m)
              ⟹ s⊢ k reachable-from (s⟨l := y⟩@@m) by simp
    have ref m ≠ nullV and ¬ s⊢ l reachable-from (ref m) by fact+
    hence l≠m ¬ s ⊢ l reachable-from (s@@m)
      by (auto intro: reach.intros)
    with hyp have s ⊢ k reachable-from (s@@m)
      by simp
    thus s⊢ k reachable-from (ref m)
      by (rule reach.Indirect) (rule Indirect.hyps)
  qed
qed
```

Lemma 3.2 (ii)

```
lemma reach2:
  ¬ s⊢ l reachable-from x ⟹ ¬ s⟨l:=y⟩⊢ l reachable-from x
  by (simp)
```

Lemma 3.2 (iv)

```
lemma reach4: ¬ s ⊢ l reachable-from (ref k) ⟹ k ≠ l ∨ (ref k) = nullV
```

```
  by (auto intro: reach.intros)

lemma reachable-isRef:
  assumes reach: s⊢l reachable-from x
  shows isRefV x
  using reach
proof (induct)
  case (Immediate l)
  show isRefV (ref l)
    by (cases l) simp-all
next
  case (Indirect l k)
  show isRefV (ref k)
    by (cases k) simp-all
qed


lemma val-ArrLen-IntgT: isArrLenLoc l ⟹ typeof (s@@l) = IntgT
proof −
  assume isArrLen: isArrLenLoc l
  have T: typeof (s@@l) ≤ ltype l
    by (simp)
  also from isArrLen have I: ltype l = IntgT
    by (cases l) simp-all
  finally show ?thesis
    by (auto elim: rtranclE simp add: le-Javatype-def subtype-defs)
qed

lemma access-alloc' [simp]:
  assumes no-arr-len: ¬ isArrLenLoc l
  shows s⟨t⟩@@l = s@@l
proof −
  from no-arr-len
  have isNewArr t ⟶ l ≠ arr-len (new s t)
    by (cases t) (auto simp add: new-def isArrLenLoc-def split: Location.splits)
  thus ?thesis
    by (rule access-alloc)
qed
```

Lemma 3.2 (v)

```
lemma reach-alloc [simp]: s⟨t⟩⊢ l reachable-from x = s⊢ l reachable-from x
proof
  assume s⟨t⟩⊢ l reachable-from x
  thus s⊢ l reachable-from x
  proof (induct)
    case (Immediate l)
    thus s⊢ l reachable-from ref l
      by (rule reach.intros)
  next
    case (Indirect l k)
    have reach-k: s⊢ l reachable-from (s⟨t⟩@@k) by fact
    moreover
    have s⟨t⟩@@k = s@@k
    proof −
```

```
    from reach-k have isRef: isRefV (s⟨t⟩@@k)
      by (rule reachable-isRef)
    have ¬ isArrLenLoc k
    proof (rule ccontr,simp)
      assume isArrLenLoc k
      then have typeof (s⟨t⟩@@k) = IntgT
        by (rule val-ArrLen-IntgT)
      with isRef
      show False
        by (cases (s⟨t⟩@@k)) simp-all
    qed
    thus ?thesis
      by (rule access-alloc')
  qed
  ultimately have s⊢ l reachable-from (s@@k)
    by simp
  thus s⊢ l reachable-from ref k
    by (rule reach.intros) (rule Indirect.hyps)
 qed
next
 assume s⊢ l reachable-from x
 thus s⟨t⟩⊢ l reachable-from x
 proof (induct)
  case (Immediate l)
  thus s⟨t⟩⊢ l reachable-from ref l
    by (rule reach.intros)
 next
  case (Indirect l k)
  have reach-k: s⟨t⟩⊢ l reachable-from (s@@k) by fact
  moreover
  have s⟨t⟩@@k = s@@k
  proof −
    from reach-k have isRef: isRefV (s@@k)
      by (rule reachable-isRef)
    have ¬ isArrLenLoc k
    proof (rule ccontr,simp)
      assume isArrLenLoc k
      then have typeof (s@@k) = IntgT
        by (rule val-ArrLen-IntgT)
      with isRef
      show False
        by (cases (s@@k)) simp-all
    qed
    thus ?thesis
      by (rule access-alloc')
  qed
  ultimately have s⟨t⟩⊢ l reachable-from (s⟨t⟩@@k)
    by simp
  thus s⟨t⟩⊢ l reachable-from ref k
    by (rule reach.intros) (rule Indirect.hyps)
 qed
qed
```

Lemma 3.2 (vi)

lemma *reach6*: *isprimitive*(*typeof x*) $\Longrightarrow \neg\ s \vdash l$ *reachable-from* x
proof
  assume *prim*: *isprimitive*(*typeof x*)
  assume $s \vdash l$ *reachable-from* x
  hence *isRefV x*
    by (*rule reachable-isRef*)
  with *prim* **show** *False*
    by (*cases x*) *simp-all*
qed

Lemma 3.2 (iii)

lemma *reach3*:
  assumes *k-y*: $\neg\ s\vdash$ *k reachable-from y*
  assumes *k-x*: $\neg\ s\vdash$ *k reachable-from x*
  shows $\neg\ s\langle l{:=}y\rangle\vdash$ *k reachable-from x*
proof
  assume $s\langle l{:=}y\rangle\vdash$ *k reachable-from x*
  from *this k-y k-x*
  show *False*
  proof (*induct*)
    case (*Immediate l*)
    have $\neg\ s\vdash$ *l reachable-from ref l* **and** *ref l* $\neq$ *nullV* **by** *fact+*
    thus *False*
      by (*iprover intro*: *reach.intros*)
  next
    case (*Indirect m k*)
    have *k-not-Null*: *ref k* $\neq$ *nullV* **by** *fact*
    have *not-m-y*: $\neg\ s\vdash$ *m reachable-from y* **by** *fact*
    have *not-m-k*: $\neg\ s\vdash$ *m reachable-from ref k* **by** *fact*
    have *hyp*: $[\![\neg\ s\vdash$ *m reachable-from y*; $\neg\ s\vdash$ *m reachable-from* $(s\langle l := y\rangle @@ k)]\!]$
          $\Longrightarrow$ *False* **by** *fact*
    have *m-upd-k*: $s\langle l := y\rangle\vdash$ *m reachable-from* $(s\langle l := y\rangle @@ k)$ **by** *fact*
    show *False*
    proof (*cases l*=*k*)
      case *False*
      then have $s\langle l := y\rangle @@ k = s @@ k$ **by** *simp*
      moreover
      from *not-m-k k-not-Null* **have** $\neg\ s\vdash$ *m reachable-from* $(s @@ k)$
        by (*iprover intro*: *reach.intros*)
      ultimately show *False*
        using *not-m-y hyp* **by** *simp*
    next
      case *True* **note** *eq-l-k* = *this*
      show *?thesis*
      proof (*cases alive* (*ref l*) $s \wedge$ *alive y s* $\wedge$ *typeof y* $\leq$ *ltype l*)
        case *True*
        with *eq-l-k* **have** $s\langle l := y\rangle @@ k = y$
          by *simp*
        with *not-m-y hyp* **show** *False* **by** *simp*
      next
        case *False*
        hence $s\langle l := y\rangle = s$
          by *auto*
        moreover

```
      from not-m-k k-not-Null have ¬ s⊢ m reachable-from (s@@k)
        by (iprover intro: reach.intros)
      ultimately show False
        using not-m-y hyp by simp
    qed
  qed
 qed
qed
```

Lemma 3.2 (vii).

```
lemma unreachable-from-init [simp,intro]: ¬ s⊢ l reachable-from (init T)
 using reach6 by (cases T) simp-all

lemma ref-reach-unalive:
 assumes unalive-x:¬ alive x s
 assumes l-x: s⊢ l reachable-from x
 shows x = ref l
using l-x unalive-x
proof induct
 case (Immediate l)
 show ref l = ref l
   by simp
next
 case (Indirect l k)
 have ref k ≠ nullV by fact
 have ¬ alive (ref k) s by fact
 hence s@@k = init (ltype k) by simp
 moreover have s⊢ l reachable-from (s@@k) by fact
 ultimately have False by simp
 thus ?case ..
qed

lemma loc-new-reach:
 assumes l: ref l = new s t
 assumes l-x: s⊢ l reachable-from x
 shows x = new s t
using l-x l
proof induct
 case (Immediate l)
 show ref l = new s t by fact
next
 case (Indirect l k)
 hence s@@k = new s t by iprover
 moreover
 have ¬ alive (new s t) s
   by simp
 moreover
 have alive (s@@k) s
   by simp
 ultimately have False by simp
 thus ?case ..
qed
```

Lemma 3.2 (viii)

lemma *alive-reach-alive*:
assumes *alive-x*: *alive x s*
assumes *reach-l*: *s* ⊢ *l reachable-from x*
shows *alive* (*ref l*) *s*
using *reach-l alive-x*
proof (*induct*)
case (*Immediate l*)
show *?case* **by** *fact*
next
case (*Indirect l k*)
have *hyp*: *alive* (*s*@@*k*) *s* ⟹ *alive* (*ref l*) *s* **by** *fact*
moreover have *alive* (*s*@@*k*) *s* **by** *simp*
ultimately
show *alive* (*ref l*) *s*
by *iprover*
qed

Lemma 3.2 (ix)

lemma *reach9*:
assumes *reach-impl-access-eq*: ∀ *l*. *s1*⊢*l reachable-from x* ⟶ (*s1*@@*l* = *s2*@@*l*)
shows *s1*⊢ *l reachable-from x* = *s2*⊢ *l reachable-from x*
proof
assume *s1*⊢ *l reachable-from x*
from *this reach-impl-access-eq*
show *s2*⊢ *l reachable-from x*
proof (*induct*)
case (*Immediate l*)
show *s2*⊢ *l reachable-from ref l*
by (*rule reach.intros*) (*rule Immediate.hyps*)
next
case (*Indirect l k*)
have *hyp*: ∀ *l*. *s1*⊢ *l reachable-from* (*s1*@@*k*) ⟶ *s1*@@*l* = *s2*@@*l*
⟹ *s2*⊢ *l reachable-from* (*s1*@@*k*) **by** *fact*
have *k-not-Null*: *ref k* ≠ *nullV* **by** *fact*
have *reach-impl-access-eq*:
∀ *l*. *s1*⊢ *l reachable-from ref k* ⟶ *s1*@@*l* = *s2*@@*l* **by** *fact*
have *s1*⊢ *l reachable-from* (*s1*@@*k*) **by** *fact*
with *k-not-Null*
have *s1*@@*k* = *s2*@@*k*
by (*iprover intro*: *reach-impl-access-eq* [*rule-format*] *reach.intros*)
moreover from *reach-impl-access-eq k-not-Null*
have ∀ *l*. *s1*⊢ *l reachable-from* (*s1*@@*k*) ⟶ *s1*@@*l* = *s2*@@*l*
by (*iprover intro*: *reach.intros*)
then have *s2*⊢ *l reachable-from* (*s1*@@*k*)
by (*rule hyp*)
ultimately have *s2*⊢ *l reachable-from* (*s2*@@*k*)
by *simp*
thus *s2*⊢ *l reachable-from ref k*
by (*rule reach.intros*) (*rule Indirect.hyps*)
qed
next
assume *s2*⊢ *l reachable-from x*
from *this reach-impl-access-eq*
show *s1*⊢ *l reachable-from x*

```
  proof (induct)
    case (Immediate l)
    show s1⊢ l reachable-from ref l
      by (rule reach.intros) (rule Immediate.hyps)
  next
    case (Indirect l k)
    have hyp: ∀ l. s1⊢ l reachable-from (s2@@k) ⟶ s1@@l = s2@@l
            ⟹ s1⊢ l reachable-from (s2@@k) by fact
    have k-not-Null: ref k ≠ nullV by fact
    have reach-impl-access-eq:
      ∀ l. s1⊢ l reachable-from ref k ⟶ s1@@l = s2@@l by fact
    have s1⊢ k reachable-from ref k
      by (rule reach.intros) (rule Indirect.hyps)
    with reach-impl-access-eq
    have eq-k: s1@@k = s2@@k
      by simp
    from reach-impl-access-eq k-not-Null
    have ∀ l. s1⊢ l reachable-from (s1@@k) ⟶ s1@@l = s2@@l
      by (iprover intro: reach.intros)
    then
    have ∀ l. s1⊢ l reachable-from (s2@@k) ⟶ s1@@l = s2@@l
      by (simp add: eq-k)
    with eq-k hyp have s1⊢ l reachable-from (s1@@k)
      by simp
    thus s1⊢ l reachable-from ref k
      by (rule reach.intros) (rule Indirect.hyps)
   qed
qed
```

13.2 Reachability of a Reference from a Reference

The predicate *rreach* tests whether a value is reachable from another value. This is an extension of the predicate *oreach* as described in [PH97, p. 54] because now arrays are handled as well.

```
consts rreach:: Store ⇒ Value ⇒ Value ⇒ bool
                        (-|−Ref - reachable′-from - [91,91,91]90)
syntax (xsymbols)
rreach:: Store ⇒ Value ⇒ Value ⇒ bool
                 (-⊢Ref - reachable′-from - [91,91,91]90)

defs rreach-def:
s⊢Ref y reachable-from x ≡ ∃ l. s⊢ l reachable-from x ∧ y = ref l
```

13.3 Disjointness of Reachable Locations

The predicate *disj* tests whether two values are disjoint in a given store. Its properties as given in [PH97, Lemma 3.3, p. 54] are then proven.

```
constdefs disj:: Value ⇒ Value ⇒ Store ⇒ bool
disj x y s ≡ ∀ l. ¬ s⊢ l reachable-from x ∨ ¬ s⊢ l reachable-from y


lemma disjI1: ⟦⋀ l. s⊢ l reachable-from x ⟹ ¬ s⊢ l reachable-from y⟧
 ⟹ disj x y s
```

by (*simp add*: *disj-def*)

lemma *disjI2*: ⟦⋀ *l*. *s*⊢ *l reachable-from y* ⟹ ¬ *s*⊢ *l reachable-from x*⟧
⟹ *disj x y s*
by (*auto simp add*: *disj-def*)

lemma *disj-cases* [*consumes 1*]:
assumes *disj x y s*
assumes ⋀ *l*. ¬ *s*⊢ *l reachable-from x* ⟹ *P*
assumes ⋀ *l*. ¬ *s*⊢ *l reachable-from y* ⟹ *P*
shows *P*
using *prems* **by** (*auto simp add*: *disj-def*)

Lemma 3.3 (i) in [PH97]

lemma *disj1*: ⟦*disj x y s*; ¬ *s*⊢ *l reachable-from x*; ¬ *s*⊢ *l reachable-from y*⟧
⟹ *disj x y* (*s*⟨*l*:=*z*⟩)
by (*auto simp add*: *disj-def*)

Lemma 3.3 (ii)

lemma *disj2*:
assumes *disj-x-y*: *disj x y s*
assumes *disj-x-z*: *disj x z s*
assumes *unreach-l-x*: ¬ *s*⊢ *l reachable-from x*
shows *disj x y* (*s*⟨*l*:=*z*⟩)
proof (*rule disjI1*)
fix *k*
assume *reach-k-x*: *s*⟨*l* := *z*⟩⊢ *k reachable-from x*
show ¬ *s*⟨*l* := *z*⟩⊢ *k reachable-from y*
proof −
from *unreach-l-x reach-k-x*
have *reach-s-k-x*: *s*⊢ *k reachable-from x*
by *simp*
with *disj-x-z*
have ¬ *s*⊢ *k reachable-from z*
by (*simp add*: *disj-def*)
moreover from *reach-s-k-x disj-x-y*
have ¬ *s*⊢ *k reachable-from y*
by (*simp add*: *disj-def*)
ultimately show *?thesis*
by (*rule reach3*)
qed
qed

Lemma 3.3 (iii)

lemma *disj3*: **assumes** *alive-x-s*: *alive x s*
shows *disj x* (*new s t*) (*s*⟨*t*⟩)
proof (*rule disjI1*,*simp only*: *reach-alloc*)
fix *l*
assume *reach-l-x*: *s*⊢ *l reachable-from x*
show ¬ *s*⊢ *l reachable-from new s t*
proof
assume *reach-l-new*: *s*⊢ *l reachable-from new s t*
have *unalive-new*: ¬ *alive* (*new s t*) *s* **by** *simp*

```
    from this reach-l-new
    have  new s t = ref l
      by (rule ref-reach-unalive)
    moreover from alive-x-s reach-l-x
    have alive (ref l) s
      by (rule alive-reach-alive)
    ultimately show False
      using unalive-new
      by simp
  qed
qed
```

Lemma 3.3 (iv)

```
lemma disj4: ⟦disj (objV C a) y s; CClassT C ≤ dtype f ⟧
          ⟹ disj (s@@(objV C a)..f) y s
  by (auto simp add: disj-def)

lemma disj4': ⟦disj (arrV T a) y s ⟧
          ⟹ disj (s@@(arrV T a).[i]) y s
  by (auto simp add: disj-def)
```

13.4 X-Equivalence

We call two stores s_1 and s_2 equivalent wrt. a given value X (which is called X-equivalence) iff X and all values reachable from X in s_1 or s_2 have the same state [PH97, p. 55]. This is tested by the predicate *xeq*. Lemma 3.4 of [PH97] is then proven for *xeq*.

```
constdefs xeq:: Value ⇒ Store ⇒ Store ⇒ bool

xeq x s t ≡ alive x s = alive x t ∧
          (∀ l. s⊢ l reachable-from x ⟶ s@@l = t@@l)



syntax (xsymbols) @xeq:: Store ⇒ Value ⇒ Store ⇒ bool
 (-/ (≡[-])/ - [900,0,900] 900)

syntax (ascii) @xeq:: Store ⇒ Value ⇒ Store ⇒ bool
(-/ (==[-])/ - [900,0,900] 900)

translations s ≡[x] t == xeq x s t
          s ==[x] t == xeq x s t


lemma xeqI: ⟦alive x s = alive x t;
          ⋀ l. s⊢ l reachable-from x ⟹ s@@l = t@@l
          ⟧ ⟹ s ≡[x] t
  by (auto simp add: xeq-def)
```

Lemma 3.4 (i) in [PH97].

```
lemma xeq1-refl: s ≡[x] s
  by (simp add: xeq-def)
```

Lemma 3.4 (i)

```
lemma xeq1-sym′:
  assumes s-t: s ≡[x] t
  shows t ≡[x] s
proof −
  from s-t have alive x s = alive x t by (simp add: xeq-def)
  moreover
  from s-t have ∀ l. s⊢ l reachable-from x ⟶ s@@l = t@@l
    by (simp add: xeq-def)
  with reach9 [OF this]
  have ∀ l. t⊢ l reachable-from x ⟶ t@@l = s@@l
    by simp
  ultimately show ?thesis
    by (simp add: xeq-def)
qed

lemma xeq1-sym: s ≡[x] t = t ≡[x] s
  by (auto intro: xeq1-sym′)
```

Lemma 3.4 (i)

```
lemma xeq1-trans [trans]:
  assumes s-t: s ≡[x] t
  assumes t-r: t ≡[x] r
  shows s ≡[x] r
proof −
  from s-t t-r
  have alive x s = alive x r
    by (simp add: xeq-def)
  moreover
  have ∀ l. s⊢ l reachable-from x ⟶ s@@l = r@@l
  proof (intro allI impI)
    fix l
    assume reach-l: s⊢ l reachable-from x
    show s@@l = r@@l
    proof −
      from reach-l s-t have s@@l=t@@l
        by (simp add: xeq-def)
      also have t@@l = r@@l
      proof −
        from s-t have ∀ l. s⊢ l reachable-from x ⟶ s@@l = t@@l
          by (simp add: xeq-def)
        from reach9 [OF this] reach-l have t⊢ l reachable-from x
          by simp
        with t-r show ?thesis
          by (simp add: xeq-def)
      qed
      finally show ?thesis .
    qed
  qed
  ultimately show ?thesis
    by (simp add: xeq-def)
qed
```

Lemma 3.4 (ii)

```
lemma xeq2:
```

```
  assumes xeq: ∀ x. s ≡[x] t
  assumes static-eq: ∀ f. s@@(staticLoc f) = t@@(staticLoc f)
  shows s = t
proof (rule Store-eqI)
  from xeq
  show ∀x. alive x s = alive x t
    by (simp add: xeq-def)
next
  show ∀l. s@@l = t@@l
  proof
    fix l
    show s@@l = t@@l
    proof (cases l)
      case (objLoc cf a)
      have l = objLoc cf a by fact
      hence s⊢ l reachable-from (objV (cls cf) a)
        by simp
      with xeq show ?thesis
        by (simp add: xeq-def)
    next
      case (staticLoc f)
      have l = staticLoc f by fact
      with static-eq show ?thesis
        by (simp add: xeq-def)
    next
      case (arrLenLoc T a)
      have l = arrLenLoc T a by fact
      hence s⊢ l reachable-from (arrV T a)
        by simp
      with xeq show ?thesis
        by (simp add: xeq-def)
    next
      case (arrLoc T a i)
      have l = arrLoc T a i by fact
      hence s⊢ l reachable-from (arrV T a)
        by simp
      with xeq show ?thesis
        by (simp add: xeq-def)
    qed
  qed
qed
```

Lemma 3.4 (iii)

```
lemma xeq3:
  assumes unreach-l: ¬ s⊢ l reachable-from x
  shows s ≡[x] s⟨l:=y⟩
proof (rule xeqI)
  show alive x s = alive x (s⟨l := y⟩)
    by simp
next
  fix k
  assume reach-k: s⊢ k reachable-from x
  with unreach-l have l≠k by auto
  then show s@@k = s⟨l := y⟩@@k
```

```
    by simp
qed
```

Lemma 3.4 (iv)

```
lemma xeq4: assumes not-new: x ≠ new s t
  shows s ≡[x] s⟨t⟩
proof (rule xeqI)
  from not-new
  show alive x s = alive x (s⟨t⟩)
    by (simp add: alive-alloc-exhaust)
next
  fix l
  assume reach-l: s⊢ l reachable-from x
  show s@@l = s⟨t⟩@@l
  proof (cases isNewArr t ⟶ l ≠ arr-len (new s t))
    case True
    with reach-l show ?thesis
      by simp
  next
    case False
    then obtain T n where t: t = new-array T n and
                          l: l = arr-len (new s t)
      by (cases t) auto
    hence ref l = new s t
      by simp
    from this reach-l
    have x = new s t
      by (rule loc-new-reach)
    with not-new show ?thesis ..
  qed
qed
```

Lemma 3.4 (v)

```
lemma xeq5: s ≡[x] t ⟹ s⊢ l reachable-from x = t⊢ l reachable-from x
  by (rule reach9) (simp add:  xeq-def)
```

13.5 T-Equivalence

T-equivalence is the extension of X-equivalence from values to types. Two stores are T-equivalent iff they are X-equivalent for all values of type T. This is formalized by the predicate *teq* [PH97, p. 55].

```
constdefs teq:: Javatype ⇒ Store ⇒ Store ⇒ bool
teq t s1 s2 ≡ ∀ x. typeof x ≤ t ⟶ s1 ≡[x] s2
```

13.6 Less Alive

To specify that methods have no side-effects, the following binary relation on stores plays a prominent role. It expresses that the two stores differ only in values that are alive in the store passed as first argument. This is formalized by the predicate *lessalive* [PH97, p. 55]. The stores have to be X-equivalent for the references of the first store that are alive, and the values of the static fields have to be the same in both stores.

```
consts lessalive:: Store ⇒ Store ⇒ bool (-/ << - [70,71] 70)
```

syntax (*xsymbols*) @*lessalive*:: *Store* ⇒ *Store* ⇒ *bool* (-/ ≪ - [*70*,*71*] *70*)
translations *s* ≪ *t* == *lessalive s t*

defs *lessalive-def*:
s ≪ *t* ≡ (∀ *x*. *alive x s* ⟶ *s* ≡[*x*] *t*) ∧ (∀ *f*. *s*@@*staticLoc f* = *t*@@*staticLoc f*)

We define an introduction rule for the new operator.

lemma *lessaliveI*:
⟦⋀ *x*. *alive x s* ⟹ *s* ≡[*x*] *t*; ⋀ *f*. *s*@@*staticLoc f* = *t*@@*staticLoc f*⟧
⟹ *s* ≪ *t*
by (*simp add*: *lessalive-def*)

It can be shown that *lessalive* is reflexive, transitive and antisymmetric.

lemma *lessalive-refl*: *s* ≪ *s*
by (*simp add*: *lessalive-def xeq1-refl*)

lemma *lessalive-trans* [*trans*]:
assumes *s-t*: *s* ≪ *t*
assumes *t-w*: *t* ≪ *w*
shows *s* ≪ *w*
proof (*rule lessaliveI*)
fix *x*
assume *alive-x-s*: *alive x s*
with *s-t* **have** *s* ≡[*x*] *t*
by (*simp add*: *lessalive-def*)
also
have *t* ≡[*x*] *w*
proof −
from *alive-x-s s-t* **have** *alive x t* **by** (*simp add*: *lessalive-def xeq-def*)
with *t-w* **show** *?thesis*
by (*simp add*: *lessalive-def*)
qed
finally show *s* ≡[*x*] *w*.
next
fix *f*
from *s-t t-w* **show** *s*@@*staticLoc f* = *w*@@*staticLoc f*
by (*simp add*: *lessalive-def*)
qed

lemma *lessalive-antisym*:
assumes *s-t*: *s* ≪ *t*
assumes *t-s*: *t* ≪ *s*
shows *s* = *t*
proof (*rule xeq2*)
show ∀ *x*. *s* ≡[*x*] *t*
proof
fix *x* **show** *s* ≡[*x*] *t*
proof (*cases alive x s*)
case *True*
with *s-t* **show** *?thesis* **by** (*simp add*: *lessalive-def*)
next
case *False* **note** *unalive-x-s* = *this*
show *?thesis*

```
    proof (cases alive x t)
      case True
      with t-s show ?thesis
        by (subst xeq1-sym) (simp add: lessalive-def)
    next
      case False
      show ?thesis
      proof (rule xeqI)
        from False unalive-x-s show alive x s = alive x t by simp
      next
        fix l assume reach-s-x: s⊢ l reachable-from x
        with unalive-x-s have x: x = ref l
          by (rule ref-reach-unalive)
        with unalive-x-s have s@@l = init (ltype l)
          by simp
        also from reach-s-x x have t⊢ l reachable-from x
          by (auto intro: reach.Immediate unreachable-Null)
        with False x have t@@l = init (ltype l)
          by simp
        finally show s@@l = t@@l
          by simp
      qed
    qed
  qed
next
  from s-t show ∀f. s@@staticLoc f = t@@staticLoc f
    by (simp add: lessalive-def)
qed
```

This gives us a partial ordering on the store. Thus, the type *Store* can be added to the appropriate type class *ord* which lets us define the $<$ and $\leq$ symbols, and to the type class *order* which axiomatizes partial orderings.

```
instance Store:: ord ..
defs (overloaded)
le-Store-def: s ≤ t ≡ s ≪ t
less-Store-def: (s::Store) < t ≡ s ≤ t ∧ s ≠ t
```

We prove Lemma 3.5 of [PH97, p. 56] for this relation.

Lemma 3.5 (i)

```
instance Store:: order
proof
  fix s t w:: Store
  {
    show s ≤ s
      by (simp add: le-Store-def lessalive-refl)
  next
    assume s ≤ t t ≤ w
    then show s ≤ w
      by (unfold le-Store-def) (rule lessalive-trans)
  next
    assume s ≤ t t ≤ s
    then show s = t
```

```
    by (unfold le-Store-def) (rule lessalive-antisym)
  next
    show (s < t) = (s ≤ t ∧ s ≠ t)
    by (simp add: less-Store-def)
  }
qed
```

Lemma 3.5 (ii)

```
lemma lessalive2: ⟦s ≪ t; alive x s⟧ ⟹ alive x t
  by (simp add: lessalive-def xeq-def)
```

Lemma 3.5 (iii)

```
lemma lessalive3:
  assumes s-t: s ≪ t
  assumes alive: alive x s ∨ ¬ alive x t
  shows s ≡[x] t
proof (cases alive x s)
  case True
  with s-t show ?thesis
    by (simp add: lessalive-def)
next
  case False
  note unalive-x-s = this
  with alive have unalive-x-t: ¬ alive x t
    by simp
  show ?thesis
  proof (rule xeqI)
    from False alive show alive x s = alive x t
      by simp
  next
    fix l assume reach-s-x: s⊢ l reachable-from x
    with unalive-x-s have x: x = ref l
      by (rule ref-reach-unalive)
    with unalive-x-s have s@@l = init (ltype l)
      by simp
    also from reach-s-x x have t⊢ l reachable-from x
      by (auto intro: reach.Immediate unreachable-Null)
    with unalive-x-t x have t@@l = init (ltype l)
      by simp
    finally show s@@l = t@@l
      by simp
  qed
qed
```

Lemma 3.5 (iv)

```
lemma lessalive-update [simp,intro]:
  assumes s-t: s ≪ t
  assumes unalive-l: ¬ alive (ref l) t
  shows s ≪ t⟨l:=x⟩
proof −
  from unalive-l have t⟨l:=x⟩ = t
    by simp
  with s-t show ?thesis by simp
```

qed

lemma *Xequ4'*:
assumes *alive*: *alive x s*
shows *s* ≡[*x*] *s*⟨*t*⟩
proof −
from *alive* **have** *x* ≠ *new s t*
by *auto*
thus *?thesis*
by (*rule xeq4*)
qed

Lemma 3.5 (v)

lemma *lessalive-alloc* [*simp*,*intro*]: *s* ≪ *s*⟨*t*⟩
by (*simp add*: *lessalive-def Xequ4'*)

13.7 Reachability of Types from Types

The predicate *treach* denotes the fact that the first type reaches the second type by stepping finitely many times from a type to the range type of one of its fields. This formalization diverges from [PH97, p. 106] in that it does not include the number of steps that are allowed to reach the second type. Reachability of types is a static approximation of reachability in the store. If I cannot reach the type of a location from the type of a reference, I cannot reach the location from the reference. See lemma *not-treach-ref-impl-not-reach* below.

inductive
treach :: *Javatype* ⇒ *Javatype* ⇒ *bool*
where
Subtype: *U* ≤ *T* ⟹ *treach T U*
| *Attribute*: ⟦*treach T S*; *S* ≤ *dtype f*; *U* ≤ *rtype f*⟧ ⟹ *treach T U*
| *ArrLength*: *treach* (*ArrT AT*) *IntgT*
| *ArrElem*: *treach* (*ArrT AT*) (*at2jt AT*)
| *Trans* [*trans*]: ⟦*treach T U*; *treach U V*⟧ ⟹ *treach T V*

lemma *treach-ref-l* [*simp*,*intro*]:
assumes *not-Null*: *ref l* ≠ *nullV*
shows *treach* (*typeof* (*ref l*)) (*ltype l*)
proof (*cases l*)
case (*objLoc cf a*)
have *l*=*objLoc cf a* **by** *fact*
moreover
have *treach* (*CClassT* (*cls cf*)) (*rtype* (*att cf*))
by (*rule treach.Attribute* [**where** *?f*=*att cf* **and** *?S*=*CClassT* (*cls cf*)])
(*auto intro*: *treach.Subtype*)
ultimately show *?thesis*
by *simp*
next
case (*staticLoc f*)
have *l*=*staticLoc f* **by** *fact*
hence *ref l* = *nullV* **by** *simp*
with *not-Null* **show** *?thesis*
by *simp*
next

```
  case (arrLenLoc T a)
  have l=arrLenLoc T a by fact
  then show ?thesis
    by (auto intro: treach.ArrLength)
next
  case (arrLoc T a i)
  have l=arrLoc T a i by fact
  then show ?thesis
    by (auto intro: treach.ArrElem)
qed

lemma treach-ref-l' [simp,intro]:
  assumes not-Null: ref l ≠ nullV
  shows treach (typeof (ref l)) (typeof (s@@l))
proof −
  from not-Null have treach (typeof (ref l)) (ltype l) by (rule treach-ref-l)
  also have typeof (s@@l) ≤ ltype l
    by simp
  hence treach (ltype l) (typeof (s@@l))
    by (rule treach.intros)
  finally show ?thesis .
qed


lemma reach-impl-treach:
  assumes reach-l: s ⊢ l reachable-from x
  shows treach (typeof x) (ltype l)
using reach-l
proof (induct)
  case (Immediate l)
  have ref l ≠ nullV by fact
  then show treach (typeof (ref l)) (ltype l)
    by (rule treach-ref-l)
next
  case (Indirect l k)
  have treach (typeof (s@@k)) (ltype l) by fact
  moreover
  have ref k ≠ nullV by fact
  hence treach (typeof (ref k)) (typeof (s@@k))
    by simp
  ultimately show treach (typeof (ref k)) (ltype l)
    by (iprover intro: treach.Trans)
qed

lemma not-treach-ref-impl-not-reach:
  assumes not-treach: ¬ treach (typeof x) (typeof (ref l))
  shows ¬ s ⊢ l reachable-from x
proof
  assume reach-l: s⊢ l reachable-from x
  from this not-treach
  show False
  proof (induct)
    case (Immediate l)
    have ¬ treach (typeof (ref l)) (typeof (ref l)) by fact
```

```
    thus False by (iprover intro: treach.intros order-refl)
  next
    case (Indirect l k)
    have hyp: ¬ treach (typeof (s@@k)) (typeof (ref l)) ⟹ False by fact
    have not-Null: ref k ≠ nullV by fact
    have not-k-l:¬ treach (typeof (ref k)) (typeof (ref l)) by fact
    show False
    proof (cases treach (typeof (s@@k)) (typeof (ref l)))
      case False thus False by (rule hyp)
    next
      case True
      from not-Null have treach (typeof (ref k)) (typeof (s@@k))
        by (rule treach-ref-l')
      also note True
      finally have treach (typeof (ref k)) (typeof (ref l)) .
      with not-k-l show False ..
    qed
  qed
qed
```

Lemma 4.6 in [PH97, p. 107].

```
lemma treach1:
  assumes x-t: typeof x ≤ T
  assumes not-treach: ¬ treach T (typeof (ref l))
  shows ¬ s ⊢ l reachable-from x
proof −
  have ¬ treach (typeof x) (typeof (ref l))
  proof
    from x-t have treach T (typeof x) by (rule treach.intros)
    also assume treach (typeof x) (typeof (ref l))
    finally have treach T (typeof (ref l)) .
    with not-treach show False ..
  qed
  thus ?thesis
    by (rule not-treach-ref-impl-not-reach)
qed


end
```

14 The Formalization of JML Operators

```
theory JML imports StoreProperties begin
```

JML operators that are to be used in Hoare formulae can be formalized here.

```
constdefs
  instanceof :: Value ⇒ Javatype ⇒ bool  (- @instanceof -)
  instanceof v t ≡ typeof v ≤ t

end
```

15 The Universal Specification

theory *UnivSpec* **imports** *JML* **begin**

This theory contains the Isabelle formalization of the program-dependent specification. This theory has to be provided by the user. In later versions of Jive, one may be able to generate it from JML model classes.

constdefs
aCounter :: *Value* ⇒ *Store* ⇒ *JavaInt*

aCounter x s == *if x* ~= *nullV* & (*alive x s*) & *typeof x* = *CClassT CounterImpl then*
aI (*s*@@(*x*..*CounterImpl*′*value*))
else arbitrary

end

References

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