Hoare Logic

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Abstract

These theories contain a Hoare logic for a simple imperative programming language with while-loops, including a verification condition generator.

Special infrastructure for modelling and reasoning about pointer programs is provided, together with many examples, including Schorr-Waite. See [1, 2] for an excellent exposition.

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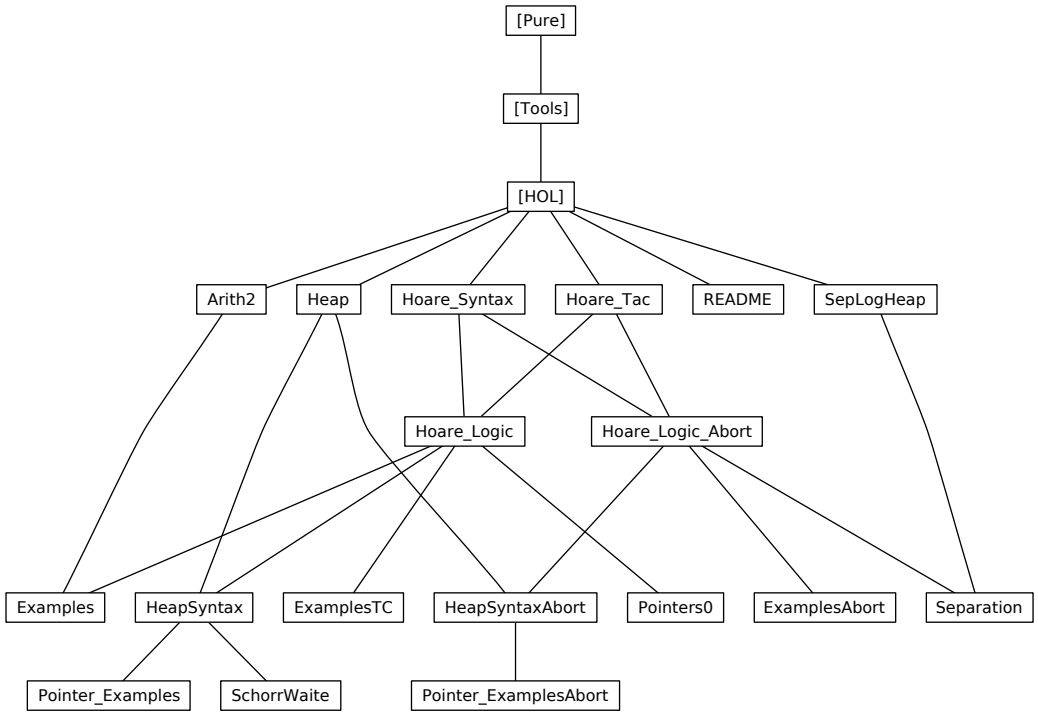
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1 Concrete syntax for Hoare logic, with translations for variables

theory *Hoare-Syntax*
imports *Main*
begin

syntax
-assign :: *idt* ⇒ *'b* ⇒ *'com* (*2- :=/ -) [70, 65] 61*)
-Seq :: *'com* ⇒ *'com* ⇒ *'com* (*-;/ -) [61,60] 60*)
-Cond :: *'bexp* ⇒ *'com* ⇒ *'com* ⇒ *'com* (*IF -/ THEN - / ELSE -/ FI) [0,0,0] 61*)
-While :: *'bexp* ⇒ *'assn* ⇒ *'var* ⇒ *'com* ⇒ *'com* (*WHILE -/ INV {(-)} / VAR {(-)} //DO - /OD) [0,0,0,0] 61*)

The *VAR* {-} syntax supports two variants:

- *VAR* $\{x = t\}$ where t::*nat* is the decreasing expression, the variant, and x a variable that can be referred to from inner annotations. The x can be necessary for nested loops, e.g. to prove that the inner loops do not mess with t.
- *VAR* $\{t\}$ where the variable is omitted because it is not needed.

syntax
-While0 :: *'bexp* ⇒ *'assn* ⇒ *'com* ⇒ *'com* (*1WHILE -/ INV {-} //DO - /OD) [0,0,0] 61*)

The *-While0* syntax is translated into the *-While* syntax with the trivial variant 0. This is ok because partial correctness proofs do not make use of the variant.

syntax
-hoare-vars :: [*idts*, *'assn*,*'com*, *'assn*] ⇒ *bool* (*VARS -// {-} // - // {-} [0,0,55,0] 50*)
-hoare-vars-tc :: [*idts*, *'assn*, *'com*, *'assn*] ⇒ *bool* (*VARS -// [-] // - // [-] [0,0,55,0] 50*)
syntax (**output**)
-hoare :: [*'assn*, *'com*, *'assn*] ⇒ *bool* (({-}//-//{-}) [0,55,0] 50*)
-hoare-tc :: [*'assn*, *'com*, *'assn*] ⇒ *bool* (([-]//-//[-]) [0,55,0] 50*)

Completeness requires(?) the ability to refer to an outer variant in an inner invariant. Thus we need to abstract over a variable equated with the variant, the x in *VAR* $\{x = t\}$. But the x should only occur in invariants. To enforce this, syntax translations in *hoare-syntax.ML* separate the program from its annotations and only the latter are abstracted over over x. (Thus x can also occur in inner variants, but that neither helps nor hurts.)

datatype *'a anno* =
Abasic |

Aseq 'a anno 'a anno |
Acond 'a anno 'a anno |
Awhile 'a set 'a ⇒ nat nat ⇒ 'a anno

⟨*ML*⟩

end

2 Hoare logic VCG tactic

theory *Hoare-Tac*
imports *Main*
begin

context
begin

qualified named-theorems *BasicRule*
qualified named-theorems *SkipRule*
qualified named-theorems *AbortRule*
qualified named-theorems *SeqRule*
qualified named-theorems *CondRule*
qualified named-theorems *WhileRule*

qualified named-theorems *BasicRuleTC*
qualified named-theorems *SkipRuleTC*
qualified named-theorems *SeqRuleTC*
qualified named-theorems *CondRuleTC*
qualified named-theorems *WhileRuleTC*

lemma *Compl-Collect*: $-(Collect\ b) = \{x.\ \neg(b\ x)\}$
⟨*proof*⟩

⟨*ML*⟩

end

end

3 Hoare logic

theory *Hoare-Logic*
imports *Hoare-Syntax Hoare-Tac*
begin

3.1 Sugared semantic embedding of Hoare logic

Strictly speaking a shallow embedding (as implemented by Norbert Galm following Mike Gordon) would suffice. Maybe the datatype com comes in useful later.

type-synonym *'a bexp = 'a set*
type-synonym *'a assn = 'a set*

datatype *'a com =*
  Basic 'a ⇒ 'a
| *Seq 'a com 'a com*
| *Cond 'a bexp 'a com 'a com*
| *While 'a bexp 'a com*

abbreviation *annskip (SKIP)* **where** *SKIP == Basic id*

type-synonym *'a sem = 'a => 'a => bool*

inductive *Sem :: 'a com ⇒ 'a sem*
where
  Sem (Basic f) s (f s)
| *Sem c1 s s'' ⟹ Sem c2 s'' s' ⟹ Sem (Seq c1 c2) s s'*
| *s ∈ b ⟹ Sem c1 s s' ⟹ Sem (Cond b c1 c2) s s'*
| *s ∉ b ⟹ Sem c2 s s' ⟹ Sem (Cond b c1 c2) s s'*
| *s ∉ b ⟹ Sem (While b c) s s*
| *s ∈ b ⟹ Sem c s s'' ⟹ Sem (While b c) s'' s' ⟹*
   Sem (While b c) s s'

definition *Valid :: 'a bexp ⇒ 'a com ⇒ 'a anno ⇒ 'a bexp ⇒ bool*
  where *Valid p c a q ≡ ∀ s s'. Sem c s s' ⟶ s ∈ p ⟶ s' ∈ q*

definition *ValidTC :: 'a bexp ⇒ 'a com ⇒ 'a anno ⇒ 'a bexp ⇒ bool*
  where *ValidTC p c a q ≡ ∀ s. s ∈ p ⟶ (∃ t. Sem c s t ∧ t ∈ q)*

inductive-cases [*elim*!]:
  Sem (Basic f) s s' Sem (Seq c1 c2) s s'
  Sem (Cond b c1 c2) s s'

lemma *Sem-deterministic*:
  assumes *Sem c s s1*
      and *Sem c s s2*
    shows *s1 = s2*
⟨*proof*⟩

lemma *tc-implies-pc*:
  ValidTC p c a q ⟹ Valid p c a q
  ⟨*proof*⟩

lemma *tc-extract-function*:

$ValidTC\ p\ c\ a\ q \Longrightarrow \exists f\ .\ \forall s\ .\ s \in p \longrightarrow f\ s \in q$
⟨*proof*⟩

lemma *SkipRule*: $p \subseteq q \Longrightarrow Valid\ p\ (Basic\ id)\ a\ q$
⟨*proof*⟩

lemma *BasicRule*: $p \subseteq \{s.\ f\ s \in q\} \Longrightarrow Valid\ p\ (Basic\ f)\ a\ q$
⟨*proof*⟩

lemma *SeqRule*: $Valid\ P\ c1\ a1\ Q \Longrightarrow Valid\ Q\ c2\ a2\ R \Longrightarrow Valid\ P\ (Seq\ c1\ c2)\ (Aseq\ a1\ a2)\ R$
⟨*proof*⟩

lemma *CondRule*:
$p \subseteq \{s.\ (s \in b \longrightarrow s \in w) \wedge (s \notin b \longrightarrow s \in w')\}$
$\Longrightarrow Valid\ w\ c1\ a1\ q \Longrightarrow Valid\ w'\ c2\ a2\ q \Longrightarrow Valid\ p\ (Cond\ b\ c1\ c2)\ (Acond\ a1\ a2)\ q$
⟨*proof*⟩

lemma *While-aux*:
assumes $Sem\ (While\ b\ c)\ s\ s'$
shows $\forall s\ s'.\ Sem\ c\ s\ s' \longrightarrow s \in I \wedge s \in b \longrightarrow s' \in I \Longrightarrow$
$s \in I \Longrightarrow s' \in I \wedge s' \notin b$
⟨*proof*⟩

lemma *WhileRule*:
$p \subseteq i \Longrightarrow Valid\ (i \cap b)\ c\ (A\ 0)\ i \Longrightarrow i \cap (-b) \subseteq q \Longrightarrow Valid\ p\ (While\ b\ c)\ (Awhile\ i\ v\ A)\ q$
⟨*proof*⟩

lemma *SkipRuleTC*:
assumes $p \subseteq q$
shows $ValidTC\ p\ (Basic\ id)\ a\ q$
⟨*proof*⟩

lemma *BasicRuleTC*:
assumes $p \subseteq \{s.\ f\ s \in q\}$
shows $ValidTC\ p\ (Basic\ f)\ a\ q$
⟨*proof*⟩

lemma *SeqRuleTC*:
assumes $ValidTC\ p\ c1\ a1\ q$
and $ValidTC\ q\ c2\ a2\ r$
shows $ValidTC\ p\ (Seq\ c1\ c2)\ (Aseq\ a1\ a2)\ r$
⟨*proof*⟩

lemma *CondRuleTC*:
assumes $p \subseteq \{s.\ (s \in b \longrightarrow s \in w) \wedge (s \notin b \longrightarrow s \in w')\}$

and *ValidTC w c1 a1 q*
and *ValidTC w' c2 a2 q*
shows *ValidTC p (Cond b c1 c2) (Acond a1 a2) q*
⟨*proof*⟩

lemma *WhileRuleTC*:
assumes $p \subseteq i$
and $\bigwedge n::nat$. *ValidTC* $(i \cap b \cap \{s$. $v\ s = n\})$ *c* $(A\ n)$ $(i \cap \{s$. $v\ s < n\})$
and $i \cap uminus\ b \subseteq q$
shows *ValidTC p (While b c) (Awhile i v* $(\lambda n.\ A\ n))$ *q*
⟨*proof*⟩

3.1.1 Concrete syntax

⟨*ML*⟩

3.1.2 Proof methods: VCG

declare *BasicRule* [*Hoare-Tac.BasicRule*]
and *SkipRule* [*Hoare-Tac.SkipRule*]
and *SeqRule* [*Hoare-Tac.SeqRule*]
and *CondRule* [*Hoare-Tac.CondRule*]
and *WhileRule* [*Hoare-Tac.WhileRule*]

declare *BasicRuleTC* [*Hoare-Tac.BasicRuleTC*]
and *SkipRuleTC* [*Hoare-Tac.SkipRuleTC*]
and *SeqRuleTC* [*Hoare-Tac.SeqRuleTC*]
and *CondRuleTC* [*Hoare-Tac.CondRuleTC*]
and *WhileRuleTC* [*Hoare-Tac.WhileRuleTC*]

⟨*ML*⟩

end

4 More arithmetic

theory *Arith2*
imports *Main*
begin

definition *cd* :: [*nat*, *nat*, *nat*] ⇒ *bool*
where *cd x m n* ⟷ *x dvd m* ∧ *x dvd n*

definition *gcd* :: [*nat*, *nat*] ⇒ *nat*
where *gcd m n* = (*SOME x. cd x m n* & (∀ *y*.(*cd y m n*) ⟶ *y*≤*x*))

primrec *fac* :: *nat* ⇒ *nat*
where
fac 0 = *Suc 0*

| *fac (Suc n) = Suc n * fac n*

4.1 cd

lemma *cd-nnn*: *0<n ⟹ cd n n n*
⟨*proof*⟩

lemma *cd-le*: *[| cd x m n; 0<m; 0<n |] ==> x<=m & x<=n*
⟨*proof*⟩

lemma *cd-swap*: *cd x m n = cd x n m*
⟨*proof*⟩

lemma *cd-diff-l*: *n≤m ⟹ cd x m n = cd x (m−n) n*
⟨*proof*⟩

lemma *cd-diff-r*: *m≤n ⟹ cd x m n = cd x m (n−m)*
⟨*proof*⟩

4.2 gcd

lemma *gcd-nnn*: *0<n ⟹ n = gcd n n*
⟨*proof*⟩

lemma *gcd-swap*: *gcd m n = gcd n m*
⟨*proof*⟩

lemma *gcd-diff-l*: *n≤m ⟹ gcd m n = gcd (m−n) n*
⟨*proof*⟩

lemma *gcd-diff-r*: *m≤n ⟹ gcd m n = gcd m (n−m)*
⟨*proof*⟩

4.3 pow

lemma *sq-pow-div2* [*simp*]:
*m mod 2 = 0 ⟹ ((n::nat)*n)^(m div 2) = n^m*
⟨*proof*⟩

end

5 Various examples

theory *Examples*
imports *Hoare-Logic Arith2*
begin

5.1 Arithmetic

5.1.1 Multiplication by successive addition

lemma *multiply-by-add*: *VARS m s a b*
$\{a{=}A \wedge b{=}B\}$
$m := 0$; $s := 0$;
WHILE $m{\neq}a$
INV $\{s{=}m{*}b \wedge a{=}A \wedge b{=}B\}$
DO $s := s{+}b$; $m := m{+}(1{::}nat)$ *OD*
$\{s = A{*}B\}$
⟨*proof*⟩

lemma *multiply-by-add-time*: *VARS m s a b t*
$\{a{=}A \wedge b{=}B \wedge t{=}0\}$
$m := 0$; $t := t{+}1$; $s := 0$; $t := t{+}1$;
WHILE $m{\neq}a$
INV $\{s{=}m{*}b \wedge a{=}A \wedge b{=}B \wedge t = 2{*}m + 2\}$
DO $s := s{+}b$; $t := t{+}1$; $m := m{+}(1{::}nat)$; $t := t{+}1$ *OD*
$\{s = A{*}B \wedge t = 2{*}A + 2\}$
⟨*proof*⟩

lemma *multiply-by-add2*: *VARS M N P* :: *int*
$\{m{=}M \wedge n{=}N\}$
IF $M < 0$ *THEN* $M := -M$; $N := -N$ *ELSE SKIP FI*;
$P := 0$;
WHILE $0 < M$
INV $\{0 \leq M \wedge (\exists p.\ p = (\textit{if } m{<}0 \textit{ then } -m \textit{ else } m)\ \&\ p{*}N = m{*}n\ \&\ P = (p{-}M){*}N)\}$
DO $P := P{+}N$; $M := M - 1$ *OD*
$\{P = m{*}n\}$
⟨*proof*⟩

lemma *multiply-by-add2-time*: *VARS M N P t* :: *int*
$\{m{=}M \wedge n{=}N \wedge t{=}0\}$
IF $M < 0$ *THEN* $M := -M$; $t := t{+}1$; $N := -N$; $t := t{+}1$ *ELSE SKIP FI*;
$P := 0$; $t := t{+}1$;
WHILE $0 < M$
INV $\{0 \leq M\ \&\ (\exists p.\ p = (\textit{if } m{<}0 \textit{ then } -m \textit{ else } m)\ \&\ p{*}N = m{*}n\ \&\ P = (p{-}M){*}N\ \&\ t \geq 0\ \&\ t \leq 2{*}(p{-}M){+}3)\}$
DO $P := P{+}N$; $t := t{+}1$; $M := M - 1$; $t := t{+}1$ *OD*
$\{P = m{*}n\ \&\ t \leq 2{*}abs\ m + 3\}$
⟨*proof*⟩

5.1.2 Euclid's algorithm for GCD

lemma *Euclid-GCD*: *VARS a b*
$\{0{<}A\ \&\ 0{<}B\}$
$a := A$; $b := B$;
WHILE $a \neq b$

INV {*0*<*a* & *0*<*b* & *gcd A B* = *gcd a b*}
DO IF a<*b THEN b* := *b*−*a ELSE a* := *a*−*b FI OD*
{*a* = *gcd A B*}
⟨*proof*⟩

lemma *Euclid-GCD-time*: *VARS a b t*
{*0*<*A* & *0*<*B* & *t*=*0*}
a := *A*; *t* := *t*+*1*; *b* := *B*; *t* := *t*+*1*;
WHILE a ≠ *b*
INV {*0*<*a* & *0*<*b* & *gcd A B* = *gcd a b* & *a*≤*A* & *b*≤*B* & *t* ≤ *max A B* − *max a b* + *2*}
DO IF a<*b THEN b* := *b*−*a*; *t* := *t*+*1 ELSE a* := *a*−*b*; *t* := *t*+*1 FI OD*
{*a* = *gcd A B* & *t* ≤ *max A B* + *2*}
⟨*proof*⟩

5.1.3 Dijkstra's extension of Euclid's algorithm for simultaneous GCD and SCM

From E.W. Disjkstra. Selected Writings on Computing, p 98 (EWD474), where it is given without the invariant. Instead of defining *scm* explicitly we have used the theorem *scm x y* = *x* ∗ *y* / *gcd x y* and avoided division by mupltiplying with *gcd x y*.

lemmas *distribs* =
diff-mult-distrib diff-mult-distrib2 add-mult-distrib add-mult-distrib2

lemma *gcd-scm*: *VARS a b x y*
{*0*<*A* & *0*<*B* & *a*=*A* & *b*=*B* & *x*=*B* & *y*=*A*}
WHILE a ~= *b*
INV {*0*<*a* & *0*<*b* & *gcd A B* = *gcd a b* & *2*∗*A*∗*B* = *a*∗*x* + *b*∗*y*}
DO IF a<*b THEN* (*b* := *b*−*a*; *x* := *x*+*y*) *ELSE* (*a* := *a*−*b*; *y* := *y*+*x*) *FI OD*
{*a* = *gcd A B* & *2*∗*A*∗*B* = *a*∗(*x*+*y*)}
⟨*proof*⟩

5.1.4 Power by iterated squaring and multiplication

lemma *power-by-mult*: *VARS a b c*
{*a*=*A* & *b*=*B*}
c := (*1*::*nat*);
WHILE b ~= *0*
INV {*A*^*B* = *c* ∗ *a*^*b*}
DO WHILE b mod 2 = *0*
INV {*A*^*B* = *c* ∗ *a*^*b*}
DO a := *a*∗*a*; *b* := *b div 2 OD*;
c := *c*∗*a*; *b* := *b* − *1*
OD
{*c* = *A*^*B*}
⟨*proof*⟩

5.1.5 Factorial

lemma *factorial*: *VARS a b*
{*a=A*}
b := 1;
WHILE a > 0
INV {*fac A = b * fac a*}
*DO b := b*a*; *a := a − 1 OD*
{*b = fac A*}
⟨*proof*⟩

lemma *factorial-time*: *VARS a b t*
{*a=A & t=0*}
b := 1; *t := t+1*;
WHILE a > 0
INV {*fac A = b * fac a & a ≤ A & t = 2*(A−a)+1*}
*DO b := b*a*; *t := t+1*; *a := a − 1*; *t := t+1 OD*
{*b = fac A & t = 2*A + 1*}
⟨*proof*⟩

lemma [*simp*]: *1 ≤ i ⟹ fac (i − Suc 0) * i = fac i*
⟨*proof*⟩

lemma *factorial2*: *VARS i f*
{*True*}
i := (1::nat); *f := 1*;
WHILE i <= n INV {*f = fac(i − 1) & 1 <= i & i <= n+1*}
*DO f := f*i*; *i := i+1 OD*
{*f = fac n*}
⟨*proof*⟩

lemma *factorial2-time*: *VARS i f t*
{*t=0*}
i := (1::nat); *t := t+1*; *f := 1*; *t := t+1*;
WHILE i ≤ n INV {*f = fac(i − 1) & 1 ≤ i & i ≤ n+1 & t = 2*(i−1)+2*}
*DO f := f*i*; *t := t+1*; *i := i+1*; *t := t+1 OD*
{*f = fac n & t = 2*n+2*}
⟨*proof*⟩

5.1.6 Square root

lemma *sqrt*: *VARS r x*
{*True*}
r := (0::nat);
WHILE (r+1)(r+1) <= X*
INV {*r*r ≤ X*}
DO r := r+1 OD
{*r*r <= X & X < (r+1)*(r+1)*}
⟨*proof*⟩

lemma *sqrt-time*: *VARS r t*
{*t=0*}
r := (*0*::*nat*); *t* := *t+1*;
WHILE (*r+1*)∗(*r+1*) <= *X*
INV {*r∗r* ≤ *X* & *t* = *r+1*}
DO r := *r+1*; *t* := *t+1 OD*
{*r∗r* <= *X* & *X* < (*r+1*)∗(*r+1*) & (*t−1*)∗(*t−1*) ≤ *X*}
⟨*proof*⟩
lemma *sqrt-without-multiplication*: *VARS u w r*
{*x=X*}
u := *1*; *w* := *1*; *r* := (*0*::*nat*);
WHILE w <= *X*
INV {*u* = *r+r+1* & *w* = (*r+1*)∗(*r+1*) & *r∗r* <= *X*}
DO r := *r* + *1*; *w* := *w* + *u* + *2*; *u* := *u* + *2 OD*
{*r∗r* <= *X* & *X* < (*r+1*)∗(*r+1*)}
⟨*proof*⟩

5.2 Lists

lemma *imperative-reverse*: *VARS y x*
{*x=X*}
y:=[];
WHILE x ~= []
INV {*rev*(*x*)@*y* = *rev*(*X*)}
DO y := (*hd x* # *y*); *x* := *tl x OD*
{*y=rev*(*X*)}
⟨*proof*⟩

lemma *imperative-reverse-time*: *VARS y x t*
{*x=X* & *t=0*}
y:=[]; *t* := *t+1*;
WHILE x ~= []
INV {*rev*(*x*)@*y* = *rev*(*X*) & *t* = *2∗*(*length y*) + *1*}
DO y := (*hd x* # *y*); *t* := *t+1*; *x* := *tl x*; *t* := *t+1 OD*
{*y=rev*(*X*) & *t* = *2∗length X* + *1*}
⟨*proof*⟩

lemma *imperative-append*: *VARS x y*
{*x=X* & *y=Y*}
x := *rev*(*x*);
WHILE x~=[]
INV {*rev*(*x*)@*y* = *X*@*Y*}
DO y := (*hd x* # *y*);
x := *tl x*
OD
{*y* = *X*@*Y*}
⟨*proof*⟩

lemma *imperative-append-time-no-rev*: *VARS x y t*

$\{x{=}X \ \&\ y{=}Y\}$
$x := rev(x);\ t := 0;$
$WHILE\ x^{\sim}{=}[]$
$INV\ \{rev(x)@y = X@Y\ \&\ length\ x \leq length\ X\ \&\ t = 2 * (length\ X - length\ x)\}$
$DO\ y := (hd\ x\ \#\ y);\ t := t{+}1;$
$\quad x := tl\ x;\ t := t{+}1$
OD
$\{y = X@Y\ \&\ t = 2 * length\ X\}$
⟨*proof*⟩

5.3 Arrays

5.3.1 Search for a key

lemma *zero-search*: $VARS\ A\ i$
$\{True\}$
$i := 0;$
$WHILE\ i < length\ A\ \&\ A!i \neq key$
$INV\ \{\forall j.\ j{<}i \dashrightarrow A!j \neq key\}$
$DO\ i := i{+}1\ OD$
$\{(i < length\ A \dashrightarrow A!i = key)\ \&$
$\ (i = length\ A \dashrightarrow (\forall j.\ j < length\ A \longrightarrow A!j \neq key))\}$
⟨*proof*⟩

lemma *zero-search-time*: $VARS\ A\ i\ t$
$\{t{=}0\}$
$i := 0;\ t := t{+}1;$
$WHILE\ i < length\ A \wedge A!i \neq key$
$INV\ \{(\forall j.\ j{<}i \longrightarrow A!j \neq key) \wedge i \leq length\ A \wedge t = i{+}1\}$
$DO\ i := i{+}1;\ t := t{+}1\ OD$
$\{(i < length\ A \longrightarrow A!i = key) \wedge$
$\ (i = length\ A \longrightarrow (\forall j.\ j < length\ A \dashrightarrow A!j \neq key)) \wedge t \leq length\ A + 1\}$
⟨*proof*⟩

The *partition* procedure for quicksort.

- A is the array to be sorted (modelled as a list).
- Elements of A must be of class order to infer at the end that the elements between u and l are equal to pivot.

Ambiguity warnings of parser are due to := being used both for assignment and list update.

lemma *lem*: $m - Suc\ 0 < n \Longrightarrow m < Suc\ n$
⟨*proof*⟩

lemma *Partition*:
$[|\ leq == \lambda A\ i.\ \forall k.\ k{<}i \longrightarrow A!k \leq pivot;$
$\quad geq == \lambda A\ i.\ \forall k.\ i{<}k \wedge k{<}length\ A \longrightarrow pivot \leq A!k\ |] \Longrightarrow$

VARS A u l
{*0 < length*(*A*::(*'a*::*order*)*list*)}
l := *0*; *u* := *length A* − *Suc 0*;
WHILE l ≤ *u*
INV {*leq A l* ∧ *geq A u* ∧ *u*<*length A* ∧ *l*≤*length A*}
DO WHILE l < *length A* ∧ *A*!*l* ≤ *pivot*
INV {*leq A l* & *geq A u* ∧ *u*<*length A* ∧ *l*≤*length A*}
DO l := *l*+*1 OD*;
WHILE 0 < *u* & *pivot* ≤ *A*!*u*
INV {*leq A l* & *geq A u* ∧ *u*<*length A* ∧ *l*≤*length A*}
DO u := *u* − *1 OD*;
IF l ≤ *u THEN A* := *A*[*l* := *A*!*u*, *u* := *A*!*l*] *ELSE SKIP FI*
OD
{*leq A u* & (∀*k*. *u*<*k* ∧ *k*<*l* −−> *A*!*k* = *pivot*) ∧ *geq A l*}
— expand and delete abbreviations first
⟨*proof*⟩

end

6 Hoare Logic with an Abort statement for modelling run time errors

theory *Hoare-Logic-Abort*
imports *Hoare-Syntax Hoare-Tac*
begin

type-synonym *'a bexp* = *'a set*
type-synonym *'a assn* = *'a set*
type-synonym *'a var* = *'a* ⇒ *nat*

datatype *'a com* =
Basic 'a ⇒ *'a*
| *Abort*
| *Seq 'a com 'a com*
| *Cond 'a bexp 'a com 'a com*
| *While 'a bexp 'a com*

abbreviation *annskip* (*SKIP*) **where** *SKIP* == *Basic id*

type-synonym *'a sem* = *'a option* => *'a option* => *bool*

inductive *Sem* :: *'a com* ⇒ *'a sem*
where
Sem (*Basic f*) *None None*
| *Sem* (*Basic f*) (*Some s*) (*Some* (*f s*))
| *Sem Abort s None*
| *Sem c1 s s''* ⟹ *Sem c2 s'' s'* ⟹ *Sem* (*Seq c1 c2*) *s s'*
| *Sem* (*Cond b c1 c2*) *None None*

$| \; s \in b \Longrightarrow Sem\ c1\ (Some\ s)\ s' \Longrightarrow Sem\ (Cond\ b\ c1\ c2)\ (Some\ s)\ s'$
$| \; s \notin b \Longrightarrow Sem\ c2\ (Some\ s)\ s' \Longrightarrow Sem\ (Cond\ b\ c1\ c2)\ (Some\ s)\ s'$
$| \; Sem\ (While\ b\ c)\ None\ None$
$| \; s \notin b \Longrightarrow Sem\ (While\ b\ c)\ (Some\ s)\ (Some\ s)$
$| \; s \in b \Longrightarrow Sem\ c\ (Some\ s)\ s'' \Longrightarrow Sem\ (While\ b\ c)\ s''\ s' \Longrightarrow$
$Sem\ (While\ b\ c)\ (Some\ s)\ s'$

inductive-cases [*elim*!]:
$Sem\ (Basic\ f)\ s\ s'\ Sem\ (Seq\ c1\ c2)\ s\ s'$
$Sem\ (Cond\ b\ c1\ c2)\ s\ s'$

lemma *Sem-deterministic*:
assumes $Sem\ c\ s\ s1$
and $Sem\ c\ s\ s2$
shows $s1 = s2$
⟨*proof*⟩

definition $Valid :: 'a\ bexp \Rightarrow 'a\ com \Rightarrow 'a\ anno \Rightarrow 'a\ bexp \Rightarrow bool$
where $Valid\ p\ c\ a\ q \equiv \forall s\ s'.\ Sem\ c\ s\ s' \longrightarrow s \in Some\ `\ p \longrightarrow s' \in Some\ `\ q$

definition $ValidTC :: 'a\ bexp \Rightarrow 'a\ com \Rightarrow 'a\ anno \Rightarrow 'a\ bexp \Rightarrow bool$
where $ValidTC\ p\ c\ a\ q \equiv \forall s\ .\ s \in p \longrightarrow (\exists t\ .\ Sem\ c\ (Some\ s)\ (Some\ t) \wedge t \in q)$

lemma *tc-implies-pc*:
$ValidTC\ p\ c\ a\ q \Longrightarrow Valid\ p\ c\ a\ q$
⟨*proof*⟩

lemma *tc-extract-function*:
$ValidTC\ p\ c\ a\ q \Longrightarrow \exists f\ .\ \forall s\ .\ s \in p \longrightarrow f\ s \in q$
⟨*proof*⟩

The proof rules for partial correctness

lemma *SkipRule*: $p \subseteq q \Longrightarrow Valid\ p\ (Basic\ id)\ a\ q$
⟨*proof*⟩

lemma *BasicRule*: $p \subseteq \{s.\ f\ s \in q\} \Longrightarrow Valid\ p\ (Basic\ f)\ a\ q$
⟨*proof*⟩

lemma *SeqRule*: $Valid\ P\ c1\ a1\ Q \Longrightarrow Valid\ Q\ c2\ a2\ R \Longrightarrow Valid\ P\ (Seq\ c1\ c2)\ (Aseq\ a1\ a2)\ R$
⟨*proof*⟩

lemma *CondRule*:
$p \subseteq \{s.\ (s \in b \longrightarrow s \in w) \wedge (s \notin b \longrightarrow s \in w')\}$
$\Longrightarrow Valid\ w\ c1\ a1\ q \Longrightarrow Valid\ w'\ c2\ a2\ q \Longrightarrow Valid\ p\ (Cond\ b\ c1\ c2)\ (Acond\ a1\ a2)\ q$
⟨*proof*⟩

lemma *While-aux*:
assumes *Sem* (*While b c*) *s s′*
shows ∀ *s s′*. *Sem c s s′* ⟶ *s* ∈ *Some* ‘ (*I* ∩ *b*) ⟶ *s′* ∈ *Some* ‘ *I* ⟹
s ∈ *Some* ‘ *I* ⟹ *s′* ∈ *Some* ‘ (*I* ∩ −*b*)
⟨*proof*⟩

lemma *WhileRule*:
p ⊆ *i* ⟹ *Valid* (*i* ∩ *b*) *c* (*A* 0) *i* ⟹ *i* ∩ (−*b*) ⊆ *q* ⟹ *Valid p* (*While b c*)
(*Awhile i v A*) *q*
⟨*proof*⟩

lemma *AbortRule*: *p* ⊆ {*s*. *False*} ⟹ *Valid p Abort a q*
⟨*proof*⟩

The proof rules for total correctness

lemma *SkipRuleTC*:
assumes *p* ⊆ *q*
shows *ValidTC p* (*Basic id*) *a q*
⟨*proof*⟩

lemma *BasicRuleTC*:
assumes *p* ⊆ {*s*. *f s* ∈ *q*}
shows *ValidTC p* (*Basic f*) *a q*
⟨*proof*⟩

lemma *SeqRuleTC*:
assumes *ValidTC p c1 a1 q*
and *ValidTC q c2 a2 r*
shows *ValidTC p* (*Seq c1 c2*) (*Aseq a1 a2*) *r*
⟨*proof*⟩

lemma *CondRuleTC*:
assumes *p* ⊆ {*s*. (*s* ∈ *b* ⟶ *s* ∈ *w*) ∧ (*s* ∉ *b* ⟶ *s* ∈ *w′*)}
and *ValidTC w c1 a1 q*
and *ValidTC w′ c2 a2 q*
shows *ValidTC p* (*Cond b c1 c2*) (*Acons a1 a2*) *q*
⟨*proof*⟩

lemma *WhileRuleTC*:
assumes *p* ⊆ *i*
and ⋀*n*::*nat* . *ValidTC* (*i* ∩ *b* ∩ {*s* . *v s* = *n*}) *c* (*A n*) (*i* ∩ {*s* . *v s* < *n*})
and *i* ∩ *uminus b* ⊆ *q*
shows *ValidTC p* (*While b c*) (*Awhile i v A*) *q*
⟨*proof*⟩

6.1 Concrete syntax

⟨*ML*⟩
syntax
-guarded-com :: *bool* ⇒ *′a com* ⇒ *′a com* ((*2- →/ -*) *71*)

-array-update :: *'a list* ⇒ *nat* ⇒ *'a* ⇒ *'a com* (*(2-[-] :=/ -) [70, 65] 61*)
translations
P → *c* ⇌ *IF P THEN c ELSE CONST Abort FI*
a[*i*] := *v* ⇀ (*i* < *CONST length a*) → (*a* := *CONST list-update a i v*)
— reverse translation not possible because of duplicate *a*

Note: there is no special syntax for guarded array access. Thus you must write *j* < *length a* → *a*[*i*] := *a*!*j*.

6.2 Proof methods: VCG

declare *BasicRule* [*Hoare-Tac.BasicRule*]
and *SkipRule* [*Hoare-Tac.SkipRule*]
and *AbortRule* [*Hoare-Tac.AbortRule*]
and *SeqRule* [*Hoare-Tac.SeqRule*]
and *CondRule* [*Hoare-Tac.CondRule*]
and *WhileRule* [*Hoare-Tac.WhileRule*]

declare *BasicRuleTC* [*Hoare-Tac.BasicRuleTC*]
and *SkipRuleTC* [*Hoare-Tac.SkipRuleTC*]
and *SeqRuleTC* [*Hoare-Tac.SeqRuleTC*]
and *CondRuleTC* [*Hoare-Tac.CondRuleTC*]
and *WhileRuleTC* [*Hoare-Tac.WhileRuleTC*]

⟨*ML*⟩

end

7 Some small examples for programs that may abort

theory *ExamplesAbort*
imports *Hoare-Logic-Abort*
begin

lemma *VARS x y z*::*nat*
{*y* = *z* & *z* ≠ *0*} *z* ≠ *0* → *x* := *y div z* {*x* = *1*}
⟨*proof*⟩

lemma
VARS a i j
{*k* <= *length a* & *i* < *k* & *j* < *k*} *j* < *length a* → *a*[*i*] := *a*!*j* {*True*}
⟨*proof*⟩

lemma *VARS* (*a*::*int list*) *i*
{*True*}
i := *0*;
WHILE i < *length a*

INV {*i* <= *length a*}
DO a[*i*] := 7; *i* := *i*+1 *OD*
{*True*}
⟨*proof*⟩

end

8 Examples using Hoare Logic for Total Correctness

theory *ExamplesTC*
imports *Hoare-Logic*
begin

This theory demonstrates a few simple partial- and total-correctness proofs. The first example is taken from HOL/Hoare/Examples.thy written by N. Galm. We have added the invariant $m \leq a$.

lemma *multiply-by-add*: *VARS m s a b*
{*a*=*A* ∧ *b*=*B*}
m := *0*; *s* := *0*;
WHILE m≠*a*
INV {*s*=*m*∗*b* ∧ *a*=*A* ∧ *b*=*B* ∧ *m*≤*a*}
DO s := *s*+*b*; *m* := *m*+(*1*::*nat*) *OD*
{*s* = *A*∗*B*}
⟨*proof*⟩

Here is the total-correctness proof for the same program. It needs the additional invariant $m \leq a$.

lemma *multiply-by-add-tc*: *VARS m s a b*
[*a*=*A* ∧ *b*=*B*]
m := *0*; *s* := *0*;
WHILE m≠*a*
INV {*s*=*m*∗*b* ∧ *a*=*A* ∧ *b*=*B* ∧ *m*≤*a*}
VAR {*a*−*m*}
DO s := *s*+*b*; *m* := *m*+(*1*::*nat*) *OD*
[*s* = *A*∗*B*]
⟨*proof*⟩

Next, we prove partial correctness of a program that computes powers.

lemma *power*: *VARS* (*p*::*int*) *i*
{ *True* }
p := *1*;
i := *0*;
WHILE i < *n*
INV { *p* = *x*^*i* ∧ *i* ≤ *n* }
DO p := *p* ∗ *x*;
i := *i* + *1*
OD

{ $p = x\hat{}n$ }
⟨*proof*⟩

Here is its total-correctness proof.

lemma *power-tc*: *VARS* (p::*int*) i
[*True*]
$p := 1$;
$i := 0$;
WHILE $i < n$
INV { $p = x\hat{}i \wedge i \leq n$ }
VAR { $n - i$ }
DO $p := p * x$;
$i := i + 1$
OD
[$p = x\hat{}n$]
⟨*proof*⟩

The last example is again taken from HOL/Hoare/Examples.thy. We have modified it to integers so it requires precondition $0 \leq x$.

lemma *sqrt-tc*: *VARS* r
[$0 \leq (x$::*int*)]
$r := 0$;
WHILE $(r+1)*(r+1) <= x$
INV {$r*r \leq x$}
VAR { *nat* $(x-r)$}
DO $r := r+1$ *OD*
[$r*r \leq x \wedge x < (r+1)*(r+1)$]
⟨*proof*⟩

A total-correctness proof allows us to extract a function for further use. For every input satisfying the precondition the function returns an output satisfying the postcondition.

lemma *sqrt-exists*:
$0 \leq (x$::*int*) $\Longrightarrow \exists r'$. $r'*r' \leq x \wedge x < (r'+1)*(r'+1)$
⟨*proof*⟩

definition *sqrt* (x::*int*) $\equiv$ (*SOME* r' . $r'*r' \leq x \wedge x < (r'+1)*(r'+1)$)

lemma *sqrt-function*:
assumes $0 \leq (x$::*int*)
and $r' = sqrt\ x$
shows $r'*r' \leq x \wedge x < (r'+1)*(r'+1)$
⟨*proof*⟩

Nested loops!

lemma *VARS* (i::*nat*) j
[*True*]
WHILE $0 < i$
INV { *True* }

```
    VAR { z = i }
    DO i := i − 1; j := i;
       WHILE 0 < j
       INV { z = i+1 }
       VAR { j }
       DO j := j − 1 OD
    OD
  [ i ≤ 0 ]
  ⟨proof⟩

end
```

9 Alternative pointers

theory *Pointers0*
  imports *Hoare-Logic*
begin

9.1 References

class *ref* =
  fixes *Null* :: *'a*

9.2 Field access and update

syntax
  -fassign :: *'a*::*ref* => *id* => *'v* => *'s com*
   (*2*-^.- :=/ -) [*70*,*1000*,*65*] *61*)
  -faccess :: *'a*::*ref* => (*'a*::*ref* ⇒ *'v*) => *'v*
   (-^.- [*65*,*1000*] *65*)
translations
  p^.*f* := *e* => *f* := *CONST fun-upd f p e*
  p^.*f* => *f p*

An example due to Suzuki:

lemma *VARS v n*
  {*distinct*[*w*,*x*,*y*,*z*]}
  w^.*v* := (*1*::*int*); *w*^.*n* := *x*;
  x^.*v* := *2*; *x*^.*n* := *y*;
  y^.*v* := *3*; *y*^.*n* := *z*;
  z^.*v* := *4*; *x*^.*n* := *z*
  {*w*^.*n*^.*n*^.*v* = *4*}
⟨*proof*⟩

9.3 The heap

9.3.1 Paths in the heap

primrec *Path* :: (*'a*::*ref* ⇒ *'a*) ⇒ *'a* ⇒ *'a list* ⇒ *'a* ⇒ *bool*

where
  $Path\ h\ x\ []\ y = (x = y)$
| $Path\ h\ x\ (a\#as)\ y = (x \neq Null \wedge x = a \wedge Path\ h\ (h\ a)\ as\ y)$

lemma [*iff*]: $Path\ h\ Null\ xs\ y = (xs = [] \wedge y = Null)$
⟨*proof*⟩

lemma [*simp*]: $a \neq Null \Longrightarrow Path\ h\ a\ as\ z =$
 $(as = [] \wedge z = a\ \vee\ (\exists\, bs.\ as = a\#bs \wedge Path\ h\ (h\ a)\ bs\ z))$
⟨*proof*⟩

lemma [*simp*]: $\bigwedge x.\ Path\ f\ x\ (as@bs)\ z = (\exists\, y.\ Path\ f\ x\ as\ y \wedge Path\ f\ y\ bs\ z)$
⟨*proof*⟩

lemma [*simp*]: $\bigwedge x.\ u \notin set\ as \Longrightarrow Path\ (f(u := v))\ x\ as\ y = Path\ f\ x\ as\ y$
⟨*proof*⟩

9.3.2 Lists on the heap

Relational abstraction **definition** $List :: ('a::ref \Rightarrow 'a) \Rightarrow 'a \Rightarrow 'a\ list \Rightarrow bool$
  where $List\ h\ x\ as = Path\ h\ x\ as\ Null$

lemma [*simp*]: $List\ h\ x\ [] = (x = Null)$
⟨*proof*⟩

lemma [*simp*]: $List\ h\ x\ (a\#as) = (x \neq Null \wedge x = a \wedge List\ h\ (h\ a)\ as)$
⟨*proof*⟩

lemma [*simp*]: $List\ h\ Null\ as = (as = [])$
⟨*proof*⟩

lemma *List-Ref*[*simp*]:
 $a \neq Null \Longrightarrow List\ h\ a\ as = (\exists\, bs.\ as = a\#bs \wedge List\ h\ (h\ a)\ bs)$
⟨*proof*⟩

theorem *notin-List-update*[*simp*]:
 $\bigwedge x.\ a \notin set\ as \Longrightarrow List\ (h(a := y))\ x\ as = List\ h\ x\ as$
⟨*proof*⟩

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

lemma *List-unique*: $\bigwedge x\ bs.\ List\ h\ x\ as \Longrightarrow List\ h\ x\ bs \Longrightarrow as = bs$
⟨*proof*⟩

lemma *List-unique1*: $List\ h\ p\ as \Longrightarrow \exists!as.\ List\ h\ p\ as$
⟨*proof*⟩

lemma *List-app*: $\bigwedge x.\ List\ h\ x\ (as@bs) = (\exists\, y.\ Path\ h\ x\ as\ y \wedge List\ h\ y\ bs)$
⟨*proof*⟩

lemma *List-hd-not-in-tl*[*simp*]: $List\ h\ (h\ a)\ as \Longrightarrow a \notin set\ as$
⟨*proof*⟩

lemma *List-distinct*[*simp*]: $\bigwedge x.\ List\ h\ x\ as \Longrightarrow distinct\ as$
⟨*proof*⟩

9.3.3 Functional abstraction

definition *islist* :: $('a{::}ref \Rightarrow 'a) \Rightarrow 'a \Rightarrow bool$
where $islist\ h\ p \longleftrightarrow (\exists\, as.\ List\ h\ p\ as)$

definition *list* :: $('a{::}ref \Rightarrow 'a) \Rightarrow 'a \Rightarrow 'a\ list$
where $list\ h\ p = (SOME\ as.\ List\ h\ p\ as)$

lemma *List-conv-islist-list*: $List\ h\ p\ as = (islist\ h\ p \wedge as = list\ h\ p)$
⟨*proof*⟩

lemma [*simp*]: $islist\ h\ Null$
⟨*proof*⟩

lemma [*simp*]: $a \neq Null \Longrightarrow islist\ h\ a = islist\ h\ (h\ a)$
⟨*proof*⟩

lemma [*simp*]: $list\ h\ Null = []$
⟨*proof*⟩

lemma *list-Ref-conv*[*simp*]:
$[\![\ a \neq Null;\ islist\ h\ (h\ a)\ ]\!] \Longrightarrow list\ h\ a = a\ \#\ list\ h\ (h\ a)$
⟨*proof*⟩

lemma [*simp*]: $islist\ h\ (h\ a) \Longrightarrow a \notin set(list\ h\ (h\ a))$
⟨*proof*⟩

lemma *list-upd-conv*[*simp*]:
$islist\ h\ p \Longrightarrow y \notin set(list\ h\ p) \Longrightarrow list\ (h(y := q))\ p = list\ h\ p$
⟨*proof*⟩

lemma *islist-upd*[*simp*]:
$islist\ h\ p \Longrightarrow y \notin set(list\ h\ p) \Longrightarrow islist\ (h(y := q))\ p$
⟨*proof*⟩

9.4 Verifications

9.4.1 List reversal

A short but unreadable proof:

lemma *VARS tl p q r*

$\{List\ tl\ p\ Ps \wedge List\ tl\ q\ Qs \wedge set\ Ps \cap set\ Qs = \{\}\}$
WHILE $p \neq Null$
INV $\{\exists ps\ qs.\ List\ tl\ p\ ps \wedge List\ tl\ q\ qs \wedge set\ ps \cap set\ qs = \{\} \wedge$
$rev\ ps\ @\ qs = rev\ Ps\ @\ Qs\}$
DO $r := p;\ p := p^{\frown}.tl;\ r^{\frown}.tl := q;\ q := r$ *OD*
$\{List\ tl\ q\ (rev\ Ps\ @\ Qs)\}$
⟨*proof*⟩

A longer readable version:

lemma *VARS tl p q r*
$\{List\ tl\ p\ Ps \wedge List\ tl\ q\ Qs \wedge set\ Ps \cap set\ Qs = \{\}\}$
WHILE $p \neq Null$
INV $\{\exists ps\ qs.\ List\ tl\ p\ ps \wedge List\ tl\ q\ qs \wedge set\ ps \cap set\ qs = \{\} \wedge$
$rev\ ps\ @\ qs = rev\ Ps\ @\ Qs\}$
DO $r := p;\ p := p^{\frown}.tl;\ r^{\frown}.tl := q;\ q := r$ *OD*
$\{List\ tl\ q\ (rev\ Ps\ @\ Qs)\}$
⟨*proof*⟩

Finaly, the functional version. A bit more verbose, but automatic!

lemma *VARS tl p q r*
$\{islist\ tl\ p \wedge islist\ tl\ q \wedge$
$Ps = list\ tl\ p \wedge Qs = list\ tl\ q \wedge set\ Ps \cap set\ Qs = \{\}\}$
WHILE $p \neq Null$
INV $\{islist\ tl\ p \wedge islist\ tl\ q \wedge$
$set(list\ tl\ p) \cap set(list\ tl\ q) = \{\} \wedge$
$rev(list\ tl\ p)\ @\ (list\ tl\ q) = rev\ Ps\ @\ Qs\}$
DO $r := p;\ p := p^{\frown}.tl;\ r^{\frown}.tl := q;\ q := r$ *OD*
$\{islist\ tl\ q \wedge list\ tl\ q = rev\ Ps\ @\ Qs\}$
⟨*proof*⟩

9.4.2 Searching in a list

What follows is a sequence of successively more intelligent proofs that a simple loop finds an element in a linked list.

We start with a proof based on the *List* predicate. This means it only works for acyclic lists.

lemma *VARS tl p*
$\{List\ tl\ p\ Ps \wedge X \in set\ Ps\}$
WHILE $p \neq Null \wedge p \neq X$
INV $\{p \neq Null \wedge (\exists ps.\ List\ tl\ p\ ps \wedge X \in set\ ps)\}$
DO $p := p^{\frown}.tl$ *OD*
$\{p = X\}$
⟨*proof*⟩

Using *Path* instead of *List* generalizes the correctness statement to cyclic lists as well:

lemma *VARS tl p*
$\{Path\ tl\ p\ Ps\ X\}$

WHILE $p \neq Null \wedge p \neq X$
INV $\{\exists ps.\ Path\ tl\ p\ ps\ X\}$
DO $p := p\hat{}.tl$ *OD*
$\{p = X\}$
⟨*proof*⟩

Now it dawns on us that we do not need the list witness at all — it suffices to talk about reachability, i.e. we can use relations directly.

lemma *VARS tl p*
$\{(p,X) \in \{(x,y).\ y = tl\ x\ \&\ x \neq Null\}^*\}$
WHILE $p \neq Null \wedge p \neq X$
INV $\{(p,X) \in \{(x,y).\ y = tl\ x\ \&\ x \neq Null\}^*\}$
DO $p := p\hat{}.tl$ *OD*
$\{p = X\}$
⟨*proof*⟩

9.4.3 Merging two lists

This is still a bit rough, especially the proof.

fun *merge* :: *'a list* ∗ *'a list* ∗ (*'a* ⇒ *'a* ⇒ *bool*) ⇒ *'a list* **where**
merge(*x*#*xs*,*y*#*ys*,*f*) = (*if f x y then x* # *merge*(*xs*,*y*#*ys*,*f*)
else y # *merge*(*x*#*xs*,*ys*,*f*)) |
merge(*x*#*xs*,[],*f*) = *x* # *merge*(*xs*,[],*f*) |
merge([],*y*#*ys*,*f*) = *y* # *merge*([],*ys*,*f*) |
merge([],[],*f*) = []

lemma *imp-disjCL*: $(P|Q \longrightarrow R) = ((P \longrightarrow R) \wedge (\sim P \longrightarrow Q \longrightarrow R))$
⟨*proof*⟩

declare *disj-not1*[*simp del*] *imp-disjL*[*simp del*] *imp-disjCL*[*simp*]

lemma *VARS hd tl p q r s*
$\{List\ tl\ p\ Ps \wedge List\ tl\ q\ Qs \wedge set\ Ps \cap set\ Qs = \{\} \wedge$
$(p \neq Null \vee q \neq Null)\}$
IF if $q = Null$ *then True else* $p \sim= Null\ \&\ p\hat{}.hd \leq q\hat{}.hd$
THEN $r := p$; $p := p\hat{}.tl$ *ELSE* $r := q$; $q := q\hat{}.tl$ *FI*;
$s := r$;
WHILE $p \neq Null \vee q \neq Null$
INV $\{\exists rs\ ps\ qs.\ Path\ tl\ r\ rs\ s \wedge List\ tl\ p\ ps \wedge List\ tl\ q\ qs \wedge$
$distinct(s\ \#\ ps\ @\ qs\ @\ rs) \wedge s \neq Null \wedge$
$merge(Ps,Qs,\lambda x\ y.\ hd\ x \leq hd\ y) =$
$rs\ @\ s\ \#\ merge(ps,qs,\lambda x\ y.\ hd\ x \leq hd\ y) \wedge$
$(tl\ s = p \vee tl\ s = q)\}$
DO IF if $q = Null$ *then True else* $p \neq Null \wedge p\hat{}.hd \leq q\hat{}.hd$
THEN $s\hat{}.tl := p$; $p := p\hat{}.tl$ *ELSE* $s\hat{}.tl := q$; $q := q\hat{}.tl$ *FI*;
$s := s\hat{}.tl$
OD
$\{List\ tl\ r\ (merge(Ps,Qs,\lambda x\ y.\ hd\ x \leq hd\ y))\}$
⟨*proof*⟩

9.4.4 Storage allocation

definition *new* :: *'a set* ⇒ *'a*::*ref*
  where *new A* = (*SOME a*. *a* ∉ *A* & *a* ≠ *Null*)

lemma *new-notin*:
⟦ ~*finite*(*UNIV*::(*'a*::*ref*)*set*); *finite*(*A*::*'a set*); *B* ⊆ *A* ⟧ ⟹
  new (*A*) ∉ *B* & *new A* ≠ *Null*
⟨*proof*⟩

lemma ~*finite*(*UNIV*::(*'a*::*ref*)*set*) ⟹
  VARS xs elem next alloc p q
  {*Xs* = *xs* ∧ *p* = (*Null*::*'a*)}
  WHILE xs ≠ []
  INV {*islist next p* ∧ *set*(*list next p*) ⊆ *set alloc* ∧
      map elem (*rev*(*list next p*)) @ *xs* = *Xs*}
  DO q := *new*(*set alloc*); *alloc* := *q*#*alloc*;
    q^.*next* := *p*; *q*^.*elem* := *hd xs*; *xs* := *tl xs*; *p* := *q*
  OD
  {*islist next p* ∧ *map elem* (*rev*(*list next p*)) = *Xs*}
⟨*proof*⟩

end

10 Pointers, heaps and heap abstractions

See the paper by Mehta and Nipkow.

theory *Heap*
  imports *Main*
begin

10.1 References

datatype *'a ref* = *Null* | *Ref 'a*

lemma *not-Null-eq* [*iff*]: (*x* ≠ *Null*) = (∃ *y*. *x* = *Ref y*)
  ⟨*proof*⟩

lemma *not-Ref-eq* [*iff*]: (∀ *y*. *x* ≠ *Ref y*) = (*x* = *Null*)
  ⟨*proof*⟩

primrec *addr* :: *'a ref* ⇒ *'a* **where**
  addr (*Ref a*) = *a*

10.2 The heap

10.2.1 Paths in the heap

primrec *Path* :: (*'a* ⇒ *'a ref*) ⇒ *'a ref* ⇒ *'a list* ⇒ *'a ref* ⇒ *bool* **where**
  Path h x [] *y* ⟷ *x* = *y*
| *Path h x* (*a*#*as*) *y* ⟷ *x* = *Ref a* ∧ *Path h* (*h a*) *as y*

lemma [*iff*]: *Path h Null xs y* = (*xs* = [] ∧ *y* = *Null*)
⟨*proof*⟩

lemma [*simp*]: *Path h* (*Ref a*) *as z* =
 (*as* = [] ∧ *z* = *Ref a* ∨ (∃ *bs*. *as* = *a*#*bs* ∧ *Path h* (*h a*) *bs z*))
⟨*proof*⟩

lemma [*simp*]: ⋀*x*. *Path f x* (*as*@*bs*) *z* = (∃ *y*. *Path f x as y* ∧ *Path f y bs z*)
⟨*proof*⟩

lemma *Path-upd*[*simp*]:
⋀*x*. *u* ∉ *set as* ⟹ *Path* (*f*(*u* := *v*)) *x as y* = *Path f x as y*
⟨*proof*⟩

lemma *Path-snoc*:
 Path (*f*(*a* := *q*)) *p as* (*Ref a*) ⟹ *Path* (*f*(*a* := *q*)) *p* (*as* @ [*a*]) *q*
⟨*proof*⟩

10.2.2 Non-repeating paths

definition *distPath* :: (*'a* ⇒ *'a ref*) ⇒ *'a ref* ⇒ *'a list* ⇒ *'a ref* ⇒ *bool*
  where *distPath h x as y* ⟷ *Path h x as y* ∧ *distinct as*

The term *distPath h x as y* expresses the fact that a non-repeating path *as* connects location x to location y by means of the h field. In the case where $x = y$, and there is a cycle from x to itself, *as* can be both [] and the non-repeating list of nodes in the cycle.

lemma *neq-dP*: *p* ≠ *q* ⟹ *Path h p Ps q* ⟹ *distinct Ps* ⟹
 ∃ *a Qs*. *p* = *Ref a* ∧ *Ps* = *a*#*Qs* ∧ *a* ∉ *set Qs*
⟨*proof*⟩

lemma *neq-dP-disp*: ⟦ *p* ≠ *q*; *distPath h p Ps q* ⟧ ⟹
 ∃ *a Qs*. *p* = *Ref a* ∧ *Ps* = *a*#*Qs* ∧ *a* ∉ *set Qs*
⟨*proof*⟩

10.2.3 Lists on the heap

Relational abstraction **definition** *List* :: (*'a* ⇒ *'a ref*) ⇒ *'a ref* ⇒ *'a list* ⇒ *bool*
  where *List h x as* = *Path h x as Null*

lemma [*simp*]: *List h x* [] = (*x* = *Null*)
⟨*proof*⟩

lemma [*simp*]: *List h x* (*a*#*as*) = (*x* = *Ref a* ∧ *List h* (*h a*) *as*)
⟨*proof*⟩

lemma [*simp*]: *List h Null as* = (*as* = [])
⟨*proof*⟩

lemma *List-Ref*[*simp*]: *List h* (*Ref a*) *as* = (∃ *bs*. *as* = *a*#*bs* ∧ *List h* (*h a*) *bs*)
⟨*proof*⟩

theorem *notin-List-update*[*simp*]:
⋀*x*. *a* ∉ *set as* ⟹ *List* (*h*(*a* := *y*)) *x as* = *List h x as*
⟨*proof*⟩

lemma *List-unique*: ⋀*x bs*. *List h x as* ⟹ *List h x bs* ⟹ *as* = *bs*
⟨*proof*⟩

lemma *List-unique1*: *List h p as* ⟹ ∃!*as*. *List h p as*
⟨*proof*⟩

lemma *List-app*: ⋀*x*. *List h x* (*as*@*bs*) = (∃ *y*. *Path h x as y* ∧ *List h y bs*)
⟨*proof*⟩

lemma *List-hd-not-in-tl*[*simp*]: *List h* (*h a*) *as* ⟹ *a* ∉ *set as*
⟨*proof*⟩

lemma *List-distinct*[*simp*]: ⋀*x*. *List h x as* ⟹ *distinct as*
⟨*proof*⟩

lemma *Path-is-List*:
⟦*Path h b Ps* (*Ref a*); *a* ∉ *set Ps*⟧ ⟹ *List* (*h*(*a* := *Null*)) *b* (*Ps* @ [*a*])
⟨*proof*⟩

10.2.4 Functional abstraction

definition *islist* :: (′*a* ⇒ ′*a ref*) ⇒ ′*a ref* ⇒ *bool*
where *islist h p* ⟷ (∃ *as*. *List h p as*)

definition *list* :: (′*a* ⇒ ′*a ref*) ⇒ ′*a ref* ⇒ ′*a list*
where *list h p* = (*SOME as*. *List h p as*)

lemma *List-conv-islist-list*: *List h p as* = (*islist h p* ∧ *as* = *list h p*)
⟨*proof*⟩

lemma [*simp*]: *islist h Null*
⟨*proof*⟩

lemma [*simp*]: *islist h* (*Ref a*) = *islist h* (*h a*)
⟨*proof*⟩

lemma [*simp*]: *list h Null* = []
⟨*proof*⟩

lemma *list-Ref-conv*[*simp*]:
islist h (*h a*) ⟹ *list h* (*Ref a*) = *a* # *list h* (*h a*)
⟨*proof*⟩

lemma [*simp*]: *islist h* (*h a*) ⟹ *a* ∉ *set*(*list h* (*h a*))
⟨*proof*⟩

lemma *list-upd-conv*[*simp*]:
islist h p ⟹ *y* ∉ *set*(*list h p*) ⟹ *list* (*h*(*y* := *q*)) *p* = *list h p*
⟨*proof*⟩

lemma *islist-upd*[*simp*]:
islist h p ⟹ *y* ∉ *set*(*list h p*) ⟹ *islist* (*h*(*y* := *q*)) *p*
⟨*proof*⟩

end

11 Heap syntax

theory *HeapSyntax*
imports *Hoare-Logic Heap*
begin

11.1 Field access and update

syntax
-refupdate :: ('*a* ⇒ '*b*) ⇒ '*a ref* ⇒ '*b* ⇒ ('*a* ⇒ '*b*)
(-/'((- → -)') [*1000*,*0*] *900*)
-fassign :: '*a ref* => *id* => '*v* => '*s com*
((*2*-^.- :=/ -) [*70*,*1000*,*65*] *61*)
-faccess :: '*a ref* => ('*a ref* ⇒ '*v*) => '*v*
(-^.- [*65*,*1000*] *65*)
translations
f(*r* → *v*) == *f*(*CONST addr r* := *v*)
p^.*f* := *e* => *f* := *f*(*p* → *e*)
p^.*f* => *f*(*CONST addr p*)

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

An example due to Suzuki:

lemma *VARS v n*
{*w* = *Ref w0* & *x* = *Ref x0* & *y* = *Ref y0* & *z* = *Ref z0* &

$distinct[w0,x0,y0,z0]\}$
$w\hat{}.v := (1::int);\ w\hat{}.n := x;$
$x\hat{}.v := 2;\ x\hat{}.n := y;$
$y\hat{}.v := 3;\ y\hat{}.n := z;$
$z\hat{}.v := 4;\ x\hat{}.n := z$
$\{w\hat{}.n\hat{}.n\hat{}.v = 4\}$
⟨*proof*⟩

end

12 Examples of verifications of pointer programs

theory *Pointer-Examples*
imports *HeapSyntax*
begin

axiomatization where *unproven*: *PROP A*

12.1 Verifications

12.1.1 List reversal

A short but unreadable proof:

lemma *VARS tl p q r*
$\{List\ tl\ p\ Ps \wedge List\ tl\ q\ Qs \wedge set\ Ps \cap set\ Qs = \{\}\}$
WHILE $p \neq Null$
INV $\{\exists ps\ qs.\ List\ tl\ p\ ps \wedge List\ tl\ q\ qs \wedge set\ ps \cap set\ qs = \{\} \wedge$
$rev\ ps\ @\ qs = rev\ Ps\ @\ Qs\}$
DO $r := p;\ p := p\hat{}.tl;\ r\hat{}.tl := q;\ q := r$ *OD*
$\{List\ tl\ q\ (rev\ Ps\ @\ Qs)\}$
⟨*proof*⟩

And now with ghost variables *ps* and *qs*. Even "more automatic".

lemma *VARS next p ps q qs r*
$\{List\ next\ p\ Ps \wedge List\ next\ q\ Qs \wedge set\ Ps \cap set\ Qs = \{\} \wedge$
$ps = Ps \wedge qs = Qs\}$
WHILE $p \neq Null$
INV $\{List\ next\ p\ ps \wedge List\ next\ q\ qs \wedge set\ ps \cap set\ qs = \{\} \wedge$
$rev\ ps\ @\ qs = rev\ Ps\ @\ Qs\}$
DO $r := p;\ p := p\hat{}.next;\ r\hat{}.next := q;\ q := r;$
$qs := (hd\ ps)\ \#\ qs;\ ps := tl\ ps$ *OD*
$\{List\ next\ q\ (rev\ Ps\ @\ Qs)\}$
⟨*proof*⟩

A longer readable version:

lemma *VARS tl p q r*
$\{List\ tl\ p\ Ps \wedge List\ tl\ q\ Qs \wedge set\ Ps \cap set\ Qs = \{\}\}$
WHILE $p \neq Null$
INV $\{\exists ps\ qs.\ List\ tl\ p\ ps \wedge List\ tl\ q\ qs \wedge set\ ps \cap set\ qs = \{\} \wedge$

$rev\ ps\ @\ qs = rev\ Ps\ @\ Qs\}$
$DO\ r := p;\ p := p\hat{}.tl;\ r\hat{}.tl := q;\ q := r\ OD$
$\{List\ tl\ q\ (rev\ Ps\ @\ Qs)\}$
⟨*proof*⟩

Finaly, the functional version. A bit more verbose, but automatic!

lemma *VARS tl p q r*
$\{islist\ tl\ p \wedge islist\ tl\ q \wedge$
$Ps = list\ tl\ p \wedge Qs = list\ tl\ q \wedge set\ Ps \cap set\ Qs = \{\}\}$
$WHILE\ p \neq Null$
$INV\ \{islist\ tl\ p \wedge islist\ tl\ q \wedge$
$set(list\ tl\ p) \cap set(list\ tl\ q) = \{\} \wedge$
$rev(list\ tl\ p)\ @\ (list\ tl\ q) = rev\ Ps\ @\ Qs\}$
$DO\ r := p;\ p := p\hat{}.tl;\ r\hat{}.tl := q;\ q := r\ OD$
$\{islist\ tl\ q \wedge list\ tl\ q = rev\ Ps\ @\ Qs\}$
⟨*proof*⟩

12.1.2 Searching in a list

What follows is a sequence of successively more intelligent proofs that a simple loop finds an element in a linked list.

We start with a proof based on the *List* predicate. This means it only works for acyclic lists.

lemma *VARS tl p*
$\{List\ tl\ p\ Ps \wedge X \in set\ Ps\}$
$WHILE\ p \neq Null \wedge p \neq Ref\ X$
$INV\ \{\exists ps.\ List\ tl\ p\ ps \wedge X \in set\ ps\}$
$DO\ p := p\hat{}.tl\ OD$
$\{p = Ref\ X\}$
⟨*proof*⟩

Using *Path* instead of *List* generalizes the correctness statement to cyclic lists as well:

lemma *VARS tl p*
$\{Path\ tl\ p\ Ps\ X\}$
$WHILE\ p \neq Null \wedge p \neq X$
$INV\ \{\exists ps.\ Path\ tl\ p\ ps\ X\}$
$DO\ p := p\hat{}.tl\ OD$
$\{p = X\}$
⟨*proof*⟩

Now it dawns on us that we do not need the list witness at all — it suffices to talk about reachability, i.e. we can use relations directly. The first version uses a relation on *'a ref*:

lemma *VARS tl p*
$\{(p,X) \in \{(Ref\ x, tl\ x)\ |x.\ True\}^*\}$
$WHILE\ p \neq Null \wedge p \neq X$
$INV\ \{(p,X) \in \{(Ref\ x, tl\ x)\ |x.\ True\}^*\}$

DO $p := p^{\frown}.tl$ *OD*
$\{p = X\}$
⟨*proof*⟩

Finally, a version based on a relation on type $'a$:

lemma *VARS tl p*
$\{p \neq Null \wedge (addr\ p,X) \in \{(x,y).\ tl\ x = Ref\ y\}^*\}$
WHILE $p \neq Null \wedge p \neq Ref\ X$
INV $\{p \neq Null \wedge (addr\ p,X) \in \{(x,y).\ tl\ x = Ref\ y\}^*\}$
DO $p := p^{\frown}.tl$ *OD*
$\{p = Ref\ X\}$
⟨*proof*⟩

12.1.3 Splicing two lists

lemma *VARS tl p q pp qq*
$\{List\ tl\ p\ Ps \wedge List\ tl\ q\ Qs \wedge set\ Ps \cap set\ Qs = \{\} \wedge size\ Qs \leq size\ Ps\}$
$pp := p$;
WHILE $q \neq Null$
INV $\{\exists as\ bs\ qs.$
$distinct\ as \wedge Path\ tl\ p\ as\ pp \wedge List\ tl\ pp\ bs \wedge List\ tl\ q\ qs \wedge$
$set\ bs \cap set\ qs = \{\} \wedge set\ as \cap (set\ bs \cup set\ qs) = \{\} \wedge$
$size\ qs \leq size\ bs \wedge splice\ Ps\ Qs = as\ @\ splice\ bs\ qs\}$
DO $qq := q^{\frown}.tl$; $q^{\frown}.tl := pp^{\frown}.tl$; $pp^{\frown}.tl := q$; $pp := q^{\frown}.tl$; $q := qq$ *OD*
$\{List\ tl\ p\ (splice\ Ps\ Qs)\}$
⟨*proof*⟩

12.1.4 Merging two lists

This is still a bit rough, especially the proof.

definition *cor* :: *bool* ⇒ *bool* ⇒ *bool*
where $cor\ P\ Q \longleftrightarrow (if\ P\ then\ True\ else\ Q)$

definition *cand* :: *bool* ⇒ *bool* ⇒ *bool*
where $cand\ P\ Q \longleftrightarrow (if\ P\ then\ Q\ else\ False)$

fun *merge* :: $'a\ list * 'a\ list * ('a \Rightarrow 'a \Rightarrow bool) \Rightarrow 'a\ list$
where
$merge(x\#xs,y\#ys,f) = (if\ f\ x\ y\ then\ x\ \#\ merge(xs,y\#ys,f)$
$\qquad\qquad\qquad\qquad\qquad else\ y\ \#\ merge(x\#xs,ys,f))$
$|\ merge(x\#xs,[],f) = x\ \#\ merge(xs,[],f)$
$|\ merge([],y\#ys,f) = y\ \#\ merge([],ys,f)$
$|\ merge([],[],f) = []$

Simplifies the proof a little:

lemma [*simp*]: $(\{\} = insert\ a\ A \cap B) = (a \notin B\ \&\ \{\} = A \cap B)$
⟨*proof*⟩
lemma [*simp*]: $(\{\} = A \cap insert\ b\ B) = (b \notin A\ \&\ \{\} = A \cap B)$
⟨*proof*⟩

lemma [*simp*]: $(\{\} = A \cap (B \cup C)) = (\{\} = A \cap B \;\&\; \{\} = A \cap C)$
⟨*proof*⟩

lemma *VARS hd tl p q r s*
{*List tl p Ps* ∧ *List tl q Qs* ∧ *set Ps* ∩ *set Qs* = {} ∧
(*p* ≠ *Null* ∨ *q* ≠ *Null*)}
IF cor (*q* = *Null*) (*cand* (*p* ≠ *Null*) (*p*^.*hd* ≤ *q*^.*hd*))
THEN r := *p*; *p* := *p*^.*tl ELSE r* := *q*; *q* := *q*^.*tl FI*;
s := *r*;
WHILE p ≠ *Null* ∨ *q* ≠ *Null*
INV {∃ *rs ps qs a. Path tl r rs s* ∧ *List tl p ps* ∧ *List tl q qs* ∧
distinct(*a* # *ps* @ *qs* @ *rs*) ∧ *s* = *Ref a* ∧
merge(*Ps*,*Qs*,λ*x y. hd x* ≤ *hd y*) =
rs @ *a* # *merge*(*ps*,*qs*,λ*x y. hd x* ≤ *hd y*) ∧
(*tl a* = *p* ∨ *tl a* = *q*)}
DO IF cor (*q* = *Null*) (*cand* (*p* ≠ *Null*) (*p*^.*hd* ≤ *q*^.*hd*))
THEN s^.*tl* := *p*; *p* := *p*^.*tl ELSE s*^.*tl* := *q*; *q* := *q*^.*tl FI*;
s := *s*^.*tl*
OD
{*List tl r* (*merge*(*Ps*,*Qs*,λ*x y. hd x* ≤ *hd y*))}
⟨*proof*⟩

And now with ghost variables:

lemma *VARS elem next p q r s ps qs rs a*
{*List next p Ps* ∧ *List next q Qs* ∧ *set Ps* ∩ *set Qs* = {} ∧
(*p* ≠ *Null* ∨ *q* ≠ *Null*) ∧ *ps* = *Ps* ∧ *qs* = *Qs*}
IF cor (*q* = *Null*) (*cand* (*p* ≠ *Null*) (*p*^.*elem* ≤ *q*^.*elem*))
THEN r := *p*; *p* := *p*^.*next*; *ps* := *tl ps*
ELSE r := *q*; *q* := *q*^.*next*; *qs* := *tl qs FI*;
s := *r*; *rs* := []; *a* := *addr s*;
WHILE p ≠ *Null* ∨ *q* ≠ *Null*
INV {*Path next r rs s* ∧ *List next p ps* ∧ *List next q qs* ∧
distinct(*a* # *ps* @ *qs* @ *rs*) ∧ *s* = *Ref a* ∧
merge(*Ps*,*Qs*,λ*x y. elem x* ≤ *elem y*) =
rs @ *a* # *merge*(*ps*,*qs*,λ*x y. elem x* ≤ *elem y*) ∧
(*next a* = *p* ∨ *next a* = *q*)}
DO IF cor (*q* = *Null*) (*cand* (*p* ≠ *Null*) (*p*^.*elem* ≤ *q*^.*elem*))
THEN s^.*next* := *p*; *p* := *p*^.*next*; *ps* := *tl ps*
ELSE s^.*next* := *q*; *q* := *q*^.*next*; *qs* := *tl qs FI*;
rs := *rs* @ [*a*]; *s* := *s*^.*next*; *a* := *addr s*
OD
{*List next r* (*merge*(*Ps*,*Qs*,λ*x y. elem x* ≤ *elem y*))}
⟨*proof*⟩

The proof is a LOT simpler because it does not need instantiations anymore, but it is still not quite automatic, probably because of this wrong orientation business.

More of the previous proof without ghost variables can be automated, but the runtime goes up drastically. In general it is usually more efficient

to give the witness directly than to have it found by proof.

Now we try a functional version of the abstraction relation *Path*. Since the result is not that convincing, we do not prove any of the lemmas.

axiomatization
ispath :: $('a \Rightarrow 'a\ ref) \Rightarrow 'a\ ref \Rightarrow 'a\ ref \Rightarrow bool$ **and**
path :: $('a \Rightarrow 'a\ ref) \Rightarrow 'a\ ref \Rightarrow 'a\ ref \Rightarrow 'a\ list$

First some basic lemmas:

lemma [*simp*]: $ispath\ f\ p\ p$
⟨*proof*⟩
lemma [*simp*]: $path\ f\ p\ p = []$
⟨*proof*⟩
lemma [*simp*]: $ispath\ f\ p\ q \Longrightarrow a \notin set(path\ f\ p\ q) \Longrightarrow ispath\ (f(a := r))\ p\ q$
⟨*proof*⟩
lemma [*simp*]: $ispath\ f\ p\ q \Longrightarrow a \notin set(path\ f\ p\ q) \Longrightarrow$
$path\ (f(a := r))\ p\ q = path\ f\ p\ q$
⟨*proof*⟩

Some more specific lemmas needed by the example:

lemma [*simp*]: $ispath\ (f(a := q))\ p\ (Ref\ a) \Longrightarrow ispath\ (f(a := q))\ p\ q$
⟨*proof*⟩
lemma [*simp*]: $ispath\ (f(a := q))\ p\ (Ref\ a) \Longrightarrow$
$path\ (f(a := q))\ p\ q = path\ (f(a := q))\ p\ (Ref\ a)\ @\ [a]$
⟨*proof*⟩
lemma [*simp*]: $ispath\ f\ p\ (Ref\ a) \Longrightarrow f\ a = Ref\ b \Longrightarrow$
$b \notin set\ (path\ f\ p\ (Ref\ a))$
⟨*proof*⟩
lemma [*simp*]: $ispath\ f\ p\ (Ref\ a) \Longrightarrow f\ a = Null \Longrightarrow islist\ f\ p$
⟨*proof*⟩
lemma [*simp*]: $ispath\ f\ p\ (Ref\ a) \Longrightarrow f\ a = Null \Longrightarrow list\ f\ p = path\ f\ p\ (Ref\ a)\ @$
$[a]$
⟨*proof*⟩

lemma [*simp*]: $islist\ f\ p \Longrightarrow distinct\ (list\ f\ p)$
⟨*proof*⟩

lemma *VARS hd tl p q r s*
$\{islist\ tl\ p \wedge Ps = list\ tl\ p \wedge islist\ tl\ q \wedge Qs = list\ tl\ q \wedge$
$set\ Ps \cap set\ Qs = \{\} \wedge$
$(p \neq Null \vee q \neq Null)\}$
IF cor $(q = Null)$ $(cand\ (p \neq Null)\ (p\hat{}.hd \leq q\hat{}.hd))$
THEN $r := p;\ p := p\hat{}.tl$ *ELSE* $r := q;\ q := q\hat{}.tl$ *FI*;
$s := r$;
WHILE $p \neq Null \vee q \neq Null$
INV $\{\exists rs\ ps\ qs\ a.\ ispath\ tl\ r\ s \wedge rs = path\ tl\ r\ s \wedge$
$islist\ tl\ p \wedge ps = list\ tl\ p \wedge islist\ tl\ q \wedge qs = list\ tl\ q \wedge$
$distinct(a\ \#\ ps\ @\ qs\ @\ rs) \wedge s = Ref\ a \wedge$
$merge(Ps,Qs,\lambda x\ y.\ hd\ x \leq hd\ y) =$
$rs\ @\ a\ \#\ merge(ps,qs,\lambda x\ y.\ hd\ x \leq hd\ y) \wedge$

$(tl\ a = p \vee tl\ a = q)\}$
DO IF cor $(q = Null)$ $(cand\ (p \neq Null)\ (p\hat{}.hd \leq q\hat{}.hd))$
THEN $s\hat{}.tl := p$; $p := p\hat{}.tl$ *ELSE* $s\hat{}.tl := q$; $q := q\hat{}.tl$ *FI*;
$s := s\hat{}.tl$
OD
$\{islist\ tl\ r\ \&\ list\ tl\ r = (merge(Ps,Qs,\lambda x\ y.\ hd\ x \leq hd\ y))\}$
⟨*proof*⟩

The proof is automatic, but requires a numbet of special lemmas.

12.1.5 Cyclic list reversal

We consider two algorithms for the reversal of circular lists.

lemma *circular-list-rev-I*:
VARS next root p q tmp
$\{root = Ref\ r \wedge distPath\ next\ root\ (r\#Ps)\ root\}$
$p := root$; $q := root\hat{}.next$;
WHILE $q \neq root$
INV $\{\exists\ ps\ qs.\ distPath\ next\ p\ ps\ root \wedge distPath\ next\ q\ qs\ root \wedge$
$root = Ref\ r \wedge r \notin set\ Ps\ \wedge set\ ps \cap set\ qs = \{\} \wedge$
$Ps = (rev\ ps)\ @\ qs\ \}$
DO $tmp := q$; $q := q\hat{}.next$; $tmp\hat{}.next := p$; $p{:=}tmp$ *OD*;
$root\hat{}.next := p$
$\{\ root = Ref\ r \wedge distPath\ next\ root\ (r\#rev\ Ps)\ root\}$
⟨*proof*⟩

In the beginning, we are able to assert *distPath next root as root*, with *as* set to [] or [r, a, b, c]. Note that *Path next root as root* would additionally give us an infinite number of lists with the recurring sequence [r, a, b, c].

The precondition states that there exists a non-empty non-repeating path r # Ps from pointer *root* to itself, given that *root* points to location r. Pointers p and q are then set to *root* and the successor of *root* respectively. If $q = root$, we have circled the loop, otherwise we set the *next* pointer field of q to point to p, and shift p and q one step forward. The invariant thus states that p and q point to two disjoint lists ps and qs, such that $Ps = rev\ ps\ @\ qs$. After the loop terminates, one extra step is needed to close the loop. As expected, the postcondition states that the *distPath* from *root* to itself is now r # $rev\ Ps$.

It may come as a surprise to the reader that the simple algorithm for acyclic list reversal, with modified annotations, works for cyclic lists as well:

lemma *circular-list-rev-II*:
VARS next p q tmp
$\{p = Ref\ r \wedge distPath\ next\ p\ (r\#Ps)\ p\}$
$q{:=}Null$;
WHILE $p \neq Null$
INV
$\{\ ((q = Null) \longrightarrow (\exists\, ps.\ distPath\ next\ p\ (ps)\ (Ref\ r) \wedge ps = r\#Ps)) \wedge$

$((q \neq Null) \longrightarrow (\exists\, ps\ qs.\ distPath\ next\ q\ (qs)\ (Ref\ r) \wedge List\ next\ p\ ps\ \wedge$
$set\ ps \cap set\ qs = \{\} \wedge rev\ qs\ @\ ps = Ps@[r])) \wedge$
$\neg\ (p = Null \wedge q = Null)\ \}$
DO $tmp := p;\ p := p\hat{}.next;\ tmp\hat{}.next := q;\ q{:=}tmp$ *OD*
$\{q = Ref\ r \wedge distPath\ next\ q\ (r\ \#\ rev\ Ps)\ q\}$
⟨*proof*⟩

12.1.6 Storage allocation

definition *new* :: *'a set* ⇒ *'a*
where $new\ A = (SOME\ a.\ a \notin A)$

lemma *new-notin*:
$[\![\ \sim finite(UNIV{::}'a\ set);\ finite(A{::}'a\ set);\ B \subseteq A\ ]\!] \Longrightarrow new\ (A) \notin B$
⟨*proof*⟩

lemma $\sim finite(UNIV{::}'a\ set) \Longrightarrow$
VARS xs elem next alloc p q
$\{Xs = xs \wedge p = (Null{::}'a\ ref)\}$
WHILE $xs \neq []$
INV $\{islist\ next\ p \wedge set(list\ next\ p) \subseteq set\ alloc \wedge$
$map\ elem\ (rev(list\ next\ p))\ @\ xs = Xs\}$
DO $q := Ref(new(set\ alloc));\ alloc := (addr\ q)\#alloc;$
$q\hat{}.next := p;\ q\hat{}.elem := hd\ xs;\ xs := tl\ xs;\ p := q$
OD
$\{islist\ next\ p \wedge map\ elem\ (rev(list\ next\ p)) = Xs\}$
⟨*proof*⟩

end

13 Heap syntax (abort)

theory *HeapSyntaxAbort*
imports *Hoare-Logic-Abort Heap*
begin

13.1 Field access and update

Heap update $p\hat{}.h := e$ is now guarded against p being Null. However, p may still be illegal, e.g. uninitialized or dangling. To guard against that, one needs a more detailed model of the heap where allocated and free addresses are distinguished, e.g. by making the heap a map, or by carrying the set of free addresses around. This is needed anyway as soon as we want to reason about storage allocation/deallocation.

syntax

-refupdate :: $('a \Rightarrow 'b) \Rightarrow 'a\ ref \Rightarrow 'b \Rightarrow ('a \Rightarrow 'b)$
(-/'((- $\rightarrow$ -)') [1000,0] 900)
-fassign :: 'a ref => id => 'v => 's com
((2-^.- :=/ -) [70,1000,65] 61)
-faccess :: 'a ref => ('a ref $\Rightarrow$ 'v) => 'v
(-^.- [65,1000] 65)
translations
-refupdate f r v == *f*(*CONST addr r* := *v*)
p^.*f* := *e* => (*p* $\neq$ *CONST Null*) $\rightarrow$ (*f* := *-refupdate f p e*)
p^.*f* => *f*(*CONST addr p*)

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

An example due to Suzuki:

lemma *VARS v n*
{*w* = *Ref w0* & *x* = *Ref x0* & *y* = *Ref y0* & *z* = *Ref z0* &
distinct[*w0*,*x0*,*y0*,*z0*]}
w^.*v* := (*1*::*int*); *w*^.*n* := *x*;
x^.*v* := *2*; *x*^.*n* := *y*;
y^.*v* := *3*; *y*^.*n* := *z*;
z^.*v* := *4*; *x*^.*n* := *z*
{*w*^.*n*^.*n*^.*v* = *4*}
⟨*proof*⟩

end

14 Examples of verifications of pointer programs

theory *Pointer-ExamplesAbort*
imports *HeapSyntaxAbort*
begin

14.1 Verifications

14.1.1 List reversal

Interestingly, this proof is the same as for the unguarded program:

lemma *VARS tl p q r*
{*List tl p Ps* $\wedge$ *List tl q Qs* $\wedge$ *set Ps* $\cap$ *set Qs* = {}}
WHILE p $\neq$ *Null*
INV {$\exists$ *ps qs*. *List tl p ps* $\wedge$ *List tl q qs* $\wedge$ *set ps* $\cap$ *set qs* = {} $\wedge$
rev ps @ *qs* = *rev Ps* @ *Qs*}
DO r := *p*; (*p* $\neq$ *Null* $\rightarrow$ *p* := *p*^.*tl*); *r*^.*tl* := *q*; *q* := *r OD*
{*List tl q* (*rev Ps* @ *Qs*)}
⟨*proof*⟩

end

15 Proof of the Schorr-Waite graph marking algorithm

theory *SchorrWaite*
imports *HeapSyntax*
begin

15.1 Machinery for the Schorr-Waite proof

definition
— Relations induced by a mapping
rel :: $('a \Rightarrow 'a\ ref) \Rightarrow ('a \times 'a)\ set$
where $rel\ m = \{(x,y).\ m\ x = Ref\ y\}$

definition
relS :: $('a \Rightarrow 'a\ ref)\ set \Rightarrow ('a \times 'a)\ set$
where $relS\ M = (\bigcup m \in M.\ rel\ m)$

definition
addrs :: $'a\ ref\ set \Rightarrow 'a\ set$
where $addrs\ P = \{a.\ Ref\ a \in P\}$

definition
reachable :: $('a \times 'a)\ set \Rightarrow 'a\ ref\ set \Rightarrow 'a\ set$
where $reachable\ r\ P = (r^*\ ``\ addrs\ P)$

lemmas *rel-defs* = *relS-def rel-def*

Rewrite rules for relations induced by a mapping

lemma *self-reachable*: $b \in B \Longrightarrow b \in R^*\ ``\ B$
⟨*proof*⟩

lemma *oneStep-reachable*: $b \in R``B \Longrightarrow b \in R^*\ ``\ B$
⟨*proof*⟩

lemma *still-reachable*: $[\![B \subseteq Ra^*``A;\ \forall\ (x,y) \in Rb - Ra.\ y \in (Ra^*``A)]\!] \Longrightarrow Rb^*\ ``\ B \subseteq Ra^*\ ``\ A$
⟨*proof*⟩

lemma *still-reachable-eq*: $[\![\ A \subseteq Rb^*``B;\ B \subseteq Ra^*``A;\ \forall\ (x,y) \in Ra - Rb.\ y \in (Rb^*``B);\ \forall\ (x,y) \in Rb - Ra.\ y \in (Ra^*``A)]\!] \Longrightarrow Ra^*``A = Rb^*``B$
⟨*proof*⟩

lemma *reachable-null*: $reachable\ mS\ \{Null\} = \{\}$
⟨*proof*⟩

lemma *reachable-empty*: $reachable\ mS\ \{\} = \{\}$
⟨*proof*⟩

lemma *reachable-union*: (*reachable mS aS* ∪ *reachable mS bS*) = *reachable mS* (*aS* ∪ *bS*)
⟨*proof*⟩

lemma *reachable-union-sym*: *reachable r* (*insert a aS*) = (*r** `` *addrs* {*a*}) ∪ *reachable r aS*
⟨*proof*⟩

lemma *rel-upd1*: (*a*,*b*) ∉ *rel* (*r*(*q*:=*t*)) ⟹ (*a*,*b*) ∈ *rel r* ⟹ *a*=*q*
⟨*proof*⟩

lemma *rel-upd2*: (*a*,*b*) ∉ *rel r* ⟹ (*a*,*b*) ∈ *rel* (*r*(*q*:=*t*)) ⟹ *a*=*q*
⟨*proof*⟩

definition
— Restriction of a relation
restr ::('*a* × '*a*) *set* ⇒ ('*a* ⇒ *bool*) ⇒ ('*a* × '*a*) *set* ((-/ | -) [*50*, *51*] *50*)
where *restr r m* = {(*x*,*y*). (*x*,*y*) ∈ *r* ∧ ¬ *m x*}

Rewrite rules for the restriction of a relation

lemma *restr-identity*[*simp*]:
(∀ *x*. ¬ *m x*) ⟹ (*R* |*m*) = *R*
⟨*proof*⟩

lemma *restr-rtrancl*[*simp*]: ⟦*m l*⟧ ⟹ (*R* | *m*)* `` {*l*} = {*l*}
⟨*proof*⟩

lemma [*simp*]: ⟦*m l*⟧ ⟹ (*l*,*x*) ∈ (*R* | *m*)* = (*l*=*x*)
⟨*proof*⟩

lemma *restr-upd*: ((*rel* (*r* (*q* := *t*)))|(*m*(*q* := *True*))) = ((*rel* (*r*))|(*m*(*q* := *True*)))

⟨*proof*⟩

lemma *restr-un*: ((*r* ∪ *s*)|*m*) = (*r*|*m*) ∪ (*s*|*m*)
⟨*proof*⟩

lemma *rel-upd3*: (*a*, *b*) ∉ (*r*|(*m*(*q* := *t*))) ⟹ (*a*,*b*) ∈ (*r*|*m*) ⟹ *a* = *q*
⟨*proof*⟩

definition
— A short form for the stack mapping function for List
S :: ('*a* ⇒ *bool*) ⇒ ('*a* ⇒ '*a ref*) ⇒ ('*a* ⇒ '*a ref*) ⇒ ('*a* ⇒ '*a ref*)
where *S c l r* = (λ*x*. *if c x then r x else l x*)

Rewrite rules for Lists using S as their mapping

lemma [*rule-format*,*simp*]:
∀ *p*. *a* ∉ *set stack* ⟶ *List* (*S c l r*) *p stack* = *List* (*S* (*c*(*a*:=*x*)) (*l*(*a*:=*y*)) (*r*(*a*:=*z*))) *p stack*

⟨*proof*⟩

lemma [*rule-format*,*simp*]:
∀ *p*. *a* ∉ *set stack* ⟶ *List* (*S c l* (*r*(*a*:=*z*))) *p stack* = *List* (*S c l r*) *p stack*
⟨*proof*⟩

lemma [*rule-format*,*simp*]:
∀ *p*. *a* ∉ *set stack* ⟶ *List* (*S c* (*l*(*a*:=*z*)) *r*) *p stack* = *List* (*S c l r*) *p stack*
⟨*proof*⟩

lemma [*rule-format*,*simp*]:
∀ *p*. *a* ∉ *set stack* ⟶ *List* (*S* (*c*(*a*:=*z*)) *l r*) *p stack* = *List* (*S c l r*) *p stack*
⟨*proof*⟩

primrec
— Recursive definition of what is means for a the graph/stack structure to be reconstructible
stkOk :: ('*a* ⇒ *bool*) ⇒ ('*a* ⇒ '*a ref*) ⇒ ('*a* ⇒ '*a ref*) ⇒ ('*a* ⇒ '*a ref*) ⇒ ('*a* ⇒ '*a ref*) ⇒ '*a ref* ⇒'*a list* ⇒ *bool*
where
stkOk-nil: *stkOk c l r iL iR t* [] = *True*
| *stkOk-cons*:
stkOk c l r iL iR t (*p*#*stk*) = (*stkOk c l r iL iR* (*Ref p*) (*stk*) ∧
iL p = (*if c p then l p else t*) ∧
iR p = (*if c p then t else r p*))

Rewrite rules for stkOk

lemma [*simp*]: ⋀*t*. ⟦ *x* ∉ *set xs*; *Ref x*≠*t* ⟧ ⟹
stkOk (*c*(*x* := *f*)) *l r iL iR t xs* = *stkOk c l r iL iR t xs*
⟨*proof*⟩

lemma [*simp*]: ⋀*t*. ⟦ *x* ∉ *set xs*; *Ref x*≠*t* ⟧ ⟹
stkOk c (*l*(*x* := *g*)) *r iL iR t xs* = *stkOk c l r iL iR t xs*
⟨*proof*⟩

lemma [*simp*]: ⋀*t*. ⟦ *x* ∉ *set xs*; *Ref x*≠*t* ⟧ ⟹
stkOk c l (*r*(*x* := *g*)) *iL iR t xs* = *stkOk c l r iL iR t xs*
⟨*proof*⟩

lemma *stkOk-r-rewrite* [*simp*]: ⋀*x*. *x* ∉ *set xs* ⟹
stkOk c l (*r*(*x* := *g*)) *iL iR* (*Ref x*) *xs* = *stkOk c l r iL iR* (*Ref x*) *xs*
⟨*proof*⟩

lemma [*simp*]: ⋀*x*. *x* ∉ *set xs* ⟹
stkOk c (*l*(*x* := *g*)) *r iL iR* (*Ref x*) *xs* = *stkOk c l r iL iR* (*Ref x*) *xs*
⟨*proof*⟩

lemma [*simp*]: ⋀*x*. *x* ∉ *set xs* ⟹
stkOk (*c*(*x* := *g*)) *l r iL iR* (*Ref x*) *xs* = *stkOk c l r iL iR* (*Ref x*) *xs*

⟨*proof*⟩

15.2 The Schorr-Waite algorithm

theorem *SchorrWaiteAlgorithm*:
VARS c m l r t p q root
{*R* = *reachable* (*relS* {*l*, *r*}) {*root*} ∧ (∀ *x*. ¬ *m x*) ∧ *iR* = *r* ∧ *iL* = *l*}
t := *root*; *p* := *Null*;
WHILE p ≠ *Null* ∨ *t* ≠ *Null* ∧ ¬ *t*^.*m*
INV {∃ *stack*.
List (*S c l r*) *p stack* ∧ — *i1*
(∀ *x* ∈ *set stack*. *m x*) ∧ — *i2*
R = *reachable* (*relS*{*l*, *r*}) {*t*,*p*} ∧ — *i3*
(∀ *x*. *x* ∈ *R* ∧ ¬*m x* ⟶ — *i4*
x ∈ *reachable* (*relS*{*l*,*r*}|*m*) ({*t*}∪*set*(*map r stack*))) ∧
(∀ *x*. *m x* ⟶ *x* ∈ *R*) ∧ — *i5*
(∀ *x*. *x* ∉ *set stack* ⟶ *r x* = *iR x* ∧ *l x* = *iL x*) ∧ — *i6*
(*stkOk c l r iL iR t stack*) — *i7*}
DO IF t = *Null* ∨ *t*^.*m*
THEN IF p^.*c*
THEN q := *t*; *t* := *p*; *p* := *p*^.*r*; *t*^.*r* := *q* — *pop*
ELSE q := *t*; *t* := *p*^.*r*; *p*^.*r* := *p*^.*l*; — *swing*
p^.*l* := *q*; *p*^.*c* := *True* *FI*
ELSE q := *p*; *p* := *t*; *t* := *t*^.*l*; *p*^.*l* := *q*; — *push*
p^.*m* := *True*; *p*^.*c* := *False* *FI* *OD*
{(∀ *x*. (*x* ∈ *R*) = *m x*) ∧ (*r* = *iR* ∧ *l* = *iL*) }
(**is** *Valid*
{(*c*, *m*, *l*, *r*, *t*, *p*, *q*, *root*). *?Pre c m l r root*}
(*Seq* - (*Seq* - (*While* {(*c*, *m*, *l*, *r*, *t*, *p*, *q*, *root*). *?whileB m t p*} -)))
(*Aseq* - (*Aseq* - (*Awhile* {(*c*, *m*, *l*, *r*, *t*, *p*, *q*, *root*). *?inv c m l r t p*} - -))) -)
⟨*proof*⟩

end

16 Heap abstractions for Separation Logic

(at the moment only Path and List)

theory *SepLogHeap*
imports *Main*
begin

type-synonym *heap* = (*nat* ⇒ *nat option*)

Some means allocated, *None* means free. Address *0* serves as the null reference.

16.1 Paths in the heap

primrec *Path* :: *heap* ⇒ *nat* ⇒ *nat list* ⇒ *nat* ⇒ *bool*

where
  Path h x [] y = (x = y)
| *Path h x (a#as) y = (x≠0 ∧ a=x ∧ (∃ b. h x = Some b ∧ Path h b as y))*

lemma [*iff*]: *Path h 0 xs y = (xs = [] ∧ y = 0)*
⟨*proof*⟩

lemma [*simp*]: *x≠0 ⟹ Path h x as z =*
 (as = [] ∧ z = x ∨ (∃ y bs. as = x#bs ∧ h x = Some y & Path h y bs z))
⟨*proof*⟩

lemma [*simp*]: *⋀x. Path f x (as@bs) z = (∃ y. Path f x as y ∧ Path f y bs z)*
⟨*proof*⟩

lemma *Path-upd*[*simp*]:
⋀x. u ∉ set as ⟹ Path (f(u := v)) x as y = Path f x as y
⟨*proof*⟩

16.2 Lists on the heap

definition *List :: heap ⇒ nat ⇒ nat list ⇒ bool*
  where *List h x as = Path h x as 0*

lemma [*simp*]: *List h x [] = (x = 0)*
⟨*proof*⟩

lemma [*simp*]:
 List h x (a#as) = (x≠0 ∧ a=x ∧ (∃ y. h x = Some y ∧ List h y as))
⟨*proof*⟩

lemma [*simp*]: *List h 0 as = (as = [])*
⟨*proof*⟩

lemma *List-non-null*: *a≠0 ⟹*
 List h a as = (∃ b bs. as = a#bs ∧ h a = Some b ∧ List h b bs)
⟨*proof*⟩

theorem *notin-List-update*[*simp*]:
⋀x. a ∉ set as ⟹ List (h(a := y)) x as = List h x as
⟨*proof*⟩

lemma *List-unique*: *⋀x bs. List h x as ⟹ List h x bs ⟹ as = bs*
⟨*proof*⟩

lemma *List-unique1*: *List h p as ⟹ ∃!as. List h p as*
⟨*proof*⟩

lemma *List-app*: *⋀x. List h x (as@bs) = (∃ y. Path h x as y ∧ List h y bs)*
⟨*proof*⟩

lemma *List-hd-not-in-tl*[*simp*]: *List h b as* $\Longrightarrow$ *h a* = *Some b* $\Longrightarrow$ *a* $\notin$ *set as*
⟨*proof*⟩

lemma *List-distinct*[*simp*]: $\bigwedge$*x. List h x as* $\Longrightarrow$ *distinct as*
⟨*proof*⟩

lemma *list-in-heap*: $\bigwedge$*p. List h p ps* $\Longrightarrow$ *set ps* $\subseteq$ *dom h*
⟨*proof*⟩

lemma *list-ortho-sum1*[*simp*]:
$\bigwedge$*p.* ⟦ *List h1 p ps*; *dom h1* $\cap$ *dom h2* = {}⟧ $\Longrightarrow$ *List* (*h1*++*h2*) *p ps*
⟨*proof*⟩

lemma *list-ortho-sum2*[*simp*]:
$\bigwedge$*p.* ⟦ *List h2 p ps*; *dom h1* $\cap$ *dom h2* = {}⟧ $\Longrightarrow$ *List* (*h1*++*h2*) *p ps*
⟨*proof*⟩

end

17 Separation logic

theory *Separation*
imports *Hoare-Logic-Abort SepLogHeap*
begin

The semantic definition of a few connectives:

definition *ortho* :: *heap* ⇒ *heap* ⇒ *bool* (**infix** ⊥ *55*)
where *h1* ⊥ *h2* ⟷ *dom h1* ∩ *dom h2* = {}

definition *is-empty* :: *heap* ⇒ *bool*
where *is-empty h* ⟷ *h* = *Map.empty*

definition *singl*:: *heap* ⇒ *nat* ⇒ *nat* ⇒ *bool*
where *singl h x y* ⟷ *dom h* = {*x*} & *h x* = *Some y*

definition *star*:: (*heap* ⇒ *bool*) ⇒ (*heap* ⇒ *bool*) ⇒ (*heap* ⇒ *bool*)
where *star P Q* = (λ*h.* ∃*h1 h2. h* = *h1*++*h2* ∧ *h1* ⊥ *h2* ∧ *P h1* ∧ *Q h2*)

definition *wand*:: (*heap* ⇒ *bool*) ⇒ (*heap* ⇒ *bool*) ⇒ (*heap* ⇒ *bool*)
where *wand P Q* = (λ*h.* ∀ *h′. h′* ⊥ *h* ∧ *P h′* ⟶ *Q*(*h*++*h′*))

This is what assertions look like without any syntactic sugar:

lemma *VARS x y z w h*
{*star* (%*h. singl h x y*) (%*h. singl h z w*) *h*}
SKIP
{*x* ≠ *z*}
⟨*proof*⟩

Now we add nice input syntax. To suppress the heap parameter of the connectives, we assume it is always called H and add/remove it upon parsing/printing. Thus every pointer program needs to have a program variable H, and assertions should not contain any locally bound Hs - otherwise they may bind the implicit H.

syntax
 -*emp* :: *bool* (*emp*)
 -*singl* :: *nat* ⇒ *nat* ⇒ *bool* ([- ↦ -])
 -*star* :: *bool* ⇒ *bool* ⇒ *bool* (**infixl** ∗∗ *60*)
 -*wand* :: *bool* ⇒ *bool* ⇒ *bool* (**infixl** −∗ *60*)

⟨*ML*⟩

Now it looks much better:

lemma *VARS H x y z w*
 {[*x*↦*y*] ∗∗ [*z*↦*w*]}
 SKIP
 {*x* ≠ *z*}
⟨*proof*⟩

lemma *VARS H x y z w*
 {*emp* ∗∗ *emp*}
 SKIP
 {*emp*}
⟨*proof*⟩

But the output is still unreadable. Thus we also strip the heap parameters upon output:

⟨*ML*⟩

Now the intermediate proof states are also readable:

lemma *VARS H x y z w*
 {[*x*↦*y*] ∗∗ [*z*↦*w*]}
 y := *w*
 {*x* ≠ *z*}
⟨*proof*⟩

lemma *VARS H x y z w*
 {*emp* ∗∗ *emp*}
 SKIP
 {*emp*}
⟨*proof*⟩

So far we have unfolded the separation logic connectives in proofs. Here comes a simple example of a program proof that uses a law of separation logic instead.

lemma *star-comm*: *P* ∗∗ *Q* = *Q* ∗∗ *P*

$\langle proof \rangle$

lemma *VARS H x y z w*
$\{P \ast\ast Q\}$
SKIP
$\{Q \ast\ast P\}$
$\langle proof \rangle$

lemma *VARS H*
$\{p \neq 0 \wedge [p \mapsto x] \ast\ast List\ H\ q\ qs\}$
$H := H(p \mapsto q)$
$\{List\ H\ p\ (p \# qs)\}$
$\langle proof \rangle$

lemma *VARS H p q r*
$\{List\ H\ p\ Ps \ast\ast List\ H\ q\ Qs\}$
WHILE $p \neq 0$
INV $\{\exists\, ps\ qs.\ (List\ H\ p\ ps \ast\ast List\ H\ q\ qs) \wedge rev\ ps\ @\ qs = rev\ Ps\ @\ Qs\}$
DO $r := p;\ p := the(H\ p);\ H := H(r \mapsto q);\ q := r$ *OD*
$\{List\ H\ q\ (rev\ Ps\ @\ Qs)\}$
$\langle proof \rangle$

end

References

[1] Farhad Mehta and Tobias Nipkow. Proving pointer programs in higher-order logic. In F. Baader, editor, *Automated Deduction — CADE-19*, volume 2741 of *LNCS*, pages 121–135. Springer, 2003.

[2] Farhad Mehta and Tobias Nipkow. Proving pointer programs in higher-order logic. *Information and Computation*, 199:200–227, 2005.