Theory of Designs in Isabelle/UTP

Simon Foster Yakoub Nemouchi Frank Zeyda

September 5, 2018

Abstract

This document describes a mechanisation of the UTP theory of designs in Isabelle/UTP. Designs enrich UTP relations with explicit precondition/postcondition pairs, as present in formal notations like VDM, B, and the refinement calculus. If a program's precondition holds, then it is guaranteed to terminate and establish its postcondition, which is an approach known as total correctness. If the precondition does not hold, the behaviour is maximally nondeterministic, which represents unspecified behaviour. In this mechanisation, we create the theory of designs, including its alphabet, signature, and healthiness conditions. We then use these to prove the key algebraic laws of programming. This development can be used to support program verification based on total correctness.

Contents

1 Design Signature and Core Laws

theory *utp-des-core*
imports *UTP.utp*
begin

UTP designs [2, 4] are a subset of the alphabetised relations that use a boolean observational variable *ok* to record the start and termination of a program. For more information on designs please see Chapter 3 of the UTP book [4], or the more accessible designs tutorial [2].

1.1 Definitions

Two named theorem sets exist are created to group theorems that, respectively, provide pre-postcondition definitions, and simplify operators to their normal design form.

named-theorems *ndes* **and** *ndes-simp*

alphabet *des-vars* =
  ok :: *bool*

declare *des-vars.defs* [*lens-defs*]

The two locale interpretations below are a technicality to improve automatic proof support via the predicate and relational tactics. This is to enable the (re-)interpretation of state spaces to remove any occurrences of lens types after the proof tactics *pred-simp* and *rel-simp*, or any of their derivatives have been applied. Eventually, it would be desirable to automate both interpretations as part of a custom outer command for defining alphabets.

interpretation *des-vars*: *lens-interp* $\lambda r.\ (ok_v\ r,\ more\ r)$
apply (*unfold-locales*)
apply (*rule injI*)
apply (*clarsimp*)
done

interpretation *des-vars-rel*:
  lens-interp $\lambda(r,\ r').\ (ok_v\ r,\ ok_v\ r',\ more\ r,\ more\ r')$

apply (*unfold-locales*)
apply (*rule injI*)
apply (*clarsimp*)
done

type-synonym $'\alpha$ *des* $= '\alpha$ *des-vars-scheme*
type-synonym $('\alpha, '\beta)$ *rel-des* $= ('\alpha$ *des*, $'\beta$ *des*) *urel*
type-synonym $'\alpha$ *hrel-des* $= ('\alpha$ *des*) *hrel*

translations
(*type*) $'\alpha$ *des* <= (*type*) $'\alpha$ *des-vars-scheme*
(*type*) $'\alpha$ *des* <= (*type*) $'\alpha$ *des-vars-ext*
(*type*) $('\alpha, '\beta)$ *rel-des* <= (*type*) $('\alpha$ *des*, $'\beta$ *des*) *urel*
(*type*) $'\alpha$ *hrel-des* <= (*type*) $'\alpha$ *des hrel*

notation *des-vars-child-lens* (Σ_D)

lemma *ok-des-bij-lens*: *bij-lens* ($ok +_L \Sigma_D$)
by (*unfold-locales*, *simp-all add*: *ok-def des-vars-child-lens-def lens-plus-def prod.case-eq-if*)

Define the lens functor for designs

definition *lmap-des-vars* :: $('\alpha \Longrightarrow '\beta) \Rightarrow ('\alpha$ *des-vars-scheme* $\Longrightarrow '\beta$ *des-vars-scheme*) ($lmap_D$)
where [*lens-defs*]: *lmap-des-vars* = *lmap*[*des-vars*]

lemma *lmap-des-vars*: *vwb-lens f* $\Longrightarrow$ *vwb-lens* (*lmap-des-vars f*)
by (*unfold-locales*, *auto simp add*: *lens-defs*)

lemma *lmap-id*: $lmap_D\ 1_L = 1_L$
by (*simp add*: *lens-defs fun-eq-iff*)

lemma *lmap-comp*: $lmap_D\ (f\ ;_L\ g) = lmap_D\ f\ ;_L\ lmap_D\ g$
by (*simp add*: *lens-defs fun-eq-iff*)

The following notations define liftings from non-design predicates into design predicates using alphabet extensions.

abbreviation *lift-desr* ($\lceil - \rceil_D$)
where $\lceil P \rceil_D \equiv P \oplus_p (\Sigma_D \times_L \Sigma_D)$

abbreviation *lift-pre-desr* ($\lceil - \rceil_{D<}$)
where $\lceil p \rceil_{D<} \equiv \lceil \lceil p \rceil_< \rceil_D$

abbreviation *lift-post-desr* ($\lceil - \rceil_{D>}$)
where $\lceil p \rceil_{D>} \equiv \lceil \lceil p \rceil_> \rceil_D$

abbreviation *drop-desr* ($\lfloor - \rfloor_D$)
where $\lfloor P \rfloor_D \equiv P \upharpoonright_e (\Sigma_D \times_L \Sigma_D)$

abbreviation *dcond* :: $('\alpha, '\beta)$ *rel-des* $\Rightarrow '\alpha$ *upred* $\Rightarrow ('\alpha, '\beta)$ *rel-des* $\Rightarrow ('\alpha, '\beta)$ *rel-des*
((*3*- $\triangleleft$ - $\triangleright_D$/ -) [*52*,*0*,*53*] *52*)
where $P \triangleleft b \triangleright_D Q \equiv P \triangleleft \lceil b \rceil_{D<} \triangleright Q$

definition *design*::$('\alpha, '\beta)$ *rel-des* $\Rightarrow ('\alpha, '\beta)$ *rel-des* $\Rightarrow ('\alpha, '\beta)$ *rel-des* (**infixl** $\vdash$ *59*) **where**
[*upred-defs*]: $P \vdash Q = (\$ok \wedge P \Rightarrow \$ok' \wedge Q)$

An rdesign is a design that uses the Isabelle type system to prevent reference to ok in the assumption and commitment.

definition $rdesign::('\alpha, '\beta)\ urel \Rightarrow ('\alpha, '\beta)\ urel \Rightarrow ('\alpha, '\beta)\ rel\text{-}des$ (**infixl** $\vdash_r$ *59*) **where**
[*upred-defs*]: $(P \vdash_r Q) = \lceil P \rceil_D \vdash \lceil Q \rceil_D$

An ndesign is a normal design, i.e. where the assumption is a condition

definition $ndesign::'\alpha\ cond \Rightarrow ('\alpha, '\beta)\ urel \Rightarrow ('\alpha, '\beta)\ rel\text{-}des$ (**infixl** $\vdash_n$ *59*) **where**
[*upred-defs*]: $(p \vdash_n Q) = (\lceil p \rceil_< \vdash_r Q)$

definition *skip-d* :: $'\alpha\ hrel\text{-}des$ (II_D) **where**
[*upred-defs*]: $II_D \equiv (true \vdash_r II)$

definition *bot-d* :: $('\alpha, '\beta)\ rel\text{-}des$ ($\bot_D$) **where**
[*upred-defs*]: $\bot_D = (false \vdash false)$

definition *pre-design* :: $('\alpha, '\beta)\ rel\text{-}des \Rightarrow ('\alpha, '\beta)\ urel$ (pre_D) **where**
[*upred-defs*]: $pre_D(P) = \lfloor \neg\ P[\![true,false/\$ok,\$ok']\!] \rfloor_D$

definition *post-design* :: $('\alpha, '\beta)\ rel\text{-}des \Rightarrow ('\alpha, '\beta)\ urel$ ($post_D$) **where**
[*upred-defs*]: $post_D(P) = \lfloor P[\![true,true/\$ok,\$ok']\!] \rfloor_D$

syntax
  -ok-f :: *logic* $\Rightarrow$ *logic* (-^{f} [*1000*] *1000*)
  -ok-t :: *logic* $\Rightarrow$ *logic* (-^{t} [*1000*] *1000*)
  -top-d :: *logic* ($\top_D$)

translations
  P^f ⇌ *CONST usubst* (*CONST subst-upd CONST id* (*CONST ovar CONST ok*) *false*) *P*
  P^t ⇌ *CONST usubst* (*CONST subst-upd CONST id* (*CONST ovar CONST ok*) *true*) *P*
  $\top_D$ => *CONST not-upred* (*CONST utp-expr.var* (*CONST ivar CONST ok*))

1.2 Lifting, Unrestriction, and Substitution

lemma *drop-desr-inv* [*simp*]: $\lfloor \lceil P \rceil_D \rfloor_D = P$
  by (*simp add*: *prod-mwb-lens*)

lemma *lift-desr-inv*:
  fixes $P :: ('\alpha, '\beta)\ rel\text{-}des$
  assumes $\$ok \sharp P$ $\$ok' \sharp P$
  shows $\lceil \lfloor P \rfloor_D \rceil_D = P$
proof −
  have *bij-lens* ($\Sigma_D \times_L \Sigma_D +_L$ (*in-var ok* $+_L$ *out-var ok*) :: (-, $'\alpha$ *des-vars-scheme* $\times$ $'\beta$ *des-vars-scheme*) *lens*)
    (**is** *bij-lens* (*?P*))
  proof −
    have $?P \approx_L (ok +_L \Sigma_D) \times_L (ok +_L \Sigma_D)$ (**is** $?P \approx_L ?Q$)
      apply (*simp add*: *in-var-def out-var-def prod-as-plus*)
      apply (*simp add*: *prod-as-plus*[*THEN sym*])
    apply (*meson lens-equiv-sym lens-equiv-trans lens-indep-prod lens-plus-comm lens-plus-prod-exchange des-vars-indeps*(*1*))
    done
    moreover have *bij-lens ?Q*
      by (*simp add*: *ok-des-bij-lens prod-bij-lens*)
    ultimately show *?thesis*
      by (*metis bij-lens-equiv lens-equiv-sym*)
  qed

  with *assms* **show** *?thesis*

apply (*rule-tac aext-arestr*[*of - in-var ok* $+_L$ *out-var ok*])
apply (*simp add*: *prod-mwb-lens*)
apply (*simp*)
apply (*metis alpha-in-var lens-indep-prod lens-indep-sym des-vars-indeps*(*1*) *out-var-def prod-as-plus*)
using *unrest-var-comp* **apply** *blast*
done
qed

lemma *unrest-out-des-lift* [*unrest*]: $out\alpha \sharp p \Longrightarrow out\alpha \sharp \lceil p \rceil_D$
by (*pred-simp*)

lemma *lift-dist-seq* [*simp*]:
$\lceil P \;;; Q \rceil_D = (\lceil P \rceil_D \;;; \lceil Q \rceil_D)$
by (*rel-auto*)

lemma *lift-des-skip-dr-unit* [*simp*]:
$(\lceil P \rceil_D \;;; \lceil II \rceil_D) = \lceil P \rceil_D$
$(\lceil II \rceil_D \;;; \lceil P \rceil_D) = \lceil P \rceil_D$
by (*rel-auto*)+

lemma *lift-des-skip-dr-unit-unrest*: $\$ok\acute{} \sharp P \Longrightarrow (P \;;; \lceil II \rceil_D) = P$
by (*rel-auto*)

lemma *state-subst-design* [*usubst*]:
$\lceil \sigma \oplus_s \Sigma_D \rceil_s \dagger (P \vdash_r Q) = (\lceil \sigma \rceil_s \dagger P) \vdash_r (\lceil \sigma \rceil_s \dagger Q)$
by (*rel-auto*)

lemma *design-subst* [*usubst*]:
$[\![\$ok \sharp \sigma; \$ok\acute{} \sharp \sigma]\!] \Longrightarrow \sigma \dagger (P \vdash Q) = (\sigma \dagger P) \vdash (\sigma \dagger Q)$
by (*simp add*: *design-def usubst*)

lemma *design-msubst* [*usubst*]:
$(P(x) \vdash Q(x))[\![x \to v]\!] = (P(x)[\![x \to v]\!] \vdash Q(x)[\![x \to v]\!])$
by (*rel-auto*)

lemma *design-ok-false* [*usubst*]: $(P \vdash Q)[\![false/\$ok]\!] = true$
by (*simp add*: *design-def usubst*)

lemma *ok-pre*: $(\$ok \wedge \lceil pre_D(P) \rceil_D) = (\$ok \wedge (\neg P^f))$
by (*pred-auto robust*)

lemma *ok-post*: $(\$ok \wedge \lceil post_D(P) \rceil_D) = (\$ok \wedge (P^t))$
by (*pred-auto robust*)

1.3 Basic Design Laws

lemma *design-export-ok*: $P \vdash Q = (P \vdash (\$ok \wedge Q))$
by (*rel-auto*)

lemma *design-export-ok'*: $P \vdash Q = (P \vdash (\$ok\acute{} \wedge Q))$
by (*rel-auto*)

lemma *design-export-pre*: $P \vdash (P \wedge Q) = P \vdash Q$
by (*rel-auto*)

lemma *design-export-spec*: $P \vdash (P \Rightarrow Q) = P \vdash Q$

by (*rel-auto*)

lemma *design-ok-pre-conj*: $(\$ok \wedge P) \vdash Q = P \vdash Q$
by (*rel-auto*)

lemma *true-is-design*: $(false \vdash true) = true$
by (*rel-auto*)

lemma *true-is-rdesign*: $(false \vdash_r true) = true$
by (*rel-auto*)

lemma *bot-d-true*: $\bot_D = true$
by (*rel-auto*)

lemma *bot-d-ndes-def* [*ndes-simp*]: $\bot_D = (false \vdash_n true)$
by (*rel-auto*)

lemma *design-false-pre*: $(false \vdash P) = true$
by (*rel-auto*)

lemma *rdesign-false-pre*: $(false \vdash_r P) = true$
by (*rel-auto*)

lemma *ndesign-false-pre*: $(false \vdash_n P) = true$
by (*rel-auto*)

lemma *ndesign-miracle*: $(true \vdash_n false) = \top_D$
by (*rel-auto*)

lemma *top-d-ndes-def* [*ndes-simp*]: $\top_D = (true \vdash_n false)$
by (*rel-auto*)

lemma *skip-d-alt-def*: $II_D = true \vdash II$
by (*rel-auto*)

lemma *skip-d-ndes-def* [*ndes-simp*]: $II_D = true \vdash_n II$
by (*rel-auto*)

lemma *design-subst-ok*:
$(P[\![true/\$ok]\!] \vdash Q[\![true/\$ok]\!]) = (P \vdash Q)$
by (*rel-auto*)

lemma *design-subst-ok-ok'*:
$(P[\![true/\$ok]\!] \vdash Q[\![true,true/\$ok,\$ok\acute{}]\!]) = (P \vdash Q)$
proof −
have $(P \vdash Q) = ((\$ok \wedge P) \vdash (\$ok \wedge \$ok\acute{} \wedge Q))$
by (*pred-auto*)
also have ... $= ((\$ok \wedge P[\![true/\$ok]\!]) \vdash (\$ok \wedge (\$ok\acute{} \wedge Q[\![true/\$ok\acute{}]\!])[\![true/\$ok]\!]))$
by (*metis conj-eq-out-var-subst conj-pos-var-subst upred-eq-true utp-pred-laws.inf-commute ok-vwb-lens*)
also have ... $= ((\$ok \wedge P[\![true/\$ok]\!]) \vdash (\$ok \wedge \$ok\acute{} \wedge Q[\![true,true/\$ok,\$ok\acute{}]\!]))$
by (*simp add*: *usubst*)
also have ... $= (P[\![true/\$ok]\!] \vdash Q[\![true,true/\$ok,\$ok\acute{}]\!])$
by (*pred-auto*)
finally show *?thesis* **..**
qed

lemma *design-subst-ok'*:
  $(P \vdash Q[\![true/\$ok']\!]) = (P \vdash Q)$
proof −
  have $(P \vdash Q) = (P \vdash (\$ok' \land Q))$
    by (*pred-auto*)
  also have ... $= (P \vdash (\$ok' \land Q[\![true/\$ok']\!]))$
    by (*metis conj-eq-out-var-subst upred-eq-true utp-pred-laws.inf-commute ok-vwb-lens*)
  also have ... $= (P \vdash Q[\![true/\$ok']\!])$
    by (*pred-auto*)
  finally show *?thesis* **..**
qed

1.4 Sequential Composition Laws

theorem *design-skip-idem* [*simp*]:
  $(II_D \;;; II_D) = II_D$
  by (*rel-auto*)

theorem *design-composition-subst*:
  assumes
    $\$ok' \sharp P1$ $\$ok \sharp P2$
  shows $((P1 \vdash Q1) \;;; (P2 \vdash Q2)) =$
        $(((\neg ((\neg P1) \;;; true)) \land \neg (Q1[\![true/\$ok']\!] \;;; (\neg P2))) \vdash (Q1[\![true/\$ok']\!] \;;; Q2[\![true/\$ok]\!]))$
proof −
  have $((P1 \vdash Q1) \;;; (P2 \vdash Q2)) = (\exists\ ok_0 \cdot ((P1 \vdash Q1)[\![\ll ok_0 \gg/\$ok']\!] \;;; (P2 \vdash Q2)[\![\ll ok_0 \gg/\$ok]\!]))$
    by (*rule seqr-middle*, *simp*)
  also have ...
      $= (((P1 \vdash Q1)[\![false/\$ok']\!] \;;; (P2 \vdash Q2)[\![false/\$ok]\!])$
        $\lor ((P1 \vdash Q1)[\![true/\$ok']\!] \;;; (P2 \vdash Q2)[\![true/\$ok]\!]))$
    by (*metis* (*no-types*, *lifting*) *calculation disj-comm ok-vwb-lens seqr-bool-split*)
  also from *assms*
  have ... $= (((\$ok \land P1 \Rightarrow Q1[\![true/\$ok']\!]) \;;; (P2 \Rightarrow \$ok' \land Q2[\![true/\$ok]\!])) \lor ((\neg (\$ok \land P1)) \;;; true))$
    by (*simp add*: *design-def usubst unrest*, *pred-auto*)
  also have ... $= ((\neg\$ok \;;; true_h) \lor ((\neg P1) \;;; true) \lor (Q1[\![true/\$ok']\!] \;;; (\neg P2)) \lor (\$ok' \land (Q1[\![true/\$ok']\!] \;;; Q2[\![true/\$ok]\!])))$
    by (*rel-auto*)
  also have ... $= (((\neg ((\neg P1) \;;; true)) \land \neg (Q1[\![true/\$ok']\!] \;;; (\neg P2))) \vdash (Q1[\![true/\$ok']\!] \;;; Q2[\![true/\$ok]\!]))$
    by (*simp add*: *precond-right-unit design-def unrest*, *rel-auto*)
  finally show *?thesis* **.**
qed

theorem *design-composition*:
  assumes
    $\$ok' \sharp P1$ $\$ok \sharp P2$ $\$ok' \sharp Q1$ $\$ok \sharp Q2$
  shows $((P1 \vdash Q1) \;;; (P2 \vdash Q2)) = (((\neg ((\neg P1) \;;; true)) \land \neg (Q1 \;;; (\neg P2))) \vdash (Q1 \;;; Q2))$
  using *assms* **by** (*simp add*: *design-composition-subst usubst*)

theorem *design-composition-runrest*:
  assumes
    $\$ok' \sharp P1$ $\$ok \sharp P2$ $ok \sharp\sharp Q1$ $ok \sharp\sharp Q2$
  shows $((P1 \vdash Q1) \;;; (P2 \vdash Q2)) = (((\neg ((\neg P1) \;;; true)) \land \neg (Q1^t \;;; (\neg P2))) \vdash (Q1 \;;; Q2))$
proof −
  have $(\$ok \land \$ok' \land (Q1^t \;;; Q2[\![true/\$ok]\!])) = (\$ok \land \$ok' \land (Q1 \;;; Q2))$
  proof −

have ($\$ok \wedge \$ok' \wedge (Q1 ;; Q2)) = ((\$ok \wedge Q1) ;; (Q2 \wedge \$ok'))$
by (*metis* (*no-types*, *lifting*) *conj-comm seqr-post-var-out seqr-pre-var-out*)
also have ... $= ((Q1 \wedge \$ok') ;; (\$ok \wedge Q2))$
by (*simp add*: *assms*(*3*) *assms*(*4*) *runrest-ident-var*)
also have ... $= (Q1^t ;; Q2[\![true/\$ok]\!])$
by (*metis ok-vwb-lens seqr-pre-transfer seqr-right-one-point true-alt-def uovar-convr upred-eq-true utp-pred-laws.inf.left-idem utp-rel.unrest-ouvar vwb-lens-mwb*)
finally show *?thesis*
by (*metis utp-pred-laws.inf.left-commute utp-pred-laws.inf-left-idem*)
qed
moreover have $(\neg (\neg P1 ;; true) \wedge \neg (Q1^t ;; (\neg P2))) \vdash (Q1^t ;; Q2[\![true/\$ok]\!]) =$
$(\neg (\neg P1 ;; true) \wedge \neg (Q1^t ;; (\neg P2))) \vdash (\$ok \wedge \$ok' \wedge (Q1^t ;; Q2[\![true/\$ok]\!]))$
by (*metis design-export-ok design-export-ok'*)
ultimately show *?thesis* **using** *assms*
by (*simp add*: *design-composition-subst usubst*, *metis design-export-ok design-export-ok'*)
qed

theorem *rdesign-composition*:
$((P1 \vdash_r Q1) ;; (P2 \vdash_r Q2)) = (((\neg ((\neg P1) ;; true)) \wedge \neg (Q1 ;; (\neg P2))) \vdash_r (Q1 ;; Q2))$
by (*simp add*: *rdesign-def design-composition unrest alpha*)

theorem *design-composition-cond*:
assumes
$out\alpha \sharp p1$ $\$ok \sharp P2$ $\$ok' \sharp Q1$ $\$ok \sharp Q2$
shows $((p1 \vdash Q1) ;; (P2 \vdash Q2)) = ((p1 \wedge \neg (Q1 ;; (\neg P2))) \vdash (Q1 ;; Q2))$
using *assms*
by (*simp add*: *design-composition unrest precond-right-unit*)

theorem *rdesign-composition-cond*:
assumes $out\alpha \sharp p1$
shows $((p1 \vdash_r Q1) ;; (P2 \vdash_r Q2)) = ((p1 \wedge \neg (Q1 ;; (\neg P2))) \vdash_r (Q1 ;; Q2))$
using *assms*
by (*simp add*: *rdesign-def design-composition-cond unrest alpha*)

theorem *design-composition-wp*:
assumes
$ok \sharp p1$ $ok \sharp p2$
$\$ok \sharp Q1$ $\$ok' \sharp Q1$ $\$ok \sharp Q2$ $\$ok' \sharp Q2$
shows $((\lceil p1 \rceil_< \vdash Q1) ;; (\lceil p2 \rceil_< \vdash Q2)) = ((\lceil p1 \wedge Q1\ wp\ p2 \rceil_<) \vdash (Q1 ;; Q2))$
using *assms* **by** (*rel-blast*)

theorem *rdesign-composition-wp*:
$((\lceil p1 \rceil_< \vdash_r Q1) ;; (\lceil p2 \rceil_< \vdash_r Q2)) = ((\lceil p1 \wedge Q1\ wp\ p2 \rceil_<) \vdash_r (Q1 ;; Q2))$
by (*rel-blast*)

theorem *ndesign-composition-wp* [*ndes-simp*]:
$((p1 \vdash_n Q1) ;; (p2 \vdash_n Q2)) = ((p1 \wedge Q1\ wp\ p2) \vdash_n (Q1 ;; Q2))$
by (*rel-blast*)

theorem *design-true-left-zero*: $(true ;; (P \vdash Q)) = true$
proof −
have $(true ;; (P \vdash Q)) = ((true[\![false/\$ok']\!] ;; (P \vdash Q)[\![false/\$ok]\!]) \vee (true[\![true/\$ok']\!] ;; (P \vdash Q)[\![true/\$ok]\!]))$
by (*rel-auto*)
also have ... $= ((true[\![false/\$ok']\!] ;; true_h) \vee (true ;; ((P \vdash Q)[\![true/\$ok]\!])))$

by (*subst-tac*, *rel-auto*)
also have ... = *true*
by (*subst-tac*, *simp add*: *precond-right-unit unrest*)
finally show *?thesis* .
qed

theorem *design-left-unit-hom*:
fixes $P\ Q$ :: $'\alpha$ *hrel-des*
shows $(II_D\ ;;\ (P \vdash_r Q)) = (P \vdash_r Q)$
proof −
have $(II_D\ ;;\ (P \vdash_r Q)) = ((true \vdash_r II)\ ;;\ (P \vdash_r Q))$
by (*simp add*: *skip-d-def*)
also have ... $= (true \wedge \neg\ (II\ ;;\ (\neg\ P))) \vdash_r (II\ ;;\ Q)$
proof −
have $out\alpha \sharp true$
by *unrest-tac*
thus *?thesis*
using *rdesign-composition-cond* **by** *blast*
qed
also have ... $= (\neg\ (\neg\ P)) \vdash_r Q$
by *simp*
finally show *?thesis* **by** *simp*
qed

theorem *rdesign-left-unit* [*simp*]:
$II_D\ ;;\ (P \vdash_r Q) = (P \vdash_r Q)$
by (*rel-auto*)

theorem *design-right-semi-unit*:
$(P \vdash_r Q)\ ;;\ II_D = ((\neg\ (\neg\ P)\ ;;\ true) \vdash_r Q)$
by (*simp add*: *skip-d-def rdesign-composition*)

theorem *design-right-cond-unit* [*simp*]:
assumes $out\alpha \sharp p$
shows $(p \vdash_r Q)\ ;;\ II_D = (p \vdash_r Q)$
using *assms*
by (*simp add*: *skip-d-def rdesign-composition-cond*)

theorem *ndesign-left-unit* [*simp*]:
$II_D\ ;;\ (p \vdash_n Q) = (p \vdash_n Q)$
by (*rel-auto*)

theorem *design-bot-left-zero*: $(\bot_D\ ;;\ (P \vdash Q)) = \bot_D$
by (*rel-auto*)

theorem *design-top-left-zero*: $(\top_D\ ;;\ (P \vdash Q)) = \top_D$
by (*rel-auto*)

1.5 Preconditions and Postconditions

theorem *design-npre*:
$(P \vdash Q)^f = (\neg\ \$ok \vee \neg\ P^f)$
by (*rel-auto*)

theorem *design-pre*:
$\neg\ (P \vdash Q)^f = (\$ok \wedge P^f)$

by (*simp add*: *design-def*, *subst-tac*)
(*metis* (*no-types*, *hide-lams*) *not-conj-deMorgans true-not-false*(*2*) *utp-pred-laws.compl-top-eq utp-pred-laws.sup.idem utp-pred-laws.sup-compl-top*)

theorem *design-post*:
$(P \vdash Q)^t = ((\$ok \land P^t) \Rightarrow Q^t)$
by (*rel-auto*)

theorem *rdesign-pre* [*simp*]: $pre_D(P \vdash_r Q) = P$
by (*pred-auto*)

theorem *rdesign-post* [*simp*]: $post_D(P \vdash_r Q) = (P \Rightarrow Q)$
by (*pred-auto*)

theorem *ndesign-pre* [*simp*]: $pre_D(p \vdash_n Q) = \lceil p \rceil_<$
by (*pred-auto*)

theorem *ndesign-post* [*simp*]: $post_D(p \vdash_n Q) = (\lceil p \rceil_< \Rightarrow Q)$
by (*pred-auto*)

lemma *design-pre-choice* [*simp*]:
$pre_D(P \sqcap Q) = (pre_D(P) \land pre_D(Q))$
by (*rel-auto*)

lemma *design-post-choice* [*simp*]:
$post_D(P \sqcap Q) = (post_D(P) \lor post_D(Q))$
by (*rel-auto*)

lemma *design-pre-condr* [*simp*]:
$pre_D(P \triangleleft \lceil b \rceil_D \triangleright Q) = (pre_D(P) \triangleleft b \triangleright pre_D(Q))$
by (*rel-auto*)

lemma *design-post-condr* [*simp*]:
$post_D(P \triangleleft \lceil b \rceil_D \triangleright Q) = (post_D(P) \triangleleft b \triangleright post_D(Q))$
by (*rel-auto*)

lemma *preD-USUP-mem*: pre_D $(\bigsqcup\ i \in A \cdot P\ i) = (\bigsqcap\ i \in A \cdot pre_D(P\ i))$
by (*rel-auto*)

lemma *preD-USUP-ind*: pre_D $(\bigsqcup\ i \cdot P\ i) = (\bigsqcap\ i \cdot pre_D(P\ i))$
by (*rel-auto*)

1.6 Distribution Laws

theorem *design-choice*:
$(P_1 \vdash P_2) \sqcap (Q_1 \vdash Q_2) = ((P_1 \land Q_1) \vdash (P_2 \lor Q_2))$
by (*rel-auto*)

theorem *rdesign-choice*:
$(P_1 \vdash_r P_2) \sqcap (Q_1 \vdash_r Q_2) = ((P_1 \land Q_1) \vdash_r (P_2 \lor Q_2))$
by (*rel-auto*)

theorem *ndesign-choice* [*ndes-simp*]:
$(p_1 \vdash_n P_2) \sqcap (q_1 \vdash_n Q_2) = ((p_1 \land q_1) \vdash_n (P_2 \lor Q_2))$
by (*rel-auto*)

theorem *ndesign-choice′* [*ndes-simp*]:
$((p_1 \vdash_n P_2) \vee (q_1 \vdash_n Q_2)) = ((p_1 \wedge q_1) \vdash_n (P_2 \vee Q_2))$
by (*rel-auto*)

theorem *design-inf*:
$(P_1 \vdash P_2) \sqcup (Q_1 \vdash Q_2) = ((P_1 \vee Q_1) \vdash ((P_1 \Rightarrow P_2) \wedge (Q_1 \Rightarrow Q_2)))$
by (*rel-auto*)

theorem *rdesign-inf*:
$(P_1 \vdash_r P_2) \sqcup (Q_1 \vdash_r Q_2) = ((P_1 \vee Q_1) \vdash_r ((P_1 \Rightarrow P_2) \wedge (Q_1 \Rightarrow Q_2)))$
by (*rel-auto*)

theorem *ndesign-inf* [*ndes-simp*]:
$(p_1 \vdash_n P_2) \sqcup (q_1 \vdash_n Q_2) = ((p_1 \vee q_1) \vdash_n ((\lceil p_1 \rceil_< \Rightarrow P_2) \wedge (\lceil q_1 \rceil_< \Rightarrow Q_2)))$
by (*rel-auto*)

theorem *design-condr*:
$((P_1 \vdash P_2) \triangleleft b \triangleright (Q_1 \vdash Q_2)) = ((P_1 \triangleleft b \triangleright Q_1) \vdash (P_2 \triangleleft b \triangleright Q_2))$
by (*rel-auto*)

theorem *ndesign-dcond* [*ndes-simp*]:
$((p_1 \vdash_n P_2) \triangleleft b \triangleright_D (q_1 \vdash_n Q_2)) = ((p_1 \triangleleft b \triangleright q_1) \vdash_n (P_2 \triangleleft b \triangleright_r Q_2))$
by (*rel-auto*)

lemma *design-UINF-mem*:
assumes $A \neq \{\}$
shows $(\bigsqcap\ i \in A \cdot P(i) \vdash Q(i)) = (\bigsqcup\ i \in A \cdot P(i)) \vdash (\bigsqcap\ i \in A \cdot Q(i))$
using *assms* **by** (*rel-auto*)

lemma *ndesign-UINF-mem* [*ndes-simp*]:
assumes $A \neq \{\}$
shows $(\bigsqcap\ i \in A \cdot p(i) \vdash_n Q(i)) = (\bigsqcup\ i \in A \cdot p(i)) \vdash_n (\bigsqcap\ i \in A \cdot Q(i))$
using *assms* **by** (*rel-auto*)

lemma *ndesign-UINF-ind* [*ndes-simp*]:
$(\bigsqcap\ i \cdot p(i) \vdash_n Q(i)) = (\bigsqcup\ i \cdot p(i)) \vdash_n (\bigsqcap\ i \cdot Q(i))$
by (*rel-auto*)

lemma *design-USUP-mem*:
$(\bigsqcup\ i \in A \cdot P(i) \vdash Q(i)) = (\bigsqcap\ i \in A \cdot P(i)) \vdash (\bigsqcup\ i \in A \cdot P(i) \Rightarrow Q(i))$
by (*rel-auto*)

lemma *ndesign-USUP-mem* [*ndes-simp*]:
$(\bigsqcup\ i \in A \cdot p(i) \vdash_n Q(i)) = (\bigsqcap\ i \in A \cdot p(i)) \vdash_n (\bigsqcup\ i \in A \cdot \lceil p(i) \rceil_< \Rightarrow Q(i))$
by (*rel-auto*)

lemma *ndesign-USUP-ind* [*ndes-simp*]:
$(\bigsqcup\ i \cdot p(i) \vdash_n Q(i)) = (\bigsqcap\ i \cdot p(i)) \vdash_n (\bigsqcup\ i \cdot \lceil p(i) \rceil_< \Rightarrow Q(i))$
by (*rel-auto*)

1.7 Refinement Introduction

lemma *ndesign-eq-intro*:
assumes $p_1 = q_1$ $P_2 = Q_2$
shows $p_1 \vdash_n P_2 = q_1 \vdash_n Q_2$
by (*simp add*: *assms*)

theorem *design-refinement*:
assumes
$\$ok \sharp P1$ $\$ok' \sharp P1$ $\$ok \sharp P2$ $\$ok' \sharp P2$
$\$ok \sharp Q1$ $\$ok' \sharp Q1$ $\$ok \sharp Q2$ $\$ok' \sharp Q2$
shows $(P1 \vdash Q1 \sqsubseteq P2 \vdash Q2) \longleftrightarrow (`P1 \Rightarrow P2` \wedge `P1 \wedge Q2 \Rightarrow Q1`)$
proof −
have $(P1 \vdash Q1) \sqsubseteq (P2 \vdash Q2) \longleftrightarrow `(\$ok \wedge P2 \Rightarrow \$ok' \wedge Q2) \Rightarrow (\$ok \wedge P1 \Rightarrow \$ok' \wedge Q1)`$
by (*pred-auto*)
also with *assms* **have** ... $= `(P2 \Rightarrow \$ok' \wedge Q2) \Rightarrow (P1 \Rightarrow \$ok' \wedge Q1)`$
by (*subst subst-bool-split*[*of in-var ok*], *simp-all*, *subst-tac*)
also with *assms* **have** ... $= `(\neg P2 \Rightarrow \neg P1) \wedge ((P2 \Rightarrow Q2) \Rightarrow P1 \Rightarrow Q1)`$
by (*subst subst-bool-split*[*of out-var ok*], *simp-all*, *subst-tac*)
also have ... $\longleftrightarrow `(P1 \Rightarrow P2)` \wedge `P1 \wedge Q2 \Rightarrow Q1`$
by (*pred-auto*)
finally show *?thesis* **.**
qed

theorem *rdesign-refinement*:
$(P1 \vdash_r Q1 \sqsubseteq P2 \vdash_r Q2) \longleftrightarrow (`P1 \Rightarrow P2` \wedge `P1 \wedge Q2 \Rightarrow Q1`)$
by (*rel-auto*)

lemma *design-refine-intro*:
assumes $`P1 \Rightarrow P2`$ $`P1 \wedge Q2 \Rightarrow Q1`$
shows $P1 \vdash Q1 \sqsubseteq P2 \vdash Q2$
using *assms* **unfolding** *upred-defs*
by (*pred-auto*)

lemma *design-refine-intro'*:
assumes $P_2 \sqsubseteq P_1$ $Q_1 \sqsubseteq (P_1 \wedge Q_2)$
shows $P_1 \vdash Q_1 \sqsubseteq P_2 \vdash Q_2$
using *assms design-refine-intro*[*of* P_1 P_2 Q_2 Q_1] **by** (*simp add*: *refBy-order*)

lemma *rdesign-refine-intro*:
assumes $`P1 \Rightarrow P2`$ $`P1 \wedge Q2 \Rightarrow Q1`$
shows $P1 \vdash_r Q1 \sqsubseteq P2 \vdash_r Q2$
using *assms* **unfolding** *upred-defs*
by (*pred-auto*)

lemma *rdesign-refine-intro'*:
assumes $P2 \sqsubseteq P1$ $Q1 \sqsubseteq (P1 \wedge Q2)$
shows $P1 \vdash_r Q1 \sqsubseteq P2 \vdash_r Q2$
using *assms* **unfolding** *upred-defs*
by (*pred-auto*)

lemma *ndesign-refinement*:
$p1 \vdash_n Q1 \sqsubseteq p2 \vdash_n Q2 \longleftrightarrow (`p1 \Rightarrow p2` \wedge `\lceil p1 \rceil_< \wedge Q2 \Rightarrow Q1`)$
by (*simp add*: *ndesign-def rdesign-def design-refinement unrest*, *rel-auto*)

lemma *ndesign-refine-intro*:
assumes $`p1 \Rightarrow p2`$ $`\lceil p1 \rceil_< \wedge Q2 \Rightarrow Q1`$
shows $p1 \vdash_n Q1 \sqsubseteq p2 \vdash_n Q2$
using *assms* **unfolding** *upred-defs*
by (*pred-auto*)

lemma *design-top*:
  $(P \vdash Q) \sqsubseteq \top_D$
  by (*rel-auto*)

lemma *design-bottom*:
  $\bot_D \sqsubseteq (P \vdash Q)$
  by (*rel-auto*)

lemma *design-refine-thms*:
  assumes $P \sqsubseteq Q$
  shows ‘$pre_D(P) \Rightarrow pre_D(Q)$‘ ‘$pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)$‘
  apply (*metis assms design-pre-choice disj-comm disj-upred-def order-refl rdesign-refinement utp-pred-laws.le-iff-sup*)
  apply (*metis assms conj-comm design-post-choice disj-upred-def refBy-order semilattice-sup-class.le-iff-sup utp-pred-laws.inf.coboundedI1*)
done

end

2 Design Healthiness Conditions

theory *utp-des-healths*
  imports *utp-des-core*
begin

2.1 H1: No observation is allowed before initiation

definition $H1 :: ('\alpha, '\beta)$ *rel-des* $\Rightarrow ('\alpha, '\beta)$ *rel-des* **where**
[*upred-defs*]: $H1(P) = (\$ok \Rightarrow P)$

lemma *H1-idem*:
  $H1\ (H1\ P) = H1(P)$
  by (*pred-auto*)

lemma *H1-monotone*:
  $P \sqsubseteq Q \Longrightarrow H1(P) \sqsubseteq H1(Q)$
  by (*pred-auto*)

lemma *H1-Continuous*: *Continuous H1*
  by (*rel-auto*)

lemma *H1-below-top*:
  $H1(P) \sqsubseteq \top_D$
  by (*pred-auto*)

lemma *H1-design-skip*:
  $H1(II) = II_D$
  by (*rel-auto*)

lemma *H1-cond*: $H1(P \triangleleft b \triangleright Q) = H1(P) \triangleleft b \triangleright H1(Q)$
  by (*rel-auto*)

lemma *H1-conj*: $H1(P \wedge Q) = (H1(P) \wedge H1(Q))$
  by (*rel-auto*)

lemma *H1-disj*: $H1(P \vee Q) = (H1(P) \vee H1(Q))$

by (*rel-auto*)

lemma *design-export-H1*: $(P \vdash Q) = (P \vdash H1(Q))$
by (*rel-auto*)

The H1 algebraic laws are valid only when $\alpha(R)$ is homogeneous. This should maybe be generalised.

theorem *H1-algebraic-intro*:
assumes
$(true_h \;;\; R) = true_h$
$(II_D \;;\; R) = R$
shows *R is H1*
proof –
have $R = (II_D \;;\; R)$ **by** (*simp add*: *assms(2)*)
also have ... $= (H1(II) \;;\; R)$
by (*simp add*: *H1-design-skip*)
also have ... $= ((\$ok \Rightarrow II) \;;\; R)$
by (*simp add*: *H1-def*)
also have ... $= (((\neg \$ok) \;;\; R) \vee R)$
by (*simp add*: *impl-alt-def seqr-or-distl*)
also have ... $= ((((\neg \$ok) \;;\; true_h) \;;\; R) \vee R)$
by (*simp add*: *precond-right-unit unrest*)
also have ... $= (((\neg \$ok) \;;\; true_h) \vee R)$
by (*metis assms(1) seqr-assoc*)
also have ... $= (\$ok \Rightarrow R)$
by (*simp add*: *impl-alt-def precond-right-unit unrest*)
finally show *?thesis* **by** (*metis H1-def Healthy-def'*)
qed

lemma *nok-not-false*:
$(\neg \$ok) \neq false$
by (*pred-auto*)

theorem *H1-left-zero*:
assumes *P is H1*
shows $(true \;;\; P) = true$
proof –
from *assms* **have** $(true \;;\; P) = (true \;;\; (\$ok \Rightarrow P))$
by (*simp add*: *H1-def Healthy-def'*)

also from *assms* **have** ... $= (true \;;\; (\neg \$ok \vee P))$ (**is** - = (*?true* ;; -))
by (*simp add*: *impl-alt-def*)
also from *assms* **have** ... $= ((?true \;;\; (\neg \$ok)) \vee (?true \;;\; P))$
using *seqr-or-distr* **by** *blast*
also from *assms* **have** ... $= (true \vee (true \;;\; P))$
by (*simp add*: *nok-not-false precond-left-zero unrest*)
finally show *?thesis*
by (*simp add*: *upred-defs urel-defs*)
qed

theorem *H1-left-unit*:
fixes P :: *'α hrel-des*
assumes *P is H1*
shows $(II_D \;;\; P) = P$
proof –

have $(II_D\ ;;\ P) = ((\$ok \Rightarrow II)\ ;;\ P)$
by (*metis H1-def H1-design-skip*)
also have ... $= (((\neg\ \$ok)\ ;;\ P) \vee P)$
by (*simp add*: *impl-alt-def seqr-or-distl*)
also from *assms* **have** ... $= ((((\neg\ \$ok)\ ;;\ true_h)\ ;;\ P) \vee P)$
by (*simp add*: *precond-right-unit unrest*)
also have ... $= (((\neg\ \$ok)\ ;;\ (true_h\ ;;\ P)) \vee P)$
by (*simp add*: *seqr-assoc*)
also from *assms* **have** ... $= (\$ok \Rightarrow P)$
by (*simp add*: *H1-left-zero impl-alt-def precond-right-unit unrest*)
finally show *?thesis* **using** *assms*
by (*simp add*: *H1-def Healthy-def'*)
qed

theorem *H1-algebraic*:
P *is* $H1 \longleftrightarrow (true_h\ ;;\ P) = true_h \wedge (II_D\ ;;\ P) = P$
using *H1-algebraic-intro H1-left-unit H1-left-zero* **by** *blast*

theorem *H1-nok-left-zero*:
fixes $P :: {'\alpha}\ hrel\text{-}des$
assumes P *is H1*
shows $((\neg\ \$ok)\ ;;\ P) = (\neg\ \$ok)$
proof –
have $((\neg\ \$ok)\ ;;\ P) = (((\neg\ \$ok)\ ;;\ true_h)\ ;;\ P)$
by (*simp add*: *precond-right-unit unrest*)
also have ... $= ((\neg\ \$ok)\ ;;\ true_h)$
by (*metis H1-left-zero assms seqr-assoc*)
also have ... $= (\neg\ \$ok)$
by (*simp add*: *precond-right-unit unrest*)
finally show *?thesis* **.**
qed

lemma *H1-design*:
$H1(P \vdash Q) = (P \vdash Q)$
by (*rel-auto*)

lemma *H1-rdesign*:
$H1(P \vdash_r Q) = (P \vdash_r Q)$
by (*rel-auto*)

lemma *H1-choice-closed* [*closure*]:
$[\![\ P\ is\ H1;\ Q\ is\ H1\ ]\!] \Longrightarrow P \sqcap Q\ is\ H1$
by (*simp add*: *H1-def Healthy-def' disj-upred-def impl-alt-def semilattice-sup-class.sup-left-commute*)

lemma *H1-inf-closed* [*closure*]:
$[\![\ P\ is\ H1;\ Q\ is\ H1\ ]\!] \Longrightarrow P \sqcup Q\ is\ H1$
by (*rel-blast*)

lemma *H1-UINF*:
assumes $A \neq \{\}$
shows $H1(\prod\ i \in A \cdot P(i)) = (\prod\ i \in A \cdot H1(P(i)))$
using *assms* **by** (*rel-auto*)

lemma *H1-Sup*:
assumes $A \neq \{\}\ \forall\ P \in A.\ P\ is\ H1$

shows ($\bigsqcap$ A) *is H1*
proof $-$
from *assms*(*2*) **have** *H1* ‘ $A = A$
by (*auto simp add*: *Healthy-def rev-image-eqI*)
with *H1-UINF*[*of A id*, *OF assms*(*1*)] **show** *?thesis*
by (*simp add*: *UINF-as-Sup-image Healthy-def*, *presburger*)
qed

lemma *H1-USUP*:
shows $H1(\bigsqcup\ i \in A \cdot P(i)) = (\bigsqcup\ i \in A \cdot H1(P(i)))$
by (*rel-auto*)

lemma *H1-Inf* [*closure*]:
assumes $\forall\ P \in A.\ P$ *is H1*
shows ($\bigsqcup$ A) *is H1*
proof $-$
from *assms* **have** *H1* ‘ $A = A$
by (*auto simp add*: *Healthy-def rev-image-eqI*)
with *H1-USUP*[*of A id*] **show** *?thesis*
by (*simp add*: *USUP-as-Inf-image Healthy-def*, *presburger*)
qed

2.2 H2: A specification cannot require non-termination

definition J :: $'\alpha$ *hrel-des* **where**
[*upred-defs*]: $J = ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D)$

definition *H2* **where**
[*upred-defs*]: $H2\ (P)\ \equiv\ P\ ;;\ J$

lemma *J-split*:
shows $(P\ ;;\ J) = (P^f \vee (P^t \wedge \$ok'))$
proof $-$
have $(P\ ;;\ J) = (P\ ;;\ ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D))$
by (*simp add*: *H2-def J-def design-def*)
also have ... $= (P\ ;;\ ((\$ok \Rightarrow \$ok \wedge \$ok') \wedge \lceil II \rceil_D))$
by (*rel-auto*)
also have ... $= ((P\ ;;\ (\neg\ \$ok \wedge \lceil II \rceil_D)) \vee (P\ ;;\ (\$ok \wedge (\lceil II \rceil_D \wedge \$ok'))))$
by (*rel-auto*)
also have ... $= (P^f \vee (P^t \wedge \$ok'))$
proof $-$
have $(P\ ;;\ (\neg\ \$ok \wedge \lceil II \rceil_D)) = P^f$
proof $-$
have $(P\ ;;\ (\neg\ \$ok \wedge \lceil II \rceil_D)) = ((P \wedge \neg\ \$ok')\ ;;\ \lceil II \rceil_D)$
by (*rel-auto*)
also have ... $= (\exists\ \$ok' \cdot P \wedge \$ok' =_u \mathit{false})$
by (*rel-auto*)
also have ... $= P^f$
by (*metis C1 one-point out-var-uvar unrest-as-exists ok-vwb-lens vwb-lens-mwb*)
finally show *?thesis* **.**
qed
moreover have $(P\ ;;\ (\$ok \wedge (\lceil II \rceil_D \wedge \$ok'))) = (P^t \wedge \$ok')$
proof $-$
have $(P\ ;;\ (\$ok \wedge (\lceil II \rceil_D \wedge \$ok'))) = (P\ ;;\ (\$ok \wedge II))$
by (*rel-auto*)
also have ... $= (P^t \wedge \$ok')$

by (*rel-auto*)
finally show *?thesis* .
qed
ultimately show *?thesis*
by *simp*
qed
finally show *?thesis* .
qed

lemma *H2-split*:
shows $H2(P) = (P^f \vee (P^t \wedge \$ok'))$
by (*simp add*: *H2-def J-split*)

theorem *H2-equivalence*:
P *is* $H2 \longleftrightarrow$ ‘$P^f \Rightarrow P^t$‘
proof −
have ‘$P \Leftrightarrow (P ;; J)$‘ $\longleftrightarrow$ ‘$P \Leftrightarrow (P^f \vee (P^t \wedge \$ok'))$‘
by (*simp add*: *J-split*)
also have ... $\longleftrightarrow$ ‘$(P \Leftrightarrow P^f \vee P^t \wedge \$ok')^f \wedge (P \Leftrightarrow P^f \vee P^t \wedge \$ok')^t$‘
by (*simp add*: *subst-bool-split*)
also have ... = ‘$(P^f \Leftrightarrow P^f) \wedge (P^t \Leftrightarrow P^f \vee P^t)$‘
by *subst-tac*
also have ... = ‘$P^t \Leftrightarrow (P^f \vee P^t)$‘
by (*pred-auto robust*)
also have ... = ‘$(P^f \Rightarrow P^t)$‘
by (*pred-auto*)
finally show *?thesis*
by (*metis H2-def Healthy-def' taut-iff-eq*)
qed

lemma *H2-equiv*:
P *is* $H2 \longleftrightarrow P^t \sqsubseteq P^f$
using *H2-equivalence refBy-order* **by** *blast*

lemma *H2-design*:
assumes $\$ok' \sharp P$ $\$ok' \sharp Q$
shows $H2(P \vdash Q) = P \vdash Q$
using *assms*
by (*simp add*: *H2-split design-def usubst unrest*, *pred-auto*)

lemma *H2-rdesign*:
$H2(P \vdash_r Q) = P \vdash_r Q$
by (*simp add*: *H2-design unrest rdesign-def*)

theorem *J-idem*:
$(J ;; J) = J$
by (*rel-auto*)

theorem *H2-idem*:
$H2(H2(P)) = H2(P)$
by (*metis H2-def J-idem seqr-assoc*)

theorem *H2-Continuous*: *Continuous H2*
by (*rel-auto*)

theorem *H2-not-okay*: $H2\ (\neg\ \$ok) = (\neg\ \$ok)$
proof −
  have $H2\ (\neg\ \$ok) = ((\neg\ \$ok)^f \lor ((\neg\ \$ok)^t \land \$ok'))$
    by (*simp add*: *H2-split*)
  also have ... $= (\neg\ \$ok \lor (\neg\ \$ok) \land \$ok')$
    by (*subst-tac*)
  also have ... $= (\neg\ \$ok)$
    by (*pred-auto*)
  finally show *?thesis* **.**
qed

lemma *H2-true*: $H2(true) = true$
  by (*rel-auto*)

lemma *H2-choice-closed* [*closure*]:
  $[\![\ P\ is\ H2;\ Q\ is\ H2\ ]\!] \Longrightarrow P \sqcap Q\ is\ H2$
  by (*metis H2-def Healthy-def′ disj-upred-def seqr-or-distl*)

lemma *H2-inf-closed* [*closure*]:
  assumes P *is H2* Q *is H2*
  shows $P \sqcup Q$ *is H2*
proof −
  have $P \sqcup Q = (P^f \lor P^t \land \$ok') \sqcup (Q^f \lor Q^t \land \$ok')$
    by (*metis H2-def Healthy-def J-split assms*(*1*) *assms*(*2*))
  moreover have *H2*(...) = ...
    by (*simp add*: *H2-split usubst*, *pred-auto*)
  ultimately show *?thesis*
    by (*simp add*: *Healthy-def*)
qed

lemma *H2-USUP*:
  shows $H2(\prod\ i \in A \cdot P(i)) = (\prod\ i \in A \cdot H2(P(i)))$
  by (*rel-auto*)

theorem *H1-H2-commute*:
  $H1\ (H2\ P) = H2\ (H1\ P)$
proof −
  have $H2\ (H1\ P) = ((\$ok \Rightarrow P)\ ;;\ J)$
    by (*simp add*: *H1-def H2-def*)
  also have ... $= ((\neg\ \$ok \lor P)\ ;;\ J)$
    by (*rel-auto*)
  also have ... $= (((\neg\ \$ok)\ ;;\ J) \lor (P\ ;;\ J))$
    using *seqr-or-distl* **by** *blast*
  also have ... $= ((H2\ (\neg\ \$ok)) \lor H2(P))$
    by (*simp add*: *H2-def*)
  also have ... $= ((\neg\ \$ok) \lor H2(P))$
    by (*simp add*: *H2-not-okay*)
  also have ... $= H1(H2(P))$
    by (*rel-auto*)
  finally show *?thesis* **by** *simp*
qed

2.3 Designs as $H1$-$H2$ predicates

abbreviation *H1-H2* :: $('\alpha, '\beta)$ *rel-des* $\Rightarrow$ $('\alpha, '\beta)$ *rel-des* (**H**) **where**
H1-H2 P $\equiv$ *H1* (*H2 P*)

lemma *H1-H2-comp*: $\mathbf{H} = H1 \circ H2$
  by (*auto*)

theorem *H1-H2-eq-design*:
  $\mathbf{H}(P) = (\neg\ P^f) \vdash P^t$
proof −
  have $\mathbf{H}(P) = (\$ok \Rightarrow H2(P))$
    by (*simp add*: *H1-def*)
  also have ... $= (\$ok \Rightarrow (P^f \lor (P^t \land \$ok')))$
    by (*metis H2-split*)
  also have ... $= (\$ok \land (\neg\ P^f) \Rightarrow \$ok' \land \$ok \land P^t)$
    by (*rel-auto*)
  also have ... $= (\neg\ P^f) \vdash P^t$
    by (*rel-auto*)
  finally show *?thesis* **.**
qed

theorem *H1-H2-is-design*:
  assumes *P is H1 P is H2*
  shows $P = (\neg\ P^f) \vdash P^t$
  using *assms* **by** (*metis H1-H2-eq-design Healthy-def*)

theorem *H1-H2-eq-rdesign*:
  $\mathbf{H}(P) = pre_D(P) \vdash_r post_D(P)$
proof −
  have $\mathbf{H}(P) = (\$ok \Rightarrow H2(P))$
    by (*simp add*: *H1-def Healthy-def'*)
  also have ... $= (\$ok \Rightarrow (P^f \lor (P^t \land \$ok')))$
    by (*metis H2-split*)
  also have ... $= (\$ok \land (\neg\ P^f) \Rightarrow \$ok' \land P^t)$
    by (*pred-auto*)
  also have ... $= (\$ok \land (\neg\ P^f) \Rightarrow \$ok' \land \$ok \land P^t)$
    by (*pred-auto*)
  also have ... $= (\$ok \land \lceil pre_D(P) \rceil_D \Rightarrow \$ok' \land \$ok \land \lceil post_D(P) \rceil_D)$
    by (*simp add*: *ok-post ok-pre*)
  also have ... $= (\$ok \land \lceil pre_D(P) \rceil_D \Rightarrow \$ok' \land \lceil post_D(P) \rceil_D)$
    by (*pred-auto*)
  also have ... $= pre_D(P) \vdash_r post_D(P)$
    by (*simp add*: *rdesign-def design-def*)
  finally show *?thesis* **.**
qed

theorem *H1-H2-is-rdesign*:
  assumes *P is H1 P is H2*
  shows $P = pre_D(P) \vdash_r post_D(P)$
  by (*metis H1-H2-eq-rdesign Healthy-def assms*(*1*) *assms*(*2*))

lemma *H1-H2-refinement*:
  assumes *P is* **H** *Q is* **H**
  shows $P \sqsubseteq Q \longleftrightarrow (`pre_D(P) \Rightarrow pre_D(Q)` \land `pre_D(P) \land post_D(Q) \Rightarrow post_D(P)`)$
  by (*metis H1-H2-eq-rdesign Healthy-if assms rdesign-refinement*)

lemma *H1-H2-refines*:
  assumes *P is* **H** *Q is* **H** $P \sqsubseteq Q$

shows $pre_D(Q) \sqsubseteq pre_D(P)$ $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$
using *H1-H2-refinement assms refBy-order* **by** *auto*

lemma *H1-H2-idempotent*: $\mathbf{H}$ ($\mathbf{H}$ P) = $\mathbf{H}$ P
by (*simp add*: *H1-H2-commute H1-idem H2-idem*)

lemma *H1-H2-Idempotent* [*closure*]: *Idempotent* $\mathbf{H}$
by (*simp add*: *Idempotent-def H1-H2-idempotent*)

lemma *H1-H2-monotonic* [*closure*]: *Monotonic* $\mathbf{H}$
by (*simp add*: *H1-monotone H2-def mono-def seqr-mono*)

lemma *H1-H2-Continuous* [*closure*]: *Continuous* $\mathbf{H}$
by (*simp add*: *Continuous-comp H1-Continuous H1-H2-comp H2-Continuous*)

lemma *design-is-H1-H2* [*closure*]:
$\llbracket$ $\$ok'$ $\sharp$ P; $\$ok'$ $\sharp$ Q $\rrbracket \Longrightarrow (P \vdash Q)$ *is* $\mathbf{H}$
by (*simp add*: *H1-design H2-design Healthy-def'*)

lemma *rdesign-is-H1-H2* [*closure*]:
$(P \vdash_r Q)$ *is* $\mathbf{H}$
by (*simp add*: *Healthy-def H1-rdesign H2-rdesign*)

lemma *top-d-is-H1-H2* [*closure*]: $\top_D$ *is* $\mathbf{H}$
by (*simp add*: *H1-def H2-not-okay Healthy-intro impl-alt-def*)

lemma *bot-d-is-H1-H2* [*closure*]: $\bot_D$ *is* $\mathbf{H}$
by (*simp add*: *bot-d-def closure unrest*)

lemma *seq-r-H1-H2-closed* [*closure*]:
assumes P *is* $\mathbf{H}$ Q *is* $\mathbf{H}$
shows $(P ;; Q)$ *is* $\mathbf{H}$
proof −
obtain P_1 P_2 **where** $P = P_1 \vdash_r P_2$
by (*metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def assms*(*1*))
moreover obtain Q_1 Q_2 **where** $Q = Q_1 \vdash_r Q_2$
by (*metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def assms*(*2*))
moreover have $((P_1 \vdash_r P_2) ;; (Q_1 \vdash_r Q_2))$ *is* $\mathbf{H}$
by (*simp add*: *rdesign-composition rdesign-is-H1-H2*)
ultimately show *?thesis* **by** *simp*
qed

lemma *UINF-H1-H2-closed* [*closure*]:
assumes $A \neq \{\}$ $\forall$ $P \in A$. P *is* $\mathbf{H}$
shows $(\bigsqcap A)$ *is H1-H2*
proof −
from *assms* **have** A: A = *H1-H2* ‘ A
by (*auto simp add*: *Healthy-def rev-image-eqI*)
also have $(\bigsqcap ...) = (\bigsqcap P \in A \cdot$ *H1-H2*$(P))$
by (*simp add*: *UINF-as-Sup-collect*)
also have ... $= (\bigsqcap P \in A \cdot (\neg P^f) \vdash P^t)$
by (*meson H1-H2-eq-design*)
also have ... $= (\bigsqcup P \in A \cdot \neg P^f) \vdash (\bigsqcap P \in A \cdot P^t)$
by (*simp add*: *design-UINF-mem assms*)
also have ... *is H1-H2*

by (*simp add*: *design-is-H1-H2 unrest*)
finally show *?thesis* **.**
qed

definition *design-inf* :: ($'\alpha$, $'\beta$) *rel-des set* $\Rightarrow$ ($'\alpha$, $'\beta$) *rel-des* ($\bigsqcap_D$- [*900*] *900*) **where**
$\bigsqcap_D$ A = (*if* (A = {}) *then* $\top_D$ *else* $\bigsqcap$ A)

abbreviation *design-sup* :: ($'\alpha$, $'\beta$) *rel-des set* $\Rightarrow$ ($'\alpha$, $'\beta$) *rel-des* ($\bigsqcup_D$- [*900*] *900*) **where**
$\bigsqcup_D$ $A \equiv \bigsqcup$ A

lemma *design-inf-H1-H2-closed*:
assumes $\forall$ $P \in A$. P *is* **H**
shows ($\bigsqcap_D$ A) *is* **H**
apply (*auto simp add*: *design-inf-def closure*)
apply (*simp add*: *H1-def H2-not-okay Healthy-def impl-alt-def*)
apply (*metis H1-def Healthy-def UINF-H1-H2-closed assms empty-iff impl-alt-def*)
done

lemma *design-sup-empty* [*simp*]: $\bigsqcap_D$ {} = $\top_D$
by (*simp add*: *design-inf-def*)

lemma *design-sup-non-empty* [*simp*]: $A \neq \{\} \Longrightarrow \bigsqcap_D$ A = $\bigsqcap$ A
by (*simp add*: *design-inf-def*)

lemma *USUP-mem-H1-H2-closed*:
assumes $\bigwedge$ i. $i \in A \Longrightarrow P$ i *is* **H**
shows ($\bigsqcup$ $i{\in}A$ $\cdot$ P i) *is* **H**
proof –
from *assms* **have** ($\bigsqcup$ $i{\in}A$ $\cdot$ P i) = ($\bigsqcup$ $i{\in}A$ $\cdot$ **H**(P i))
by (*auto intro*: *USUP-cong simp add*: *Healthy-def*)
also have ... = ($\bigsqcup$ $i{\in}A$ $\cdot$ ($\neg$ (P i)^f) $\vdash$ (P i)^t)
by (*meson H1-H2-eq-design*)
also have ... = ($\bigsqcap$ $i{\in}A$ $\cdot$ $\neg$ (P i)^f) $\vdash$ ($\bigsqcup$ $i{\in}A$ $\cdot$ $\neg$ (P i)^f $\Rightarrow$ (P i)^t)
by (*simp add*: *design-USUP-mem*)
also have ... *is* **H**
by (*simp add*: *design-is-H1-H2 unrest*)
finally show *?thesis* **.**
qed

lemma *USUP-ind-H1-H2-closed*:
assumes $\bigwedge$ i. P i *is* **H**
shows ($\bigsqcup$ i $\cdot$ P i) *is* **H**
using *assms USUP-mem-H1-H2-closed*[*of UNIV P*] **by** *simp*

lemma *Inf-H1-H2-closed*:
assumes $\forall$ $P \in A$. P *is* **H**
shows ($\bigsqcup$ A) *is* **H**
proof –
from *assms* **have** A: A = **H** ‘ A
by (*auto simp add*: *Healthy-def rev-image-eqI*)
also have ($\bigsqcup$ ...) = ($\bigsqcup$ $P \in A$ $\cdot$ **H**(P))
by (*simp add*: *USUP-as-Inf-collect*)
also have ... = ($\bigsqcup$ $P \in A$ $\cdot$ ($\neg$ P^f) $\vdash$ P^t)
by (*meson H1-H2-eq-design*)
also have ... = ($\bigsqcap$ $P \in A$ $\cdot$ $\neg$ P^f) $\vdash$ ($\bigsqcup$ $P \in A$ $\cdot$ $\neg$ P^f $\Rightarrow$ P^t)

by (*simp add*: *design-USUP-mem*)
also have ... *is* **H**
by (*simp add*: *design-is-H1-H2 unrest*)
finally show *?thesis* **.**
qed

lemma *rdesign-ref-monos*:
assumes P *is* **H** Q *is* **H** $P \sqsubseteq Q$
shows $pre_D(Q) \sqsubseteq pre_D(P)$ $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$
proof −
have r: $P \sqsubseteq Q \longleftrightarrow$ (‘$pre_D(P) \Rightarrow pre_D(Q)$‘ $\wedge$ ‘$pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)$‘)
by (*metis H1-H2-eq-rdesign Healthy-if assms*(*1*) *assms*(*2*) *rdesign-refinement*)
from *r assms* **show** $pre_D(Q) \sqsubseteq pre_D(P)$
by (*auto simp add*: *refBy-order*)
from *r assms* **show** $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$
by (*auto simp add*: *refBy-order*)
qed

2.4 H3: The design assumption is a precondition

definition *H3* :: ($'\alpha$, $'\beta$) *rel-des* $\Rightarrow$ ($'\alpha$, $'\beta$) *rel-des* **where**
[*upred-defs*]: *H3* (P) $\equiv$ P ;; II_D

theorem *H3-idem*:
H3(*H3*(P)) = *H3*(P)
by (*metis H3-def design-skip-idem seqr-assoc*)

theorem *H3-mono*:
$P \sqsubseteq Q \Longrightarrow$ *H3*(P) $\sqsubseteq$ *H3*(Q)
by (*simp add*: *H3-def seqr-mono*)

theorem *H3-Monotonic*:
Monotonic H3
by (*simp add*: *H3-mono mono-def*)

theorem *H3-Continuous*: *Continuous H3*
by (*rel-auto*)

theorem *design-condition-is-H3*:
assumes $out\alpha \sharp p$
shows ($p \vdash Q$) *is H3*
proof −
have $((p \vdash Q) ;; II_D) = (\neg ((\neg p) ;; true)) \vdash (Q^t ;; II[\![true/\$ok]\!])$
by (*simp add*: *skip-d-alt-def design-composition-subst unrest assms*)
also have ... $= p \vdash (Q^t ;; II[\![true/\$ok]\!])$
using *assms precond-equiv seqr-true-lemma* **by** *force*
also have ... $= p \vdash Q$
by (*rel-auto*)
finally show *?thesis*
by (*simp add*: *H3-def Healthy-def'*)
qed

theorem *rdesign-H3-iff-pre*:
$P \vdash_r Q$ *is H3* $\longleftrightarrow P = (P ;; true)$
proof −
have $(P \vdash_r Q) ;; II_D = (P \vdash_r Q) ;; (true \vdash_r II)$

by (*simp add*: *skip-d-def*)
also have ... $= (\neg ((\neg P) ;; true) \wedge \neg (Q ;; (\neg true))) \vdash_r (Q ;; II)$
by (*simp add*: *rdesign-composition*)
also have ... $= (\neg ((\neg P) ;; true) \wedge \neg (Q ;; (\neg true))) \vdash_r Q$
by *simp*
also have ... $= (\neg ((\neg P) ;; true)) \vdash_r Q$
by (*pred-auto*)
finally have $P \vdash_r Q$ *is H3* $\longleftrightarrow P \vdash_r Q = (\neg ((\neg P) ;; true)) \vdash_r Q$
by (*metis H3-def Healthy-def′*)
also have ... $\longleftrightarrow P = (\neg ((\neg P) ;; true))$
by (*metis rdesign-pre*)
thm *seqr-true-lemma*
also have ... $\longleftrightarrow P = (P ;; true)$
by (*simp add*: *seqr-true-lemma*)
finally show *?thesis* **.**
qed

theorem *design-H3-iff-pre*:
assumes $\$ok \sharp P$ $\$ok' \sharp P$ $\$ok \sharp Q$ $\$ok' \sharp Q$
shows $P \vdash Q$ *is H3* $\longleftrightarrow P = (P ;; true)$
proof −
have $P \vdash Q = \lfloor P \rfloor_D \vdash_r \lfloor Q \rfloor_D$
by (*simp add*: *assms lift-desr-inv rdesign-def*)
moreover hence $\lfloor P \rfloor_D \vdash_r \lfloor Q \rfloor_D$ *is H3* $\longleftrightarrow \lfloor P \rfloor_D = (\lfloor P \rfloor_D ;; true)$
using *rdesign-H3-iff-pre* **by** *blast*
ultimately show *?thesis*
by (*metis assms*(*1*,*2*) *drop-desr-inv lift-desr-inv lift-dist-seq aext-true*)
qed

theorem *H1-H3-commute*:
$H1\ (H3\ P) = H3\ (H1\ P)$
by (*rel-auto*)

lemma *skip-d-absorb-J-1*:
$(II_D ;; J) = II_D$
by (*metis H2-def H2-rdesign skip-d-def*)

lemma *skip-d-absorb-J-2*:
$(J ;; II_D) = II_D$
proof −
have $(J ;; II_D) = ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D) ;; (true \vdash II)$
by (*simp add*: *J-def skip-d-alt-def*)
also have ... $= ((((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D)[\![false/\$ok']\!] ;; (true \vdash II)[\![false/\$ok]\!])$
$\vee (((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D)[\![true/\$ok']\!] ;; (true \vdash II)[\![true/\$ok]\!]))$
by (*rel-auto*)
also have ... $= ((\neg \$ok \wedge \lceil II \rceil_D ;; true) \vee (\lceil II \rceil_D ;; \$ok' \wedge \lceil II \rceil_D))$
by (*rel-auto*)
also have ... $= II_D$
by (*rel-auto*)
finally show *?thesis* **.**
qed

lemma *H2-H3-absorb*:
$H2\ (H3\ P) = H3\ P$
by (*metis H2-def H3-def seqr-assoc skip-d-absorb-J-1*)

lemma *H3-H2-absorb*:
  $H3\ (H2\ P) = H3\ P$
  by (*metis H2-def H3-def seqr-assoc skip-d-absorb-J-2*)

theorem *H2-H3-commute*:
  $H2\ (H3\ P) = H3\ (H2\ P)$
  by (*simp add*: *H2-H3-absorb H3-H2-absorb*)

theorem *H3-design-pre*:
  assumes $\$ok \sharp p$ $out\alpha \sharp p$ $\$ok \sharp Q$ $\$ok' \sharp Q$
  shows $H3(p \vdash Q) = p \vdash Q$
  using *assms*
  by (*metis Healthy-def' design-H3-iff-pre precond-right-unit unrest-outα-var ok-vwb-lens vwb-lens-mwb*)

theorem *H3-rdesign-pre*:
  assumes $out\alpha \sharp p$
  shows $H3(p \vdash_r Q) = p \vdash_r Q$
  using *assms*
  by (*simp add*: *H3-def*)

theorem *H3-ndesign*: $H3(p \vdash_n Q) = (p \vdash_n Q)$
  by (*simp add*: *H3-def ndesign-def unrest-pre-outα*)

theorem *ndesign-is-H3* [*closure*]: $p \vdash_n Q$ *is H3*
  by (*simp add*: *H3-ndesign Healthy-def*)

2.5 Normal Designs as $H1$-$H3$ predicates

A normal design [3] refers only to initial state variables in the precondition.

abbreviation *H1-H3* :: $('\alpha, '\beta)$ *rel-des* $\Rightarrow$ $('\alpha, '\beta)$ *rel-des* (**N**) **where**
H1-H3 $p \equiv H1\ (H3\ p)$

lemma *H1-H3-comp*: *H1-H3* $= H1 \circ H3$
  by (*auto*)

theorem *H1-H3-is-design*:
  assumes P *is H1* P *is H3*
  shows $P = (\neg P^f) \vdash P^t$
  by (*metis H1-H2-eq-design H2-H3-absorb Healthy-def' assms*(*1*) *assms*(*2*))

theorem *H1-H3-is-rdesign*:
  assumes P *is H1* P *is H3*
  shows $P = pre_D(P) \vdash_r post_D(P)$
  by (*metis H1-H2-is-rdesign H2-H3-absorb Healthy-def' assms*)

theorem *H1-H3-is-normal-design*:
  assumes P *is H1* P *is H3*
  shows $P = \lfloor pre_D(P) \rfloor_< \vdash_n post_D(P)$
  by (*metis H1-H3-is-rdesign assms drop-pre-inv ndesign-def precond-equiv rdesign-H3-iff-pre*)

lemma *H1-H3-idempotent*: $\mathbf{N}\ (\mathbf{N}\ P) = \mathbf{N}\ P$
  by (*simp add*: *H1-H3-commute H1-idem H3-idem*)

lemma *H1-H3-Idempotent* [*closure*]: *Idempotent* **N**

by (*simp add*: *Idempotent-def H1-H3-idempotent*)

lemma *H1-H3-monotonic* [*closure*]: *Monotonic* **N**
by (*simp add*: *H1-monotone H3-mono mono-def*)

lemma *H1-H3-Continuous* [*closure*]: *Continuous* **N**
by (*simp add*: *Continuous-comp H1-Continuous H1-H3-comp H3-Continuous*)

lemma *H1-H3-intro*:
assumes P *is* **H** $out\alpha \sharp pre_D(P)$
shows P *is* **N**
by (*metis H1-H2-eq-rdesign H1-rdesign H3-rdesign-pre Healthy-def′ assms*)

lemma *H1-H3-impl-H2* [*closure*]: P *is* **N** $\Longrightarrow$ P *is* **H**
by (*metis H1-H2-commute H1-idem H2-H3-absorb Healthy-def′*)

lemma *H1-H3-eq-design-d-comp*: $\mathbf{N}(P) = ((\neg P^f) \vdash P^t) ;; II_D$
by (*metis H1-H2-eq-design H1-H3-commute H3-H2-absorb H3-def*)

lemma *H1-H3-eq-design*: $\mathbf{N}(P) = (\neg (P^f ;; true)) \vdash P^t$
apply (*simp add*: *H1-H3-eq-design-d-comp skip-d-alt-def*)
apply (*subst design-composition-subst*)
apply (*simp-all add*: *usubst unrest*)
apply (*rel-auto*)
done

lemma *H3-unrest-out-alpha-nok* [*unrest*]:
assumes P *is* **N**
shows $out\alpha \sharp P^f$
proof −
have $P = (\neg (P^f ;; true)) \vdash P^t$
by (*metis H1-H3-eq-design Healthy-def assms*)
also have $out\alpha \sharp (...^f)$
by (*simp add*: *design-def usubst unrest*, *rel-auto*)
finally show *?thesis* **.**
qed

lemma *H3-unrest-out-alpha* [*unrest*]: P *is* **N** $\Longrightarrow$ $out\alpha \sharp pre_D(P)$
by (*metis H1-H3-commute H1-H3-is-rdesign H1-idem Healthy-def′ precond-equiv rdesign-H3-iff-pre*)

lemma *ndesign-H1-H3* [*closure*]: $p \vdash_n Q$ *is* **N**
by (*simp add*: *H1-rdesign H3-def Healthy-def′ ndesign-def unrest-pre-out*α)

lemma *ndesign-form*: P *is* **N** $\Longrightarrow$ $(\lfloor pre_D(P) \rfloor_< \vdash_n post_D(P)) = P$
by (*metis H1-H2-eq-rdesign H1-H3-impl-H2 H3-unrest-out-alpha Healthy-def drop-pre-inv ndesign-def*)

lemma *des-bot-H1-H3* [*closure*]: $\bot_D$ *is* **N**
by (*metis H1-design H3-def Healthy-def′ design-false-pre design-true-left-zero skip-d-alt-def bot-d-def*)

lemma *des-top-is-H1-H3* [*closure*]: $\top_D$ *is* **N**
by (*metis ndesign-H1-H3 ndesign-miracle*)

lemma *skip-d-is-H1-H3* [*closure*]: II_D *is* **N**
by (*simp add*: *ndesign-H1-H3 skip-d-ndes-def*)

lemma *seq-r-H1-H3-closed* [*closure*]:
  assumes P *is* **N** Q *is* **N**
  shows $(P \;;\; Q)$ *is* **N**
  by (*metis* (*no-types*) *H1-H2-eq-design H1-H3-eq-design-d-comp H1-H3-impl-H2 Healthy-def assms*(*1*) *assms*(*2*) *seq-r-H1-H2-closed seqr-assoc*)

lemma *dcond-H1-H2-closed* [*closure*]:
  assumes P *is* **N** Q *is* **N**
  shows $(P \triangleleft b \triangleright_D Q)$ *is* **N**
  by (*metis assms ndesign-H1-H3 ndesign-dcond ndesign-form*)

lemma *inf-H1-H2-closed* [*closure*]:
  assumes P *is* **N** Q *is* **N**
  shows $(P \sqcap Q)$ *is* **N**
  by (*metis assms ndesign-H1-H3 ndesign-choice ndesign-form*)

lemma *sup-H1-H2-closed* [*closure*]:
  assumes P *is* **N** Q *is* **N**
  shows $(P \sqcup Q)$ *is* **N**
  by (*metis assms ndesign-H1-H3 ndesign-inf ndesign-form*)

lemma *ndes-seqr-miracle*:
  assumes P *is* **N**
  shows $P \;;\; \top_D = \lfloor pre_D\ P \rfloor_< \vdash_n false$
proof –
  have $P \;;\; \top_D = (\lfloor pre_D(P) \rfloor_< \vdash_n post_D(P)) \;;\; (true \vdash_n false)$
    by (*simp add*: *assms ndesign-form ndesign-miracle*)
  also have ... $= \lfloor pre_D\ P \rfloor_< \vdash_n false$
    by (*simp add*: *ndesign-composition-wp wp alpha*)
  finally show *?thesis* **.**
qed

lemma *ndes-seqr-abort*:
  assumes P *is* **N**
  shows $P \;;\; \bot_D = (\lfloor pre_D\ P \rfloor_< \wedge post_D\ P\ wp\ false) \vdash_n false$
proof –
  have $P \;;\; \bot_D = (\lfloor pre_D(P) \rfloor_< \vdash_n post_D(P)) \;;\; (false \vdash_n false)$
    by (*simp add*: *assms bot-d-true ndesign-false-pre ndesign-form*)
  also have ... $= (\lfloor pre_D\ P \rfloor_< \wedge post_D\ P\ wp\ false) \vdash_n false$
    by (*simp add*: *ndesign-composition-wp alpha*)
  finally show *?thesis* **.**
qed

lemma *USUP-ind-H1-H3-closed* [*closure*]:
  $\llbracket \bigwedge i.\ P\ i$ *is* **N** $\rrbracket \Longrightarrow (\bigsqcup\ i \cdot P\ i)$ *is* **N**
  by (*rule H1-H3-intro*, *simp-all add*: *H1-H3-impl-H2 USUP-ind-H1-H2-closed preD-USUP-ind unrest*)

2.6 H4: Feasibility

definition *H4* :: $('\alpha, '\beta)$ *rel-des* $\Rightarrow$ $('\alpha, '\beta)$ *rel-des* **where**
[*upred-defs*]: $H4(P) = ((P;;true) \Rightarrow P)$

theorem *H4-idem*:
  $H4(H4(P)) = H4(P)$
  by (*rel-auto*)

lemma *is-H4-alt-def*:
  P *is H4* $\longleftrightarrow$ $(P\ ;;\ \mathit{true}) = \mathit{true}$
  by (*rel-blast*)

end

2.7 UTP theory of Designs

theory *utp-des-theory*
  imports *utp-des-healths*
begin

2.8 UTP theories

typedecl *DES*
typedecl *NDES*

abbreviation $\mathit{DES} \equiv \mathit{UTHY}(\mathit{DES}, {'\alpha}\ \mathit{des})$
abbreviation $\mathit{NDES} \equiv \mathit{UTHY}(\mathit{NDES}, {'\alpha}\ \mathit{des})$

overloading
  des-hcond == *utp-hcond* :: $(\mathit{DES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow ({'\alpha}\ \mathit{des} \times {'\alpha}\ \mathit{des})\ \mathit{health}$
  des-unit == *utp-unit* :: $(\mathit{DES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow {'\alpha}\ \mathit{hrel\text{-}des}$ (**unchecked**)

  ndes-hcond == *utp-hcond* :: $(\mathit{NDES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow ({'\alpha}\ \mathit{des} \times {'\alpha}\ \mathit{des})\ \mathit{health}$
  ndes-unit == *utp-unit* :: $(\mathit{NDES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow {'\alpha}\ \mathit{hrel\text{-}des}$ (**unchecked**)

begin
  definition *des-hcond* :: $(\mathit{DES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow ({'\alpha}\ \mathit{des} \times {'\alpha}\ \mathit{des})\ \mathit{health}$ **where**
  [*upred-defs*]: *des-hcond* t = *H1-H2*

  definition *des-unit* :: $(\mathit{DES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow {'\alpha}\ \mathit{hrel\text{-}des}$ **where**
  [*upred-defs*]: *des-unit* $t = \mathit{II}_D$

  definition *ndes-hcond* :: $(\mathit{NDES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow ({'\alpha}\ \mathit{des} \times {'\alpha}\ \mathit{des})\ \mathit{health}$ **where**
  [*upred-defs*]: *ndes-hcond* t = *H1-H3*

  definition *ndes-unit* :: $(\mathit{NDES}, {'\alpha}\ \mathit{des})\ \mathit{uthy} \Rightarrow {'\alpha}\ \mathit{hrel\text{-}des}$ **where**
  [*upred-defs*]: *ndes-unit* $t = \mathit{II}_D$

end

interpretation *des-utp-theory*: *utp-theory DES*
  by (*simp add*: *H1-H2-commute H1-idem H2-idem des-hcond-def utp-theory-def*)

interpretation *ndes-utp-theory*: *utp-theory NDES*
  by (*simp add*: *H1-H3-commute H1-idem H3-idem ndes-hcond-def utp-theory.intro*)

interpretation *des-left-unital*: *utp-theory-left-unital DES*
  apply (*unfold-locales*)
  apply (*simp-all add*: *des-hcond-def des-unit-def*)
  using *seq-r-H1-H2-closed* **apply** *blast*
  apply (*simp add*: *rdesign-is-H1-H2 skip-d-def*)
  apply (*metis H1-idem H1-left-unit Healthy-def'*)
done

interpretation *ndes-unital*: *utp-theory-unital NDES*
  apply (*unfold-locales*, *simp-all add*: *ndes-hcond-def ndes-unit-def*)
  using *seq-r-H1-H3-closed* **apply** *blast*
  apply (*metis H1-rdesign H3-def Healthy-def′ design-skip-idem skip-d-def*)
  apply (*metis H1-idem H1-left-unit Healthy-def′*)
  apply (*metis H1-H3-commute H3-def H3-idem Healthy-def′*)
done

interpretation *design-theory-continuous*: *utp-theory-continuous DES*
  rewrites $\bigwedge P.\ P \in carrier\ (uthy\text{-}order\ DES) \longleftrightarrow P\ is\ \mathbf{H}$
  and $carrier\ (uthy\text{-}order\ DES) \to carrier\ (uthy\text{-}order\ DES) \equiv [\![\mathbf{H}]\!]_H \to [\![\mathbf{H}]\!]_H$
  and $[\![\mathcal{H}_{DES}]\!]_H \to [\![\mathcal{H}_{DES}]\!]_H \equiv [\![\mathbf{H}]\!]_H \to [\![\mathbf{H}]\!]_H$
  and $le\ (uthy\text{-}order\ DES) = (\sqsubseteq)$
  and $eq\ (uthy\text{-}order\ DES) = (=)$
  by (*unfold-locales*, *simp-all add*: *des-hcond-def H1-H2-Continuous utp-order-def*)

interpretation *normal-design-theory-continuous*: *utp-theory-continuous NDES*
  rewrites $\bigwedge P.\ P \in carrier\ (uthy\text{-}order\ NDES) \longleftrightarrow P\ is\ \mathbf{N}$
  and $carrier\ (uthy\text{-}order\ NDES) \to carrier\ (uthy\text{-}order\ NDES) \equiv [\![\mathbf{N}]\!]_H \to [\![\mathbf{N}]\!]_H$
  and $[\![\mathcal{H}_{NDES}]\!]_H \to [\![\mathcal{H}_{NDES}]\!]_H \equiv [\![\mathbf{N}]\!]_H \to [\![\mathbf{N}]\!]_H$
  and $le\ (uthy\text{-}order\ NDES) = (\sqsubseteq)$
  and $A \subseteq carrier\ (uthy\text{-}order\ NDES) \longleftrightarrow A \subseteq [\![\mathbf{N}]\!]_H$
  and $eq\ (uthy\text{-}order\ NDES) = (=)$
  by (*unfold-locales*, *simp-all add*: *ndes-hcond-def H1-H3-Continuous utp-order-def*)

lemma *design-lat-top*: $\top_{DES} = \mathbf{H}(false)$
  by (*simp add*: *design-theory-continuous.healthy-top*, *simp add*: *des-hcond-def*)

lemma *design-lat-bottom*: $\bot_{DES} = \mathbf{H}(true)$
  by (*simp add*: *design-theory-continuous.healthy-bottom*, *simp add*: *des-hcond-def*)

lemma *ndesign-lat-top*: $\top_{NDES} = \mathbf{N}(false)$
  by (*metis ndes-hcond-def normal-design-theory-continuous.healthy-top*)

lemma *ndesign-lat-bottom*: $\bot_{NDES} = \mathbf{N}(true)$
  by (*metis ndes-hcond-def normal-design-theory-continuous.healthy-bottom*)

2.9 Galois Connection

Example Galois connection between designs and relations. Based on Jim's example in COMPASS deliverable D23.5.

definition [*upred-defs*]: $Des(R) = \mathbf{H}(\lceil R \rceil_D \wedge \$ok')$
definition [*upred-defs*]: $Rel(D) = \lfloor D[\![true,true/\$ok,\$ok']\!] \rfloor_D$

lemma *Des-design*: $Des(R) = true \vdash_r R$
  by (*rel-auto*)

lemma *Rel-design*: $Rel(P \vdash_r Q) = (P \Rightarrow Q)$
  by (*rel-auto*)

interpretation *Des-Rel-coretract*:
  $coretract\ DES \leftarrow\langle Des,Rel\rangle\rightarrow REL$
  rewrites
    $\bigwedge x.\ x \in carrier\ \mathcal{X}_{DES \leftarrow\langle Des,Rel\rangle\rightarrow REL} = (x\ is\ \mathbf{H})$ **and**
    $\bigwedge x.\ x \in carrier\ \mathcal{Y}_{DES \leftarrow\langle Des,Rel\rangle\rightarrow REL} = True$ **and**

$\pi_{*DES} \leftarrow\langle Des,Rel\rangle\rightarrow REL = Des$ **and**
$\pi^{*}{}_{DES} \leftarrow\langle Des,Rel\rangle\rightarrow REL = Rel$ **and**
$le\ \mathcal{X}_{DES} \leftarrow\langle Des,Rel\rangle\rightarrow REL = (\sqsubseteq)$ **and**
$le\ \mathcal{Y}_{DES} \leftarrow\langle Des,Rel\rangle\rightarrow REL = (\sqsubseteq)$
proof (*unfold-locales*, *simp-all add*: *rel-hcond-def des-hcond-def*)
  show $\bigwedge x.\ x$ *is id*
    by (*simp add*: *Healthy-def*)
next
  show $Rel \in [\![\mathbf{H}]\!]_H \rightarrow [\![id]\!]_H$
    by (*auto simp add*: *Rel-def rel-hcond-def Healthy-def*)
next
  show $Des \in [\![id]\!]_H \rightarrow [\![\mathbf{H}]\!]_H$
    by (*auto simp add*: *Des-def des-hcond-def Healthy-def H1-H2-commute H1-idem H2-idem*)
next
  fix R :: *'a hrel*
  show $R \sqsubseteq Rel\ (Des\ R)$
    by (*simp add*: *Des-design Rel-design*)
next
  fix R :: *'a hrel* **and** D :: *'a hrel-des*
  assume a: D *is* **H**
  then obtain $D_1\ D_2$ **where** D: $D = D_1 \vdash_r D_2$
    by (*metis H1-H2-commute H1-H2-is-rdesign H1-idem Healthy-def'*)
  show $(Rel\ D \sqsubseteq R) = (D \sqsubseteq Des\ R)$
  proof −
    have $(D \sqsubseteq Des\ R) = (D_1 \vdash_r D_2 \sqsubseteq true \vdash_r R)$
      by (*simp add*: *D Des-design*)
    also have ... = ‘$D_1 \wedge R \Rightarrow D_2$‘
      by (*simp add*: *rdesign-refinement*)
    also have ... = $((D_1 \Rightarrow D_2) \sqsubseteq R)$
      by (*rel-auto*)
    also have ... = $(Rel\ D \sqsubseteq R)$
      by (*simp add*: *D Rel-design*)
    finally show *?thesis* **..**
  qed
qed

From this interpretation we gain many Galois theorems. Some require simplification to remove superfluous assumptions.

thm *Des-Rel-coretract.deflation*[*simplified*]
thm *Des-Rel-coretract.inflation*
thm *Des-Rel-coretract.upper-comp*[*simplified*]
thm *Des-Rel-coretract.lower-comp*

2.10 Fixed Points

abbreviation *design-lfp* :: ($'\alpha$ *hrel-des* $\Rightarrow$ $'\alpha$ *hrel-des*) $\Rightarrow$ $'\alpha$ *hrel-des* (μ_D) **where**
$\mu_D\ F \equiv \boldsymbol{\mu}_{DES}\ F$

abbreviation *design-gfp* :: ($'\alpha$ *hrel-des* $\Rightarrow$ $'\alpha$ *hrel-des*) $\Rightarrow$ $'\alpha$ *hrel-des* (ν_D) **where**
$\nu_D\ F \equiv \boldsymbol{\nu}_{DES}\ F$

syntax
  -dmu :: *pttrn* $\Rightarrow$ *logic* $\Rightarrow$ *logic* (μ_D - • - [0, 10] 10)
  -dnu :: *pttrn* $\Rightarrow$ *logic* $\Rightarrow$ *logic* (ν_D - • - [0, 10] 10)

translations
  $\mu_D\ X \cdot P == \boldsymbol{\mu}_{CONST\ DES}\ (\lambda\ X.\ P)$
  $\nu_D\ X \cdot P == \boldsymbol{\nu}_{CONST\ DES}\ (\lambda\ X.\ P)$

thm *design-theory-continuous.GFP-unfold*
thm *design-theory-continuous.LFP-unfold*

Specialise *mu-refine-intro* to designs.

lemma *design-mu-refine-intro*:
  assumes $\$ok' \sharp C$ $\$ok' \sharp S$ $(C \vdash S) \sqsubseteq F(C \vdash S)$ ‘$C \Rightarrow (\mu_D\ F \Leftrightarrow \nu_D\ F)$‘
  shows $(C \vdash S) \sqsubseteq \mu_D\ F$
proof −
  from *assms* **have** $(C \vdash S) \sqsubseteq \nu_D\ F$
    thm *design-theory-continuous.weak.GFP-upperbound*
    by (*simp add*: *design-is-H1-H2 design-theory-continuous.weak.GFP-upperbound*)
  with *assms* **show** *?thesis*
    by (*rel-auto*, *metis* (*no-types*, *lifting*))
qed

lemma *rdesign-mu-refine-intro*:
  assumes $(C \vdash_r S) \sqsubseteq F(C \vdash_r S)$ ‘$\lceil C \rceil_D \Rightarrow (\mu_D\ F \Leftrightarrow \nu_D\ F)$‘
  shows $(C \vdash_r S) \sqsubseteq \mu_D\ F$
  using *assms* **by** (*simp add*: *rdesign-def design-mu-refine-intro unrest*)

lemma *H1-H2-mu-refine-intro*:
  assumes P *is* **H** $P \sqsubseteq F(P)$ ‘$\lceil pre_D(P) \rceil_D \Rightarrow (\mu_D\ F \Leftrightarrow \nu_D\ F)$‘
  shows $P \sqsubseteq \mu_D\ F$
  by (*metis H1-H2-eq-rdesign Healthy-if assms rdesign-mu-refine-intro*)

Foundational theorem for recursion introduction using a well-founded relation. Contributed by Dr. Yakoub Nemouchi.

theorem *rdesign-mu-wf-refine-intro*:
  assumes *WF*: *wf R*
    and *M*: *Monotonic F*
    and *H*: $F \in [\![\mathbf{H}]\!]_H \to [\![\mathbf{H}]\!]_H$
    and *induct-step*:
    $\bigwedge st.\ (P \wedge \lceil e \rceil_< =_u \ll st \gg) \vdash_r Q \sqsubseteq F\ ((P \wedge (\lceil e \rceil_<, \ll st \gg)_u \in_u \ll R \gg) \vdash_r Q)$
  shows $(P \vdash_r Q) \sqsubseteq \mu_D\ F$
proof −
  {
  fix *st*
  have $(P \wedge \lceil e \rceil_< =_u \ll st \gg) \vdash_r Q \sqsubseteq \mu_D\ F$
  using *WF* **proof** (*induction rule*: *wf-induct-rule*)
    case (*less st*)
    hence *0*: $(P \wedge (\lceil e \rceil_<, \ll st \gg)_u \in_u \ll R \gg) \vdash_r Q \sqsubseteq \mu_D\ F$
      by *rel-blast*
    from *M H design-theory-continuous.LFP-lemma3 mono-Monotone-utp-order*
    have *1*: $\mu_D\ F \sqsubseteq\ F\ (\mu_D\ F)$
      by *blast*
    from *0 1* **have** *2*:$(P \wedge (\lceil e \rceil_<, \ll st \gg)_u \in_u \ll R \gg) \vdash_r Q \sqsubseteq F\ (\mu_D\ F)$
      by *simp*
    have *3*: $F\ ((P \wedge (\lceil e \rceil_<, \ll st \gg)_u \in_u \ll R \gg) \vdash_r Q) \sqsubseteq F\ (\mu_D\ F)$
      by (*simp add*: *0 M monoD*)
    have *4*:$(P \wedge \lceil e \rceil_< =_u \ll st \gg) \vdash_r Q \sqsubseteq \ldots$
      by (*rule induct-step*)

show *?case*
using *order-trans*[*OF 3 4*] *H M design-theory-continuous.LFP-lemma2 dual-order.trans mono-Monotone-utp-order*

by *blast*
qed
}
thus *?thesis*
by (*pred-simp*)
qed

theorem *ndesign-mu-wf-refine-intro'*:
assumes *WF*: *wf R*
and *M*: *Monotonic F*
and *H*: $F \in [\![\mathbf{H}]\!]_H \to [\![\mathbf{H}]\!]_H$
and *induct-step*:
$\bigwedge st.\ ((p \wedge e =_u \ll st\gg) \vdash_n Q) \sqsubseteq F\ ((p \wedge (e, \ll st\gg)_u \in_u \ll R\gg) \vdash_n Q)$
shows $(p \vdash_n Q) \sqsubseteq \mu_D\ F$
using *assms* **unfolding** *ndesign-def*
by (*rule-tac rdesign-mu-wf-refine-intro*[*of R F* $\lceil p \rceil_<$ *e*], *simp-all add*: *alpha*)

theorem *ndesign-mu-wf-refine-intro*:
assumes *WF*: *wf R*
and *M*: *Monotonic F*
and *H*: $F \in [\![\mathbf{N}]\!]_H \to [\![\mathbf{N}]\!]_H$
and *induct-step*:
$\bigwedge st.\ ((p \wedge e =_u \ll st\gg) \vdash_n Q) \sqsubseteq F\ ((p \wedge (e, \ll st\gg)_u \in_u \ll R\gg) \vdash_n Q)$
shows $(p \vdash_n Q) \sqsubseteq \boldsymbol{\mu}_{NDES}\ F$
proof −
{
fix *st*
have $(p \wedge e =_u \ll st\gg) \vdash_n Q \sqsubseteq \boldsymbol{\mu}_{NDES}\ F$
using *WF* **proof** (*induction rule*: *wf-induct-rule*)
case (*less st*)
hence *0*: $(p \wedge (e, \ll st\gg)_u \in_u \ll R\gg) \vdash_n Q \sqsubseteq \boldsymbol{\mu}_{NDES}\ F$
by *rel-blast*
from *M H design-theory-continuous.LFP-lemma3 mono-Monotone-utp-order*
have *1*: $\boldsymbol{\mu}_{NDES}\ F \sqsubseteq\ F\ (\boldsymbol{\mu}_{NDES}\ F)$
by (*simp add*: *mono-Monotone-utp-order normal-design-theory-continuous.LFP-lemma3*)
from *0 1* **have** *2*:$(p \wedge (e, \ll st\gg)_u \in_u \ll R\gg) \vdash_n Q \sqsubseteq F\ (\boldsymbol{\mu}_{NDES}\ F)$
by *simp*
have *3*: $F\ ((p \wedge (e, \ll st\gg)_u \in_u \ll R\gg) \vdash_n Q) \sqsubseteq F\ (\boldsymbol{\mu}_{NDES}\ F)$
by (*simp add*: *0 M monoD*)
have *4*:$(p \wedge e =_u \ll st\gg) \vdash_n Q \sqsubseteq \ldots$
by (*rule induct-step*)
show *?case*
using *order-trans*[*OF 3 4*] *H M normal-design-theory-continuous.LFP-lemma2 dual-order.trans mono-Monotone-utp-order*
by *blast*
qed
}
thus *?thesis*
by (*pred-simp*)
qed

end

3 Design Proof Tactics

theory *utp-des-tactics*
imports *utp-des-theory*
begin

The tactics split apart a healthy normal design predicate into its pre-postcondition form, using elimination rules, and then attempt to prove refinement conjectures.

named-theorems *ND-elim*

lemma *ndes-elim*: $[\![\ P\ is\ \mathbf{N};\ Q(\lfloor pre_D(P)\rfloor_< \vdash_n post_D(P))\ ]\!] \Longrightarrow Q(P)$
by (*simp add*: *ndesign-form*)

lemma *ndes-ind-elim*: $[\![\ \bigwedge\ i.\ P\ i\ is\ \mathbf{N};\ Q(\lambda\ i.\ \lfloor pre_D(P\ i)\rfloor_< \vdash_n post_D(P\ i))\ ]\!] \Longrightarrow Q(P)$
by (*simp add*: *ndesign-form*)

lemma *ndes-split* [*ND-elim*]: $[\![\ P\ is\ \mathbf{N};\ \bigwedge\ pre\ post.\ Q(pre \vdash_n post)\ ]\!] \Longrightarrow Q(P)$
by (*metis H1-H2-eq-rdesign H1-H3-impl-H2 H3-unrest-out-alpha Healthy-def drop-pre-inv ndesign-def*)

Use given closure laws (cls) to expand normal design predicates

method *ndes-expand* **uses** *cls* = (*insert cls*, (*erule ND-elim*)+)

Expand and simplify normal designs

method *ndes-simp* **uses** *cls* =
((*ndes-expand cls*: *cls*)?, (*simp add*: *ndes-simp closure alpha usubst unrest wp prod.case-eq-if*))

Attempt to discharge a refinement between two normal designs

method *ndes-refine* **uses** *cls* =
(*ndes-simp cls*: *cls*; *rule-tac ndesign-refine-intro*; (*insert cls*; *rel-simp*; *auto?*))

Attempt to discharge an equality between two normal designs

method *ndes-eq* **uses** *cls* =
(*ndes-simp cls*: *cls*; *rule-tac antisym*; *rule-tac ndesign-refine-intro*; (*insert cls*; *rel-simp*; *auto?*))

end

4 Imperative Programming in Designs

theory *utp-des-prog*
imports *utp-des-tactics*
begin

4.1 Assignment

definition *assigns-d* :: $'\alpha$ *usubst* $\Rightarrow$ $'\alpha$ *hrel-des* ($\langle\text{-}\rangle_D$) **where**
[*upred-defs*]: *assigns-d* σ = (*true* $\vdash_r$ *assigns-r* σ)

syntax
-assignmentd :: *svids* $\Rightarrow$ *uexprs* $\Rightarrow$ *logic* (**infixr** $:=_D$ *62*)

translations

-assignmentd xs vs => CONST assigns-d (-mk-usubst (CONST id) xs vs)
-assignmentd x v <= CONST assigns-d (CONST subst-upd (CONST id) x v)
-assignmentd x v <= -assignmentd (-spvar x) v
$x,y :=_D u,v$ *<= CONST assigns-d (CONST subst-upd (CONST subst-upd (CONST id) (CONST svar x) u) (CONST svar y) v)*

lemma *assigns-d-is-H1-H2* [*closure*]: $\langle\sigma\rangle_D$ *is* **H**
by (*simp add*: *assigns-d-def rdesign-is-H1-H2*)

lemma *assigns-d-H1-H3* [*closure*]: $\langle\sigma\rangle_D$ *is* **N**
by (*metis H1-rdesign H3-ndesign Healthy-def' aext-true assigns-d-def ndesign-def*)

Designs are closed under substitutions on state variables only (via lifting)

lemma *state-subst-H1-H2-closed* [*closure*]:
P *is* **H** $\Longrightarrow \lceil \sigma \oplus_s \Sigma_D \rceil_s \dagger P$ *is* **H**
by (*metis H1-H2-eq-rdesign Healthy-if rdesign-is-H1-H2 state-subst-design*)

lemma *assigns-d-ndes-def* [*ndes-simp*]:
$\langle\sigma\rangle_D = (true \vdash_n \langle\sigma\rangle_a)$
by (*rel-auto*)

lemma *assigns-d-id* [*simp*]: $\langle id\rangle_D = II_D$
by (*rel-auto*)

lemma *assign-d-left-comp*:
$(\langle f\rangle_D \;;;\; (P \vdash_r Q)) = (\lceil f \rceil_s \dagger P \vdash_r \lceil f \rceil_s \dagger Q)$
by (*simp add*: *assigns-d-def rdesign-composition assigns-r-comp subst-not*)

lemma *assign-d-right-comp*:
$((P \vdash_r Q) \;;;\; \langle f\rangle_D) = ((\neg ((\neg P) \;;;\; true)) \vdash_r (Q \;;;\; \langle f\rangle_a))$
by (*simp add*: *assigns-d-def rdesign-composition*)

lemma *assigns-d-comp*:
$(\langle f\rangle_D \;;;\; \langle g\rangle_D) = \langle g \circ f\rangle_D$
by (*simp add*: *assigns-d-def rdesign-composition assigns-comp*)

lemma *assigns-d-comp-ext*:
fixes P :: *'α hrel-des*
assumes P *is* **H**
shows $(\langle\sigma\rangle_D \;;;\; P) = \lceil \sigma \oplus_s \Sigma_D \rceil_s \dagger P$
proof −
have $\langle\sigma\rangle_D \;;;\; P = \langle\sigma\rangle_D \;;;\; (pre_D(P) \vdash_r post_D(P))$
by (*metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def' assms*)
also have ... $= \lceil\sigma\rceil_s \dagger pre_D(P) \vdash_r \lceil\sigma\rceil_s \dagger post_D(P)$
by (*simp add*: *assign-d-left-comp*)
also have ... $= \lceil \sigma \oplus_s \Sigma_D \rceil_s \dagger (pre_D(P) \vdash_r post_D(P))$
by (*rel-auto*)
also have ... $= \lceil \sigma \oplus_s \Sigma_D \rceil_s \dagger P$
by (*metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def' assms*)
finally show *?thesis* **.**
qed

Normal designs are closed under substitutions on state variables only

lemma *state-subst-H1-H3-closed* [*closure*]:
P *is* **N** $\Longrightarrow \lceil \sigma \oplus_s \Sigma_D \rceil_s \dagger P$ *is* **N**

by (*metis H1-H2-eq-rdesign H1-H3-impl-H2 Healthy-if assign-d-left-comp assigns-d-H1-H3 seq-r-H1-H3-closed state-subst-design*)

lemma *H4-assigns-d*: $\langle\sigma\rangle_D$ *is H4*
proof −
  have $(\langle\sigma\rangle_D\ ;;\ (\mathit{false} \vdash_r \mathit{true}_h)) = (\mathit{false} \vdash_r \mathit{true})$
    by (*simp add*: *assigns-d-def rdesign-composition assigns-r-feasible*)
  moreover have ... = *true*
    by (*rel-auto*)
  ultimately show *?thesis*
    using *is-H4-alt-def* **by** *auto*
qed

4.2 Guarded Commands

definition *GrdCommD* :: $'\alpha$ *upred* ⇒ $('\alpha, '\beta)$ *rel-des* ⇒ $('\alpha, '\beta)$ *rel-des* (- $\to_D$ - [*85*, *86*] *85*) **where**
[*upred-defs*]: $b \to_D P = P \triangleleft b \triangleright_D \top_D$

lemma *GrdCommD-ndes-simp* [*ndes-simp*]:
  $b \to_D (p_1 \vdash_n P_2) = ((b \Rightarrow p_1) \vdash_n (\lceil b\rceil_< \wedge P_2))$
  by (*rel-auto*)

lemma *GrdCommD-H1-H3-closed* [*closure*]: P *is* **N** ⟹ $b \to_D P$ *is* **N**
  by (*simp add*: *GrdCommD-def closure*)

lemma *GrdCommD-true* [*simp*]: $\mathit{true} \to_D P = P$
  by (*rel-auto*)

lemma *GrdCommD-false* [*simp*]: $\mathit{false} \to_D P = \top_D$
  by (*rel-auto*)

lemma *GrdCommD-abort* [*simp*]: $b \to_D \mathit{true} = ((\neg\ b) \vdash_n \mathit{false})$
  by (*rel-auto*)

4.3 Alternation

consts
  ualtern :: $'a\ \mathit{set} \Rightarrow ('a \Rightarrow 'p) \Rightarrow ('a \Rightarrow 'r) \Rightarrow 'r \Rightarrow 'r$
  ualtern-list :: $('a \times 'r)\ \mathit{list} \Rightarrow 'r \Rightarrow 'r$

definition *AlternateD* :: $'a\ \mathit{set} \Rightarrow ('a \Rightarrow '\alpha\ \mathit{upred}) \Rightarrow ('a \Rightarrow ('\alpha, '\beta)\ \mathit{rel\text{-}des}) \Rightarrow ('\alpha, '\beta)\ \mathit{rel\text{-}des} \Rightarrow ('\alpha, '\beta)\ \mathit{rel\text{-}des}$ **where**
[*upred-defs*, *ndes-simp*]:
$\mathit{AlternateD}\ A\ g\ P\ Q = (\bigsqcap\ i{\in}A \cdot g(i) \to_D P(i)) \sqcap (\bigwedge\ i{\in}A \cdot \neg\ g(i)) \to_D Q$

This lemma shows that our generalised alternation is the same operator as Marcel Oliveira's definition of alternation when the else branch is abort.

lemma *AlternateD-abort-alternate*:
  assumes $\bigwedge\ i.\ P(i)$ *is* **N**
  shows
  $\mathit{AlternateD}\ A\ g\ P\ \bot_D =$
  $((\bigvee\ i{\in}A \cdot g(i)) \wedge (\bigwedge\ i{\in}A \cdot g(i) \Rightarrow \lfloor \mathit{pre}_D(P\ i)\rfloor_<)) \vdash_n (\bigvee\ i{\in}A \cdot \lceil g(i)\rceil_< \wedge \mathit{post}_D(P\ i))$
proof (*cases* $A = \{\}$)
  case *False*
  have $\mathit{AlternateD}\ A\ g\ P\ \bot_D =$
    $(\bigsqcap\ i{\in}A \cdot g(i) \to_D (\lfloor \mathit{pre}_D(P\ i)\rfloor_< \vdash_n \mathit{post}_D(P\ i))) \sqcap (\bigwedge\ i{\in}A \cdot \neg\ g(i)) \to_D (\mathit{false} \vdash_n \mathit{true})$

by (*simp add*: *AlternateD-def ndesign-form bot-d-ndes-def assms*)
also have ... = $((\bigvee i{\in}A \cdot g(i)) \wedge (\bigwedge i{\in}A \cdot g(i) \Rightarrow \lfloor pre_D(P\ i)\rfloor_<)) \vdash_n (\bigvee i{\in}A \cdot \lceil g(i)\rceil_< \wedge post_D(P\ i))$
by (*simp add*: *ndes-simp False*, *rel-auto*)
finally show *?thesis* **by** *simp*
next
case *True*
thus *?thesis*
by (*simp add*: *AlternateD-def*, *rel-auto*)
qed

definition *AlternateD-list* :: $('\alpha\ upred \times ('\alpha, '\beta)\ rel\text{-}des)\ list \Rightarrow ('\alpha, '\beta)\ rel\text{-}des \Rightarrow ('\alpha, '\beta)\ rel\text{-}des$
where
[*upred-defs*, *ndes-simp*]:
AlternateD-list xs P =
AlternateD $\{0..<length\ xs\}$ $(\lambda\ i.\ map\ fst\ xs\ !\ i)$ $(\lambda\ i.\ map\ snd\ xs\ !\ i)$ *P*

adhoc-overloading
ualtern AlternateD **and**
ualtern-list AlternateD-list

nonterminal *gcomm* **and** *gcomms*

syntax
-altind-els :: *pttrn* ⇒ *logic* ⇒ *logic* ⇒ *logic* ⇒ *logic* ⇒ *logic* (*if* -∈- · - → - *else* - *fi*)
-altind :: *pttrn* ⇒ *logic* ⇒ *logic* ⇒ *logic* ⇒ *logic* (*if* -∈- · - → - *fi*)
-gcomm :: *logic* ⇒ *logic* ⇒ *gcomm* (- → - [*60*, *60*] *61*)
-gcomm-nil :: *gcomm* ⇒ *gcomms* (-)
-gcomm-cons :: *gcomm* ⇒ *gcomms* ⇒ *gcomms* (- |/ - [*60*, *61*] *61*)
-gcomm-show :: *logic* ⇒ *logic*
-altgcomm-els :: *gcomms* ⇒ *logic* ⇒ *logic* (*if*/ - /*else* - /*fi*)
-altgcomm :: *gcomms* ⇒ *logic* (*if*/ - /*fi*)

translations
-altind-els x A g P Q => *CONST ualtern A* (λ *x*. *g*) (λ *x*. *P*) *Q*
-altind-els x A g P Q <= *CONST ualtern A* (λ *x*. *g*) (λ *x′*. *P*) *Q*
-altind x A g P => *CONST ualtern A* (λ *x*. *g*) (λ *x*. *P*) (*CONST Orderings.top*)
-altind x A g P <= *CONST ualtern A* (λ *x*. *g*) (λ *x′*. *P*) (*CONST Orderings.top*)
-altgcomm cs => *CONST ualtern-list cs* (*CONST Orderings.top*)
-altgcomm (*-gcomm-show cs*) <= *CONST ualtern-list cs* (*CONST Orderings.top*)
-altgcomm-els cs P => *CONST ualtern-list cs P*
-altgcomm-els (*-gcomm-show cs*) *P* <= *CONST ualtern-list cs P*

-gcomm g P => (*g*, *P*)
-gcomm g P <= *-gcomm-show* (*g*, *P*)
-gcomm-cons c cs => *c* # *cs*
-gcomm-cons (*-gcomm-show c*) (*-gcomm-show* (*d* # *cs*)) <= *-gcomm-show* (*c* # *d* # *cs*)
-gcomm-nil c => [*c*]
-gcomm-nil (*-gcomm-show c*) <= *-gcomm-show* [*c*]

lemma *AlternateD-H1-H3-closed* [*closure*]:
assumes $\bigwedge i.\ i \in A \Longrightarrow P\ i\ is\ \mathbf{N}$ *Q is* **N**
shows *if* $i{\in}A \cdot g(i) \to P(i)$ *else Q fi is* **N**
proof (*cases A* = {})
case *True*

then show *?thesis*
by (*simp add*: *AlternateD-def closure false-upred-def assms*)
next
case *False*
then show *?thesis*
by (*simp add*: *AlternateD-def closure assms*)
qed

lemma *AltD-ndes-simp* [*ndes-simp*]:
$\mathit{if}\ i{\in}A \cdot g(i) \rightarrow (P_1(i) \vdash_n P_2(i))\ \mathit{else}\ Q_1 \vdash_n Q_2\ \mathit{fi}$
$= ((\bigwedge\ i \in A \cdot g\ i \Rightarrow P_1\ i) \wedge ((\bigwedge\ i \in A \cdot \neg\ g\ i) \Rightarrow Q_1)) \vdash_n$
$((\bigvee\ i \in A \cdot \lceil g\ i \rceil_< \wedge P_2\ i) \vee (\bigwedge\ i \in A \cdot \neg\ \lceil g\ i \rceil_<) \wedge Q_2)$
proof (*cases* $A = \{\}$)
case *True*
then show *?thesis* **by** (*simp add*: *AlternateD-def*)
next
case *False*
then show *?thesis*
by (*simp add*: *ndes-simp*, *rel-auto*)
qed

declare *UINF-upto-expand-first* [*ndes-simp*]
declare *UINF-Suc-shift* [*ndes-simp*]
declare *USUP-upto-expand-first* [*ndes-simp*]
declare *USUP-Suc-shift* [*ndes-simp*]
declare *true-upred-def* [*THEN sym*, *ndes-simp*]

lemma *AlternateD-mono-refine*:
assumes $\bigwedge\ i.\ P\ i \sqsubseteq Q\ i\ R \sqsubseteq S$
shows $(\mathit{if}\ i{\in}A \cdot g(i) \rightarrow P(i)\ \mathit{else}\ R\ \mathit{fi}) \sqsubseteq (\mathit{if}\ i{\in}A \cdot g(i) \rightarrow Q(i)\ \mathit{else}\ S\ \mathit{fi})$
using *assms* **by** (*rel-auto*, *meson*)

lemma *Monotonic-AlternateD* [*closure*]:
$\llbracket \bigwedge\ i.\ \mathit{Monotonic}\ (F\ i);\ \mathit{Monotonic}\ G\ \rrbracket \Longrightarrow \mathit{Monotonic}\ (\lambda\ X.\ \mathit{if}\ i{\in}A \cdot g(i) \rightarrow F\ i\ X\ \mathit{else}\ G(X)\ \mathit{fi})$
by (*rel-auto*, *meson*)

lemma *AlternateD-eq*:
assumes $A = B\ \bigwedge\ i.\ i{\in}A \Longrightarrow g(i) = h(i)\ \bigwedge\ i.\ i{\in}A \Longrightarrow P(i) = Q(i)\ R = S$
shows $\mathit{if}\ i{\in}A \cdot g(i) \rightarrow P(i)\ \mathit{else}\ R\ \mathit{fi} = \mathit{if}\ i{\in}B \cdot h(i) \rightarrow Q(i)\ \mathit{else}\ S\ \mathit{fi}$
by (*insert assms*, *rel-blast*)

lemma *AlternateD-empty*:
$\mathit{if}\ i{\in}\{\} \cdot g(i) \rightarrow P(i)\ \mathit{else}\ Q\ \mathit{fi} = Q$
by (*rel-auto*)

lemma *AlternateD-true-singleton*:
assumes $P\ \mathit{is}\ \mathbf{N}$
shows $\mathit{if}\ \mathit{true} \rightarrow P\ \mathit{fi} = P$
by (*ndes-eq cls*: *assms*)

lemma *AlernateD-no-ind*:
assumes $A \neq \{\}\ P\ \mathit{is}\ \mathbf{N}\ Q\ \mathit{is}\ \mathbf{N}$
shows $\mathit{if}\ i{\in}A \cdot b \rightarrow P\ \mathit{else}\ Q\ \mathit{fi} = \mathit{if}\ b \rightarrow P\ \mathit{else}\ Q\ \mathit{fi}$
by (*ndes-eq cls*: *assms*)

lemma *AlernateD-singleton*:
  assumes $P\ k$ *is* **N** Q *is* **N**
  shows *if* $i{\in}\{k\} \cdot b(i) \rightarrow P(i)$ *else* Q *fi* $=$ *if* $b(k) \rightarrow P(k)$ *else* Q *fi* (**is** *?lhs* $=$ *?rhs*)
proof −
  have *?lhs* $=$ *if* $i{\in}\{k\} \cdot b(k) \rightarrow P(k)$ *else* Q *fi*
    by (*auto intro*: *AlternateD-eq simp add*: *assms ndesign-form*)
  also have ... $=$ *?rhs*
    by (*simp add*: *AlernateD-no-ind assms closure*)
  finally show *?thesis* **.**
qed

lemma *AlternateD-commute*:
  assumes P *is* **N** Q *is* **N**
  shows *if* $g_1 \rightarrow P \mid g_2 \rightarrow Q$ *fi* $=$ *if* $g_2 \rightarrow Q \mid g_1 \rightarrow P$ *fi*
  by (*ndes-eq cls*:*assms*)

lemma *AlternateD-dcond*:
  assumes P *is* **N** Q *is* **N**
  shows *if* $g \rightarrow P$ *else* Q *fi* $= P \triangleleft g \triangleright_D Q$
  by (*ndes-eq cls*:*assms*)

lemma *AlternateD-cover*:
  assumes P *is* **N** Q *is* **N**
  shows *if* $g \rightarrow P$ *else* Q *fi* $=$ *if* $g \rightarrow P \mid (\neg\ g) \rightarrow Q$ *fi*
  by (*ndes-eq cls*: *assms*)

lemma *UINF-ndes-expand*:
  assumes $\bigwedge\ i.\ i{\in}A \Longrightarrow P(i)$ *is* **N**
  shows $(\bigsqcap\ i \in A \cdot \lfloor pre_D(P(i)) \rfloor_< \vdash_n post_D(P(i))) = (\bigsqcap\ i \in A \cdot P(i))$
  by (*rule UINF-cong*, *simp add*: *assms ndesign-form*)

lemma *USUP-ndes-expand*:
  assumes $\bigwedge\ i.\ i{\in}A \Longrightarrow P(i)$ *is* **N**
  shows $(\bigsqcup\ i \in A \cdot \lfloor pre_D(P(i)) \rfloor_< \vdash_n post_D(P(i))) = (\bigsqcup\ i \in A \cdot P(i))$
  by (*rule USUP-cong*, *simp add*: *assms ndesign-form*)

lemma *AlternateD-ndes-expand*:
  assumes $\bigwedge\ i.\ i{\in}A \Longrightarrow P(i)$ *is* **N** Q *is* **N**
  shows *if* $i{\in}A \cdot g(i) \rightarrow P(i)$ *else* Q *fi* $=$
        if $i{\in}A \cdot g(i) \rightarrow (\lfloor pre_D(P(i)) \rfloor_< \vdash_n post_D(P(i)))$ *else* $\lfloor pre_D(Q) \rfloor_< \vdash_n post_D(Q)$ *fi*
  apply (*simp add*: *AlternateD-def*)
  apply (*subst UINF-ndes-expand*[*THEN sym*])
   apply (*simp add*: *assms closure*)
  apply (*ndes-simp cls*: *assms*)
  apply (*rel-auto*)
  done

lemma *AlternateD-ndes-expand'*:
  assumes $\bigwedge\ i.\ i{\in}A \Longrightarrow P(i)$ *is* **N**
  shows *if* $i{\in}A \cdot g(i) \rightarrow P(i)$ *fi* $=$ *if* $i{\in}A \cdot g(i) \rightarrow (\lfloor pre_D(P(i)) \rfloor_< \vdash_n post_D(P(i)))$ *fi*
  apply (*simp add*: *AlternateD-def*)
  apply (*subst UINF-ndes-expand*[*THEN sym*])
   apply (*simp add*: *assms closure*)
  apply (*ndes-simp cls*: *assms*)
  apply (*rel-auto*)

done

lemma *ndesign-ind-form*:
assumes $\bigwedge$ *i*. $P(i)$ *is* **N**
shows $(\lambda\ i.\ \lfloor pre_D(P(i))\rfloor_< \vdash_n post_D(P(i))) = P$
by (*simp add*: *assms ndesign-form*)

lemma *AlternateD-insert*:
assumes $\bigwedge$ *i*. $i{\in}(insert\ x\ A) \Longrightarrow P(i)$ *is* **N** Q *is* **N**
shows *if* $i{\in}(insert\ x\ A) \cdot g(i) \rightarrow P(i)$ *else* Q *fi* =
if $g(x) \rightarrow P(x)$ |
$(\bigvee\ i{\in}A \cdot g(i)) \rightarrow$ *if* $i{\in}A \cdot g(i) \rightarrow P(i)$ *fi*
else Q
fi (**is** *?lhs* = *?rhs*)
proof −
have *?lhs* = *if* $i{\in}(insert\ x\ A) \cdot g(i) \rightarrow (\lfloor pre_D(P(i))\rfloor_< \vdash_n post_D(P(i)))$ *else* $(\lfloor pre_D(Q)\rfloor_< \vdash_n post_D(Q))$ *fi*
using *AlternateD-ndes-expand assms(1) assms(2)* **by** *blast*
also
have ... =
if $g(x) \rightarrow (\lfloor pre_D(P(x))\rfloor_< \vdash_n post_D(P(x)))$ |
$(\bigvee\ i{\in}A \cdot g(i)) \rightarrow$ *if* $i{\in}A \cdot g(i) \rightarrow \lfloor pre_D(P(i))\rfloor_< \vdash_n post_D(P(i))$ *fi*
else $\lfloor pre_D(Q)\rfloor_< \vdash_n post_D(Q)$
fi
by (*ndes-simp cls*:*assms*, *rel-auto*)
also have ... = *?rhs*
by (*simp add*: *AlternateD-ndes-expand′ ndesign-form assms*)
finally show *?thesis* **.**
qed

4.4 Iteration

theorem *ndesign-iteration-wp* [*ndes-simp*]:
$(p \vdash_n Q)\ ;;\ (p \vdash_n Q)\ \hat{}\ n = ((\bigwedge\ i{\in}\{0..n\} \cdot (Q\ \hat{}\ i)\ wp\ p) \vdash_n Q\ \hat{}\ Suc\ n)$
proof (*induct n*)
case *0*
then show *?case* **by** (*rel-auto*)
next
case (*Suc n*) **note** *hyp* = *this*
have $(p \vdash_n Q)\ ;;\ (p \vdash_n Q)\ \hat{}\ Suc\ n = (p \vdash_n Q)\ ;;\ (p \vdash_n Q)\ ;;\ (p \vdash_n Q)\ \hat{}\ n$
by (*simp add*: *upred-semiring.power-Suc*)
also have ... = $(p \vdash_n Q)\ ;;\ ((\bigsqcup\ i \in \{0..n\} \cdot Q\ \hat{}\ i\ wp\ p) \vdash_n Q\ \hat{}\ Suc\ n)$
by (*simp add*: *hyp*)
also have ... = $(p \wedge Q\ wp\ (\bigsqcup\ i \in \{0..n\} \cdot Q\ \hat{}\ i\ wp\ p)) \vdash_n (Q\ ;;\ Q)\ ;;\ Q\ \hat{}\ n$
by (*simp add*: *upred-semiring.power-Suc ndesign-composition-wp seqr-assoc*)
also have ... = $(p \wedge (\bigsqcup\ i \in \{0..n\} \cdot Q\ \hat{}\ Suc\ i\ wp\ p)) \vdash_n (Q\ ;;\ Q)\ ;;\ Q\ \hat{}\ n$
by (*simp add*: *upred-semiring.power-Suc wp*)
also have ... = $(p \wedge (\bigsqcup\ i \in \{0..n\}.\ Q\ \hat{}\ Suc\ i\ wp\ p)) \vdash_n (Q\ ;;\ Q)\ ;;\ Q\ \hat{}\ n$
by (*simp add*: *USUP-as-Inf-image*)
also have ... = $(p \wedge (\bigsqcup\ i \in \{1..Suc\ n\}.\ Q\ \hat{}\ i\ wp\ p)) \vdash_n (Q\ ;;\ Q)\ ;;\ Q\ \hat{}\ n$
by (*metis* (*no-types*, *lifting*) *One-nat-def image-Suc-atLeastAtMost image-cong image-image*)
also have ... = $(Q\ \hat{}\ 0\ wp\ p \wedge (\bigsqcup\ i \in \{1..Suc\ n\}.\ Q\ \hat{}\ i\ wp\ p)) \vdash_n (Q\ ;;\ Q)\ ;;\ Q\ \hat{}\ n$
by (*simp add*: *wp*)
also have ... = $((\bigsqcup\ i \in \{0..Suc\ n\}.\ Q\ \hat{}\ i\ wp\ p)) \vdash_n (Q\ ;;\ Q)\ ;;\ Q\ \hat{}\ n$
by (*simp add*: *atMost-Suc-eq-insert-0 atLeast0AtMost conj-upred-def image-Suc-atMost*)
also have ... = $(\bigsqcup\ i \in \{0..Suc\ n\} \cdot Q\ \hat{}\ i\ wp\ p) \vdash_n Q\ \hat{}\ Suc\ (Suc\ n)$

by (*simp add*: *upred-semiring.power-Suc USUP-as-Inf-image upred-semiring.mult-assoc*)
finally show *?case* **.**
qed

Overloadable Syntax

consts
uiterate :: $'a\ set \Rightarrow ('a \Rightarrow 'p) \Rightarrow ('a \Rightarrow 'r) \Rightarrow 'r$
uiterate-list :: $('a \times 'r)\ list \Rightarrow 'r$

syntax
-iterind :: $pttrn \Rightarrow logic \Rightarrow logic \Rightarrow logic \Rightarrow logic$ (*do -∈- · - → - od*)
-itergcomm :: $gcomms \Rightarrow logic$ (*do - od*)

translations
-iterind x A g P => CONST uiterate A (λ *x. g*) (λ *x. P*)
-iterind x A g P <= CONST uiterate A (λ *x. g*) (λ *x'. P*)
-itergcomm cs => CONST uiterate-list cs
-itergcomm (*-gcomm-show cs*) *<= CONST uiterate-list cs*

definition *IterateD* :: $'a\ set \Rightarrow ('a \Rightarrow '\alpha\ upred) \Rightarrow ('a \Rightarrow '\alpha\ hrel\text{-}des) \Rightarrow '\alpha\ hrel\text{-}des$ **where**
[*upred-defs*, *ndes-simp*]:
IterateD A g P = ($\boldsymbol{\mu}_{NDES}$ *X* · *if i*∈*A* · *g*(*i*) → *P*(*i*) ;; *X else* II_D *fi*)

definition *IterateD-list* :: $('\alpha\ upred \times '\alpha\ hrel\text{-}des)\ list \Rightarrow '\alpha\ hrel\text{-}des$ **where**
[*upred-defs*, *ndes-simp*]:
IterateD-list xs = *IterateD* {*0..<length xs*} (λ *i. fst* (*nth xs i*)) (λ *i. snd* (*nth xs i*))

adhoc-overloading
uiterate IterateD **and**
uiterate-list IterateD-list

lemma *IterateD-H1-H3-closed* [*closure*]:
assumes $\bigwedge$ *i. i* ∈ *A* ⟹ *P i is* **N**
shows *do i*∈*A* · *g*(*i*) → *P*(*i*) *od is* **N**
proof (*cases A* = {})
case *True*
then show *?thesis*
by (*simp add*: *IterateD-def closure assms*)
next
case *False*
then show *?thesis*
by (*simp add*: *IterateD-def closure assms*)
qed

lemma *IterateD-empty*:
do i∈{} · *g*(*i*) → *P*(*i*) *od* = II_D
by (*simp add*: *IterateD-def AlternateD-empty normal-design-theory-continuous.LFP-const skip-d-is-H1-H3*)

lemma *IterateD-list-single-expand*:
do b → *P od* = ($\boldsymbol{\mu}_{NDES}$ *X* · *if b* → *P* ;; *X else* II_D *fi*)
oops

lemma *IterateD-singleton*:
assumes *P is* **N**
shows *do b* → *P od* = *do i*∈{*0*} · *b* → *P od*

```
  apply (simp add: IterateD-list-def IterateD-def AlernateD-singleton assms)
  apply (subst AlernateD-singleton)
  apply (simp)
  apply (rel-auto)
oops

lemma IterateD-mono-refine:
  assumes
    ⋀ i. P i is N ⋀ i. Q i is N
    ⋀ i. P i ⊑ Q i
  shows (do i∈A · g(i) → P(i) od) ⊑ (do i∈A · g(i) → Q(i) od)
  apply (simp add: IterateD-def normal-design-theory-continuous.utp-lfp-def)
  apply (subst normal-design-theory-continuous.utp-lfp-def)
  apply (simp-all add: closure assms)
  apply (subst normal-design-theory-continuous.utp-lfp-def)
  apply (simp-all add: closure assms)
  apply (simp add: ndes-hcond-def)
  apply (rule gfp-mono)
  apply (rule AlternateD-mono-refine)
  apply (simp-all add: closure seqr-mono assms)
done

lemma IterateD-single-refine:
  assumes
    P is N Q is N P ⊑ Q
  shows (do g → P od) ⊑ (do g → Q od)
oops

lemma IterateD-refine-intro:
  fixes V :: (nat, 'a) uexpr
  assumes vwb-lens w
  shows
  I ⊢ₙ (w:[⌈I ∧ ¬ (⋁ i∈A · g(i))⌉>]) ⊑
   do i∈A · g(i) → (I ∧ g(i)) ⊢ₙ (w:[⌈I⌉> ∧ ⌈V⌉> <ᵤ ⌈V⌉<]) od
proof (cases A = {})
  case True
  with assms show ?thesis
    by (simp add: IterateD-empty, rel-auto)
next
  case False
  then show ?thesis
  using assms
    apply (simp add: IterateD-def)
    apply (rule ndesign-mu-wf-refine-intro[where e=V and R={(x, y). x < y}])
    apply (simp-all add: wf closure)
    apply (simp add: ndes-simp unrest)
    apply (rule ndesign-refine-intro)
    apply (rel-auto)
    apply (rel-auto)
    apply (metis mwb-lens.put-put vwb-lens-mwb)
  done
qed

lemma IterateD-single-refine-intro:
  fixes V :: (nat, 'a) uexpr
```

assumes *vwb-lens w*
shows
$I \vdash_n (w{:}[\lceil I \wedge \neg\ g \rceil_>]) \sqsubseteq$
$do\ g \rightarrow ((I \wedge g) \vdash_n (w{:}[\lceil I \rceil_> \wedge \lceil V \rceil_> <_u \lceil V \rceil_<]))\ od$
apply (*rule order-trans*)
defer
apply (*rule IterateD-refine-intro*[*of w* {*0*} λ *i. g I V*, *simplified*, *OF assms*(*1*)])
oops

4.5 Let and Local Variables

definition *LetD* :: (*'a*, *'α*) *uexpr* ⇒ (*'a* ⇒ *'α hrel-des*) ⇒ *'α hrel-des* **where**
[*upred-defs*]: $LetD\ v\ P = (P\ x)[\![x \rightarrow \lceil v \rceil_{D<}]\!]$

syntax
-LetD :: [*letbinds*, *'a*] ⇒ *'a* ((let_D (-)/ *in* (-)) [*0*, *10*] *10*)

translations
-LetD (*-binds b bs*) *e* ⇌ *-LetD b* (*-LetD bs e*)
let_D *x* = *a in e* ⇌ *CONST LetD a* (λ*x*. *e*)

lemma *LetD-ndes-simp* [*ndes-simp*]:
$LetD\ v\ (\lambda\ x.\ p(x) \vdash_n Q(x)) = (p(x)[\![x \rightarrow v]\!]) \vdash_n (Q(x)[\![x \rightarrow \lceil v \rceil_<]\!])$
by (*rel-auto*)

lemma *LetD-H1-H3-closed* [*closure*]:
$[\![\bigwedge x.\ P(x)\ is\ \mathbf{N}\ ]\!] \Longrightarrow LetD\ v\ P\ is\ \mathbf{N}$
by (*rel-auto*)

end

4.6 Design Hoare Logic

theory *utp-des-hoare*
imports *utp-des-prog*
begin

definition *HoareD* :: *'s upred* ⇒ *'s hrel-des* ⇒ *'s upred* ⇒ *bool* ($\{\text{-}\}\text{-}\{\text{-}\}_D$) **where**
[*upred-defs*, *ndes-simp*]: $HoareD\ p\ S\ q = ((p \vdash_n \lceil q \rceil_>) \sqsubseteq S)$

lemma *assigns-hoare-d* [*hoare-safe*]: $`p \Rightarrow \sigma \dagger q` \Longrightarrow \{p\}\langle\sigma\rangle_D\{q\}_D$
by *rel-auto*

lemma *skip-hoare-d*: $\{p\}II_D\{p\}_D$
by (*rel-auto*)

lemma *assigns-backward-hoare-d*:
$\{\sigma \dagger p\}\langle\sigma\rangle_D\{p\}_D$
by *rel-auto*

lemma *seq-hoare-d*:
assumes $C\ is\ \mathbf{N}\ D\ is\ \mathbf{N}\ \{p\}C\{q\}_D\ \{q\}D\{r\}_D$
shows $\{p\}C\ ;;\ D\{r\}_D$
proof −
obtain $c_1\ C_2$ **where** *C*: $C = c_1 \vdash_n C_2$
by (*metis assms*(*1*) *ndesign-form*)

obtain d_1 D_2 **where** D: $D = d_1 \vdash_n D_2$
  by (*metis assms*(*2*) *ndesign-form*)
  from *assms*(*3*−*4*) **show** *?thesis*
  apply (*simp add*: *C D*)
  apply (*ndes-simp*)
  apply (*simp add*: *ndesign-refinement*)
  apply (*rel-blast*)
  done
qed

end

5 Design Weakest Preconditions

theory *utp-des-wp*
  imports *utp-des-prog utp-des-hoare*
begin

definition *wp-design* :: $('\alpha, '\beta)$ *rel-des* $\Rightarrow$ $'\beta$ *cond* $\Rightarrow$ $'\alpha$ *cond* (**infix** wp_D *60*) **where**
[*upred-defs*]: $Q\ wp_D\ r = (\lfloor pre_D(Q)\ ;;\ true :: ('\alpha, '\beta)\ urel\rfloor_< \wedge (post_D(Q)\ wp\ r))$

If two normal designs have the same weakest precondition for any given postcondition, then the two designs are equivalent.

theorem *wpd-eq-intro*: $[\![\bigwedge r.\ (p_1 \vdash_n Q_1)\ wp_D\ r = (p_2 \vdash_n Q_2)\ wp_D\ r]\!] \Longrightarrow (p_1 \vdash_n Q_1) = (p_2 \vdash_n Q_2)$
apply (*rel-simp robust*; *metis curry-conv*)
done

theorem *wpd-H3-eq-intro*: $[\![P\ is\ H1\text{-}H3;\ Q\ is\ H1\text{-}H3;\ \bigwedge r.\ P\ wp_D\ r = Q\ wp_D\ r]\!] \Longrightarrow P = Q$
  by (*metis H1-H3-commute H1-H3-is-normal-design H3-idem Healthy-def′ wpd-eq-intro*)

lemma *wp-d-abort* [*wp*]: $true\ wp_D\ p = false$
  by (*rel-auto*)

lemma *wp-assigns-d* [*wp*]: $\langle\sigma\rangle_D\ wp_D\ r = \sigma \dagger r$
  by (*rel-auto*)

theorem *rdesign-wp* [*wp*]:
  $(\lceil p\rceil_< \vdash_r Q)\ wp_D\ r = (p \wedge Q\ wp\ r)$
  by (*rel-auto*)

theorem *ndesign-wp* [*wp*]:
  $(p \vdash_n Q)\ wp_D\ r = (p \wedge Q\ wp\ r)$
  by (*simp add*: *ndesign-def rdesign-wp*)

theorem *wpd-seq-r*:
  fixes *Q1 Q2* :: $'\alpha$ *hrel*
  shows $((\lceil p1\rceil_< \vdash_r Q1)\ ;;\ (\lceil p2\rceil_< \vdash_r Q2))\ wp_D\ r = (\lceil p1\rceil_< \vdash_r Q1)\ wp_D\ ((\lceil p2\rceil_< \vdash_r Q2)\ wp_D\ r)$
  apply (*simp add*: *wp*)
  apply (*subst rdesign-composition-wp*)
  apply (*simp only*: *wp*)
  apply (*rel-auto*)
done

theorem *wpnd-seq-r* [*wp*]:
  fixes *Q1 Q2* :: $'\alpha$ *hrel*

shows $((p1 \vdash_n Q1) ;; (p2 \vdash_n Q2))\ wp_D\ r = (p1 \vdash_n Q1)\ wp_D\ ((p2 \vdash_n Q2)\ wp_D\ r)$
by (*simp add*: *ndesign-def wpd-seq-r*)

theorem *wpd-seq-r-H1-H3* [*wp*]:
fixes $P\ Q$ :: $'\alpha$ *hrel-des*
assumes P *is* **N** Q *is* **N**
shows $(P ;; Q)\ wp_D\ r = P\ wp_D\ (Q\ wp_D\ r)$
by (*metis H1-H3-commute H1-H3-is-normal-design H1-idem Healthy-def' assms*(*1*) *assms*(*2*) *wpnd-seq-r*)

theorem *wp-hoare-d-link*:
assumes Q *is* **N**
shows $\{p\}Q\{r\}_D \longleftrightarrow (Q\ wp_D\ r \sqsubseteq p)$
by (*ndes-simp cls*: *assms*, *rel-auto*)

end

6 Refinement Calculus

theory *utp-des-refcalc*
imports *utp-des-prog*
begin

definition *des-spec* :: $('a \Longrightarrow '\alpha) \Rightarrow '\alpha\ upred \Rightarrow ('\alpha \Rightarrow '\alpha\ upred) \Rightarrow '\alpha\ hrel\text{-}des$ **where**
[*upred-defs*]: $des\text{-}spec\ x\ p\ q = (\bigsqcup\ v \cdot ((p \wedge \&\mathbf{v} =_u \ll v \gg) \vdash_n x{:}[\lceil q(v) \rceil_>]))$

syntax
-init-var :: *logic*
-des-spec :: *salpha* ⇒ *logic* ⇒ *logic* ⇒ *logic* (-:[-,/ -]$_D$ [*99*,*0*,*0*] *100*)
-des-log-const :: *pttrn* ⇒ *logic* ⇒ *logic* (*con*$_D$ - • - [*0*, *10*] *10*)

translations
-des-spec x p q => *CONST des-spec x p* (λ *-init-var*. *q*)
-des-spec (*-salphaset* (*-salphamk x*)) *p q* <= *CONST des-spec x p* (λ *iv*. *q*)
-des-log-const x P => $\bigsqcup$ *x* • *P*

parse-translation ⟪
let
fun init-var-tr [] = *Syntax.free iv*
| *init-var-tr* - = *raise Match*;
in
[(@{*syntax-const -init-var*}, *K init-var-tr*)]
end
⟫

abbreviation $choose_D\ x \equiv \{\&x\}{:}[true,true]_D$

lemma *des-spec-simple-def*:
$x{:}[pre,post]_D = (pre \vdash_n x{:}[\lceil post \rceil_>])$
by (*rel-auto*)

lemma *des-spec-abort*:
$x{:}[false,post]_D = \bot_D$
by (*rel-auto*)

lemma *des-spec-skip*: $\emptyset{:}[true,true]_D = II_D$

by (*rel-auto*)

lemma *des-spec-strengthen-post*:
assumes ‘*post'* ⇒ *post*‘
shows w:[*pre*, *post*]$_D$ ⊑ w:[*pre*, *post'*]$_D$
using *assms* **by** (*rel-auto*)

lemma *des-spec-weaken-pre*:
assumes ‘*pre* ⇒ *pre'*‘
shows w:[*pre*, *post*]$_D$ ⊑ w:[*pre'*, *post*]$_D$
using *assms* **by** (*rel-auto*)

lemma *des-spec-refine-skip*:
assumes *vwb-lens w* ‘*pre* ⇒ *post*‘
shows w:[*pre*, *post*]$_D$ ⊑ II_D
using *assms* **by** (*rel-auto*)

lemma *rc-iter*:
fixes V :: (*nat*, *'a*) *uexpr*
assumes *vwb-lens w*
shows w:[*ivr*, *ivr* ∧ ¬ (⋁ i∈A · $g(i)$)]$_D$
⊑ (*do* i∈A · $g(i)$ → ⨆ *iv* · w:[*ivr* ∧ $g(i)$ ∧ «*iv*» $=_u$ &**v**, *ivr* ∧ ($V <_u V$⟦«*iv*»/**v**⟧)]$_D$ *od*) (**is** *?lhs* ⊑ *?rhs*)
apply (*rule order-trans*)
defer
apply (*simp add*: *des-spec-simple-def*)
apply (*rule IterateD-refine-intro*[*of - - - - V*])
apply (*simp add*: *assms*)
apply (*rule IterateD-mono-refine*)
apply (*simp-all add*: *ndes-simp closure*)
apply (*rel-auto*)
using *assms*
apply (*rel-auto*)
done

end

7 Theory of Invariants

theory *utp-des-invariants*
imports *utp-des-theory*
begin

The theory of invariants formalises operation and state invariants based on the theory of designs. For more information, please see the associated paper [1, Section 4].

7.1 Operation Invariants

definition $OIH(\psi)(D) = (D \wedge (\$ok \wedge \neg D^f \Rightarrow \psi))$

declare *OIH-def* [*upred-defs*]

lemma *OIH-design*:
assumes *D is H1-H2*
shows $OIH(\psi)(D) = ((\neg D^f) \vdash (D^t \wedge \psi))$

proof –
  have $OIH(\psi)(D) = (((\neg D^f) \vdash D^t) \wedge (\$ok \wedge \neg D^f \Rightarrow \psi))$
    by (*metis H1-H2-commute H1-H2-is-design H1-idem Healthy-def′ OIH-def assms*)
  also have ... $= ((\$ok \wedge \neg D^f \Rightarrow \$ok' \wedge D^t) \wedge (\$ok \wedge \neg D^f \Rightarrow \psi))$
    by (*simp add*: *design-def*)
  also have ... $= ((\neg D^f) \vdash (D^t \wedge \psi))$
    by (*pred-auto*)
  finally show *?thesis* **.**
qed

lemma *OIH-idem*:
  assumes *D is H1-H2* $\$ok' \sharp \psi$
  shows $OIH(\psi)(OIH(\psi)(D)) = OIH(\psi)(D)$
  using *assms*
  by (*simp add*: *OIH-design design-is-H1-H2 unrest*) (*simp add*: *design-def usubst*, *rel-auto*)

lemma *OIH-of-design*:
  $\$ok' \sharp P \Longrightarrow OIH(\psi)(P \vdash Q) = (P \vdash (Q \wedge \psi))$
  by (*simp add*: *OIH-def design-def usubst*, *rel-auto*)

7.2 State Invariants

definition $ISH(\psi)(D) = (D \vee (\$ok \wedge \neg D^f \wedge \lceil\psi\rceil_< \Rightarrow \$ok' \wedge D^t))$

declare *ISH-def* [*upred-defs*]

lemma *ISH-design*: $ISH(\psi)(D) = (\neg D^f \wedge \lceil\psi\rceil_<) \vdash D^t$
  by (*rel-auto*, *metis+*)

lemma *ISH-idem*: $ISH(\psi)(ISH(\psi)(D)) = ISH(\psi)(D)$
  by (*simp add*: *ISH-design usubst design-def*, *pred-auto*)

lemma *ISH-of-design*:
  $\llbracket \$ok' \sharp P; \$ok' \sharp Q \rrbracket \Longrightarrow ISH(\psi)(P \vdash Q) = ((P \wedge \lceil\psi\rceil_<) \vdash Q)$
  by (*simp add*: *ISH-design design-def usubst*, *pred-auto*)

definition $OSH(\psi)(D) = (D \wedge (\$ok \wedge \neg D^f \wedge \lceil\psi\rceil_< \Rightarrow \lceil\psi\rceil_>))$

declare *OSH-def* [*upred-defs*]

lemma *OSH-as-OIH*:
  $OSH(\psi)(D) = OIH(\lceil\psi\rceil_< \Rightarrow \lceil\psi\rceil_>)(D)$
  by (*simp add*: *OSH-def OIH-def*, *pred-auto*)

lemma *OSH-design*:
  assumes *D is H1-H2*
  shows $OSH(\psi)(D) = ((\neg D^f) \vdash (D^t \wedge (\lceil\psi\rceil_< \Rightarrow \lceil\psi\rceil_>)))$
  by (*simp add*: *OSH-as-OIH OIH-design assms*)

lemma *OSH-of-design*:
  $\llbracket \$ok' \sharp P; \$ok' \sharp Q \rrbracket \Longrightarrow OSH(\psi)(P \vdash Q) = (P \vdash (Q \wedge (\lceil\psi\rceil_< \Rightarrow \lceil\psi\rceil_>)))$
  by (*simp add*: *OSH-design design-is-H1-H2 unrest*, *simp add*: *design-def usubst*, *pred-auto*)

definition $SIH(\psi) = ISH(\psi) \circ OSH(\psi)$

declare *SIH-def* [*upred-defs*]

lemma *SIH-of-design*:
$[\![\ \$ok' \sharp P; \$ok' \sharp Q; ok \sharp \psi \ ]\!] \Longrightarrow SIH(\psi)(P \vdash Q) = ((P \wedge \lceil\psi\rceil_<) \vdash (Q \wedge \lceil\psi\rceil_>))$
by (*simp add*: *SIH-def OSH-of-design ISH-of-design unrest*, *pred-auto*)

end

8 Meta Theory for UTP Designs

theory *utp-designs*
imports
utp-des-core
utp-des-healths
utp-des-theory
utp-des-tactics
utp-des-hoare
utp-des-prog
utp-des-wp
utp-des-refcalc
utp-des-invariants
begin end

References

[1] A. Cavalcanti, A. Wellings, and J. Woodcock. The Safety-Critical Java memory model formalised. *Formal Aspects of Computing*, 25(1):37–57, 2012.

[2] A. Cavalcanti and J. Woodcock. A tutorial introduction to designs in unifying theories of programming. In *Proc. 4th Intl. Conf. on Integrated Formal Methods (IFM)*, volume 2999 of *LNCS*, pages 40–66. Springer, 2004.

[3] W. Guttman and B. Möller. Normal design algebra. *Journal of Logic and Algebraic Programming*, 79(2):144–173, February 2010.

[4] T. Hoare and J. He. *Unifying Theories of Programming.* Prentice-Hall, 1998.