# Theory of Designs in Isabelle/UTP

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**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**

**lemma** *ok-ord* [*usubst*]:
  $\$ok \prec_v \$ok´$
  **by** (*simp add*: *var-name-ord-def*)

**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* $(\Sigma_D)$

**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* $(\lceil\text{-}\rceil_D)$
**where** $\lceil P\rceil_D \equiv P \oplus_p (\Sigma_D \times_L \Sigma_D)$

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

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

**abbreviation** *drop-desr* $(\lfloor\text{-}\rfloor_D)$
**where** $\lfloor P\rfloor_D \equiv P \restriction_e (\Sigma_D \times_L \Sigma_D)$

**abbreviation** *dcond* :: $('\alpha, '\beta)$ *rel-des* $\Rightarrow$ $'\alpha$ *upred* $\Rightarrow$ $('\alpha, '\beta)$ *rel-des* $\Rightarrow$ $('\alpha, '\beta)$ *rel-des*
  $((3\text{-} \triangleleft \text{-} \triangleright_D/ \text{-})\ [52,0,53]\ 52)$

**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** $\vdash$ *60*) **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-des* (**infixl** $\vdash_r$ *60*) **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-des* (**infixl** $\vdash_n$ *60*) **where**
[*upred-defs*]: $(p \vdash_n Q) = (\lceil p \rceil_< \vdash_r Q)$

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

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

**definition** *pre-design* :: $('\alpha, '\beta)$ *rel-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-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**
  $P^f$ $\rightleftharpoons$ *CONST usubst* (*CONST subst-upd CONST id* (*CONST ovar CONST ok*) *false*) *P*
  $P^t$ $\rightleftharpoons$ *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-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*: $\$ok' \sharp P \Longrightarrow (P ;; \lceil II \rceil_D) = P$
**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*]:
$[\![ \$ok \sharp \sigma; \$ok' \sharp \sigma ]\!] \Longrightarrow \sigma \dagger (P \vdash Q) = (\sigma \dagger P) \vdash (\sigma \dagger Q)$
**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′*: $P \vdash Q = (P \vdash (\$ok' \wedge Q))$
  **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*: $(\mathit{false} \vdash \mathit{true}) = \mathit{true}$
  **by** (*rel-auto*)

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

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

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

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

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

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

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

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

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

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

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

**lemma** *design-subst-ok-ok′*:
  $(P[\![\mathit{true}/\$ok]\!] \vdash Q[\![\mathit{true},\mathit{true}/\$ok,\$ok']\!]) = (P \vdash Q)$
**proof** −
  **have** $(P \vdash Q) = ((\$ok \wedge P) \vdash (\$ok \wedge \$ok' \wedge Q))$
    **by** (*pred-auto*)

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

**lemma** *design-subst-ok'*:
$(P \vdash Q[\![true/\$ok']\!]) = (P \vdash Q)$
**proof** –
**have** $(P \vdash Q) = (P \vdash (\$ok' \wedge Q))$
**by** (*pred-auto*)
**also have** ... = $(P \vdash (\$ok' \wedge Q[\![true/\$ok']\!]))$
**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** $((P1 \vdash Q1) \;;;\; (P2 \vdash Q2)) =$
$(((\neg ((\neg P1) \;;;\; true)) \wedge \neg (Q1[\![true/\$ok']\!] \;;;\; (\neg P2))) \vdash (Q1[\![true/\$ok']\!] \;;;\; Q2[\![true/\$ok]\!]))$
**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** ...
$= (((P1 \vdash Q1)[\![false/\$ok']\!] \;;;\; (P2 \vdash Q2)[\![false/\$ok]\!])$
$\vee ((P1 \vdash Q1)[\![true/\$ok']\!] \;;;\; (P2 \vdash Q2)[\![true/\$ok]\!]))$
**by** (*simp add*: *true-alt-def false-alt-def*, *pred-auto*)
**also from** *assms*
**have** ... = $(((\$ok \wedge P1 \Rightarrow Q1[\![true/\$ok']\!]) \;;;\; (P2 \Rightarrow \$ok' \wedge Q2[\![true/\$ok]\!])) \vee ((\neg (\$ok \wedge P1)) \;;;\; true))$
**by** (*simp add*: *design-def usubst unrest*, *pred-auto*)
**also have** ... = $((\neg\$ok \;;;\; true_h) \vee ((\neg P1) \;;;\; true) \vee (Q1[\![true/\$ok']\!] \;;;\; (\neg P2)) \vee (\$ok' \wedge (Q1[\![true/\$ok']\!] \;;;\; Q2[\![true/\$ok]\!])))$
**by** (*rel-auto*)
**also have** ... = $(((\neg ((\neg P1) \;;;\; true)) \wedge \neg (Q1[\![true/\$ok']\!] \;;;\; (\neg P2))) \vdash (Q1[\![true/\$ok']\!] \;;;\; Q2[\![true/\$ok]\!]))$
**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** $((P1 \vdash Q1) \;;;\; (P2 \vdash Q2)) = (((\neg ((\neg P1) \;;;\; true)) \wedge \neg (Q1 \;;;\; (\neg P2))) \vdash (Q1 \;;;\; Q2))$
**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** $((P1 \vdash Q1) ;; (P2 \vdash Q2)) = (((\neg ((\neg P1) ;; true)) \wedge \neg (Q1^t ;; (\neg P2))) \vdash (Q1 ;; Q2))$
**proof** −
  **have** $(\$ok \wedge \$ok' \wedge (Q1^t ;; Q2[\![true/\$ok]\!])) = (\$ok \wedge \$ok' \wedge (Q1 ;; Q2))$
  **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** $(true\ ;;\ (P \vdash Q)) = (\exists\ ok_0 \cdot true[\![\ll ok_0 \gg/\$ok']\!]\ ;;\ (P \vdash Q)[\![\ll ok_0 \gg/\$ok]\!])$
**by** (*subst seqr-middle*[*of ok*], *simp-all*)
**also have** ... $= ((true[\![false/\$ok']\!]\ ;;\ (P \vdash Q)[\![false/\$ok]\!]) \vee (true[\![true/\$ok']\!]\ ;;\ (P \vdash Q)[\![true/\$ok]\!]))$
**by** (*simp add*: *disj-comm false-alt-def true-alt-def*)
**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*:
$(P \vdash Q)^t = ((\$ok \wedge P^t) \Rightarrow Q^t)$
**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*]:
$pre_D(P \sqcap Q) = (pre_D(P) \wedge pre_D(Q))$
**by** (*rel-auto*)

**lemma** *design-post-choice* [*simp*]:
$post_D(P \sqcap Q) = (post_D(P) \vee post_D(Q))$
**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*:
$(P_1 \vdash P_2) \sqcap (Q_1 \vdash Q_2) = ((P_1 \wedge Q_1) \vdash (P_2 \vee Q_2))$

**by** (*rel-auto*)

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

**theorem** *ndesign-choice* [*ndes-simp*]:
$(p_1 \vdash_n P_2) \sqcap (q_1 \vdash_n Q_2) = ((p_1 \wedge q_1) \vdash_n (P_2 \vee Q_2))$
**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** $P$ :: $'\alpha$ *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-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*]:
$[\![ P \textit{ is } H1; Q \textit{ is } H1 ]\!] \Longrightarrow P \sqcap Q \textit{ is } H1$
**by** (*simp add*: *H1-def Healthy-def' disj-upred-def impl-alt-def semilattice-sup-class.sup-left-commute*)

**lemma** *H1-inf-closed* [*closure*]:

$[\![ P \textit{ is } H1; Q \textit{ is } H1 ]\!] \Longrightarrow P \sqcup Q \textit{ is } H1$
**by** (*rel-blast*)

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

**lemma** *H1-Sup*:
**assumes** $A \neq \{\}$ $\forall P \in A.\ P \textit{ is } H1$
**shows** $(\bigsqcap A) \textit{ is } H1$
**proof** −
**from** *assms*(2) **have** $H1 \text{ ` } A = A$
**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** $\forall P \in A.\ P \textit{ is } H1$
**shows** $(\bigsqcup A) \textit{ is } H1$
**proof** −
**from** *assms* **have** $H1 \text{ ` } A = A$
**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** $J :: {}'\alpha \textit{ hrel-des}$ **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** ... $= (\exists \$ok' \cdot P \wedge \$ok' =_u \textit{false})$

**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** $H2\ (\neg\ \$ok) = ((\neg\ \$ok)^f \vee ((\neg\ \$ok)^t \wedge \$ok'))$
**by** (*simp add*: *H2-split*)
**also have** ... $= (\neg\ \$ok \vee (\neg\ \$ok) \wedge \$ok')$
**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** $P \sqcup Q = (P^f \vee P^t \wedge \$ok') \sqcup (Q^f \vee Q^t \wedge \$ok')$
**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** $H2(\bigsqcap\ i \in A \cdot P(i)) = (\bigsqcap\ i \in A \cdot H2(P(i)))$
**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** ... $= ((\neg\ \$ok \vee P) \;;\; J)$
**by** (*rel-auto*)
**also have** ... $= (((\neg\ \$ok) \;;\; J) \vee (P \;;\; J))$
**using** *seqr-or-distl* **by** *blast*
**also have** ... $= ((H2\ (\neg\ \$ok)) \vee H2(P))$
**by** (*simp add*: *H2-def*)

also have ... = $((\neg \$ok) \vee H2(P))$
  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**
$H1\text{-}H2\ P \equiv H1\ (H2\ P)$

**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** ... = $(\$ok \Rightarrow (P^f \vee (P^t \wedge \$ok')))$
    **by** (*metis H2-split*)
  **also have** ... = $(\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge \$ok \wedge P^t)$
    **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** ... = $(\$ok \Rightarrow (P^f \vee (P^t \wedge \$ok')))$
    **by** (*metis H2-split*)
  **also have** ... = $(\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge P^t)$
    **by** (*pred-auto*)
  **also have** ... = $(\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge \$ok \wedge P^t)$
    **by** (*pred-auto*)
  **also have** ... = $(\$ok \wedge \lceil pre_D(P) \rceil_D \Rightarrow \$ok' \wedge \$ok \wedge \lceil post_D(P) \rceil_D)$
    **by** (*simp add*: *ok-post ok-pre*)
  **also have** ... = $(\$ok \wedge \lceil pre_D(P) \rceil_D \Rightarrow \$ok' \wedge \lceil post_D(P) \rceil_D)$
    **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** $P \sqsubseteq Q \longleftrightarrow (`pre_D(P) \Rightarrow pre_D(Q)` \wedge `pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)`)$
**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*: **H** (**H** $P$) = **H** $P$
**by** (*simp add*: *H1-H2-commute H1-idem H2-idem*)

**lemma** *H1-H2-Idempotent* [*closure*]: *Idempotent* **H**
**by** (*simp add*: *Idempotent-def H1-H2-idempotent*)

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

**lemma** *H1-H2-Continuous* [*closure*]: *Continuous* **H**
**by** (*simp add*: *Continuous-comp H1-Continuous H1-H2-comp H2-Continuous*)

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

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

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

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

**lemma** *seq-r-H1-H2-closed* [*closure*]:
**assumes** $P$ *is* **H** $Q$ *is* **H**
**shows** $(P ;; Q)$ *is* **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* **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* **H**
**shows** $(\bigsqcap A)$ *is H1-H2*

**proof** –
  **from** *assms* **have** $A$: $A = H1\text{-}H2$ ‘ $A$
    **by** (*auto simp add*: *Healthy-def rev-image-eqI*)
  **also have** ($\bigsqcap$ ...) = ($\bigsqcap$ $P \in A \cdot H1\text{-}H2(P)$)
    **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** $\forall\ P \in A.\ P\ \mathit{is}\ \mathbf{H}$
**shows** $(\bigsqcup\ A)\ \mathit{is}\ \mathbf{H}$
**proof** −
**from** *assms* **have** $A$: $A = \mathbf{H}\ `\ A$
**by** (*auto simp add*: *Healthy-def rev-image-eqI*)
**also have** $(\bigsqcup\ ...) = (\bigsqcup\ P \in A \cdot \mathbf{H}(P))$
**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** $P\ \mathit{is}\ \mathbf{H}\ Q\ \mathit{is}\ \mathbf{H}\ P \sqsubseteq Q$
**shows** $\mathit{pre}_D(Q) \sqsubseteq \mathit{pre}_D(P)\ \mathit{post}_D(P) \sqsubseteq (\mathit{pre}_D(P) \wedge \mathit{post}_D(Q))$
**proof** −
**have** $r$: $P \sqsubseteq Q \longleftrightarrow (`\mathit{pre}_D(P) \Rightarrow \mathit{pre}_D(Q)` \wedge `\mathit{pre}_D(P) \wedge \mathit{post}_D(Q) \Rightarrow \mathit{post}_D(P)`)$
**by** (*metis H1-H2-eq-rdesign Healthy-if assms*(*1*) *assms*(*2*) *rdesign-refinement*)
**from** *r assms* **show** $\mathit{pre}_D(Q) \sqsubseteq \mathit{pre}_D(P)$
**by** (*auto simp add*: *refBy-order*)
**from** *r assms* **show** $\mathit{post}_D(P) \sqsubseteq (\mathit{pre}_D(P) \wedge \mathit{post}_D(Q))$
**by** (*auto simp add*: *refBy-order*)
**qed**

## 2.4 H3: The design assumption is a precondition

**definition** $\mathit{H3} :: ('\alpha, '\beta)\ \mathit{rel\text{-}des} \Rightarrow ('\alpha, '\beta)\ \mathit{rel\text{-}des}$ **where**
[*upred-defs*]: $\mathit{H3}\ (P) \equiv P\ ;;\ \mathit{II}_D$

**theorem** *H3-idem*:
$\mathit{H3}(\mathit{H3}(P)) = \mathit{H3}(P)$
**by** (*metis H3-def design-skip-idem seqr-assoc*)

**theorem** *H3-mono*:
$P \sqsubseteq Q \Longrightarrow \mathit{H3}(P) \sqsubseteq \mathit{H3}(Q)$
**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** $\mathit{out}\alpha \sharp p$
**shows** $(p \vdash Q)\ \mathit{is}\ \mathit{H3}$
**proof** −
**have** $((p \vdash Q)\ ;;\ \mathit{II}_D) = (\neg\ ((\neg\ p)\ ;;\ \mathit{true})) \vdash (Q^t\ ;;\ \mathit{II}[\![\mathit{true}/\$ok]\!])$
**by** (*simp add*: *skip-d-alt-def design-composition-subst unrest assms*)
**also have** $... = p \vdash (Q^t\ ;;\ \mathit{II}[\![\mathit{true}/\$ok]\!])$
**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** ... $= (\exists\ ok_0 \cdot ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D)[\![\ll ok_0 \gg/\$ok']\!] ;; (true \vdash II)[\![\ll ok_0 \gg/\$ok]\!])$
**by** (*subst seqr-middle*[*of ok*], *simp-all*)
**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** (*simp add*: *disj-comm false-alt-def true-alt-def*)
**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-out$\alpha$-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-out$\alpha$*)

**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* $\mathbf{N}$
**by** (*simp add*: *Idempotent-def H1-H3-idempotent*)

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

**lemma** *H1-H3-Continuous* [*closure*]: *Continuous* $\mathbf{N}$
**by** (*simp add*: *Continuous-comp H1-Continuous H1-H3-comp H3-Continuous*)

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

**lemma** *H1-H3-impl-H2* [*closure*]: $P$ *is* $\mathbf{N} \Longrightarrow P$ *is* $\mathbf{H}$
**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* $\mathbf{N}$
**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* $\mathbf{N} \Longrightarrow out\alpha \sharp pre_D(P)$
**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* $\mathbf{N}$
**by** (*simp add*: *H1-rdesign H3-def Healthy-def′ ndesign-def unrest-pre-out*$\alpha$)

**lemma** *ndesign-form*: $P$ *is* $\mathbf{N} \Longrightarrow (\lfloor pre_D(P) \rfloor_< \vdash_n post_D(P)) = P$
**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* $\mathbf{N}$
**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* $\mathbf{N}$
**by** (*metis ndesign-H1-H3 ndesign-miracle*)

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

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

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

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

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

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

**lemma** *USUP-ind-H1-H3-closed* [*closure*]:
  $[\![ \bigwedge i.\ P\ i\ is\ \mathbf{N} ]\!] \Longrightarrow (\bigsqcup\ i \cdot P\ i)\ is\ \mathbf{N}$
  **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** $H4 :: ('\alpha, '\beta)\ rel\text{-}des \Rightarrow ('\alpha, '\beta)\ rel\text{-}des$ **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*:
  $P\ is\ H4 \longleftrightarrow (P\ ;;\ true) = true$
  **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** $DES \equiv UTHY(DES, '\alpha\ des)$
**abbreviation** $NDES \equiv UTHY(NDES, '\alpha\ des)$

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

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

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

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

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

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

**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*: $D\ is\ \mathbf{H}$
  **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* :: $('\alpha\ hrel\text{-}des \Rightarrow '\alpha\ hrel\text{-}des) \Rightarrow '\alpha\ hrel\text{-}des$ ($\mu_D$) **where**
$\mu_D\ F \equiv \boldsymbol{\mu}_{DES}\ F$

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

**syntax**
  *-dmu* :: *pttrn* $\Rightarrow$ *logic* $\Rightarrow$ *logic* ($\mu_D$ - $\cdot$ - [*0*, *10*] *10*)
  *-dnu* :: *pttrn* $\Rightarrow$ *logic* $\Rightarrow$ *logic* ($\nu_D$ - $\cdot$ - [*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*:
    $\bigwedge st.\ (P \wedge \lceil e \rceil_< =_u «st») \vdash_r Q \sqsubseteq F\ ((P \wedge (\lceil e \rceil_<, «st»)_u \in_u «R») \vdash_r Q)$
  **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* $\sigma$ = (*true* $\vdash_r$ *assigns-r* $\sigma$)

**syntax**
  *-assignmentd* :: *svids* $\Rightarrow$ *uexprs* $\Rightarrow$ *logic* (**infixr** $:=_D$ *72*)

**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** $P$ :: $'\alpha$ *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* $\mathbf{N} \Longrightarrow \lceil\sigma \oplus_s \Sigma_D\rceil_s \dagger P$ *is* $\mathbf{N}$
**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** $(\langle\sigma\rangle_D$ ;; $(false \vdash_r true_h)) = (false \vdash_r true)$
  **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* $\Rightarrow$ $('\alpha, '\beta)$ *rel-des* $\Rightarrow$ $('\alpha, '\beta)$ *rel-des* (- $\rightarrow_D$ - [*85*, *86*] *85*) **where**
[*upred-defs*]: $b \rightarrow_D P = P \triangleleft b \triangleright_D \top_D$

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

**lemma** *GrdCommD-H1-H3-closed* [*closure*]: $P$ *is* $\mathbf{N} \Longrightarrow b \rightarrow_D P$ *is* $\mathbf{N}$
**by** (*simp add*: *GrdCommD-def closure*)

**lemma** *GrdCommD-true* [*simp*]: $true \rightarrow_D P = P$
**by** (*rel-auto*)

**lemma** *GrdCommD-false* [*simp*]: $false \rightarrow_D P = \top_D$
**by** (*rel-auto*)

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

## 4.3 Alternation

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

**definition** *AlternateD* :: $'a$ *set* $\Rightarrow ('a \Rightarrow '\alpha$ *upred*$) \Rightarrow ('a \Rightarrow ('\alpha, '\beta)$ *rel-des*$) \Rightarrow ('\alpha, '\beta)$ *rel-des* $\Rightarrow ('\alpha, '\beta)$ *rel-des* **where**

$[upred\text{-}defs,\ ndes\text{-}simp]$:
$AlternateD\ A\ g\ P\ Q = (\prod\ i{\in}A \cdot g(i) \rightarrow_D P(i)) \sqcap (\bigwedge\ i{\in}A \cdot \neg\ g(i)) \rightarrow_D Q$

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**
  $AlternateD\ A\ g\ P\ \bot_D =$
  $((\bigvee\ i{\in}A \cdot g(i)) \wedge (\bigwedge\ i{\in}A \cdot g(i) \Rightarrow \lfloor pre_D(P\ i)\rfloor_<)) \vdash_n (\bigvee\ i{\in}A \cdot \lceil g(i)\rceil_< \wedge post_D(P\ i))$
**proof** (*cases* $A = \{\}$)
  **case** *False*
  **have** $AlternateD\ A\ g\ P\ \bot_D =$
        $(\prod\ i{\in}A \cdot g(i) \rightarrow_D (\lfloor pre_D(P\ i)\rfloor_< \vdash_n post_D(P\ i))) \sqcap (\bigwedge\ i{\in}A \cdot \neg\ g(i)) \rightarrow_D (false \vdash_n true)$
    **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**
$[upred\text{-}defs,\ ndes\text{-}simp]$:
*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* (- → - [*65*, *66*] *65*)
  *-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** $\bigwedge i.\ i \in A \Longrightarrow P\ i\ is\ \mathbf{N}$ $Q\ is\ \mathbf{N}$
**shows** $if\ i{\in}A \cdot g(i) \rightarrow P(i)\ else\ Q\ fi\ is\ \mathbf{N}$
**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*]:
$if\ i{\in}A \cdot g(i) \rightarrow (P_1(i) \vdash_n P_2(i))\ else\ Q_1 \vdash_n Q_2\ fi$
$= ((\bigwedge i \in A \cdot g\ i \Rightarrow P_1\ i) \wedge ((\bigwedge i \in A \cdot \neg\ g\ i) \Rightarrow Q_1)) \vdash_n$
$((\bigvee i \in A \cdot \lceil g\ i\rceil_< \wedge P_2\ i) \vee (\bigwedge i \in A \cdot \neg\ \lceil g\ i\rceil_<) \wedge Q_2)$
**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** $(if\ i{\in}A \cdot g(i) \rightarrow P(i)\ else\ R\ fi) \sqsubseteq (if\ i{\in}A \cdot g(i) \rightarrow Q(i)\ else\ S\ fi)$
**using** *assms* **by** (*rel-auto*, *meson*)

**lemma** *Monotonic-AlternateD* [*closure*]:
$\llbracket \bigwedge i.\ Monotonic\ (F\ i);\ Monotonic\ G\ \rrbracket \Longrightarrow Monotonic\ (\lambda\ X.\ if\ i{\in}A \cdot g(i) \rightarrow F\ i\ X\ else\ G(X)\ fi)$
**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** $if\ i{\in}A \cdot g(i) \rightarrow P(i)\ else\ R\ fi = if\ i{\in}B \cdot h(i) \rightarrow Q(i)\ else\ S\ fi$
**by** (*insert assms*, *rel-blast*)

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

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

**lemma** *AlernateD-no-ind*:
  **assumes** $A \neq \{\}$ $P$ *is* **N** $Q$ *is* **N**
  **shows** $if\ i{\in}A \cdot b \rightarrow P\ else\ Q\ fi = if\ b \rightarrow P\ else\ Q\ fi$
  **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*]:
$(p \vdash_n Q)$ ;; $(p \vdash_n Q)$ ^ $n = ((\bigwedge i \in \{0..n\} \cdot (Q$ ^ $i)$ *wp* $p) \vdash_n Q$ ^ *Suc* $n)$
**proof** (*induct n*)
**case** *0*
**then show** *?case* **by** (*rel-auto*)
**next**
**case** (*Suc n*) **note** *hyp* = *this*
**have** $(p \vdash_n Q)$ ;; $(p \vdash_n Q)$ ^ *Suc* $n = (p \vdash_n Q)$ ;; $(p \vdash_n Q)$ ;; $(p \vdash_n Q)$ ^ $n$
 **by** (*simp add*: *upred-semiring.power-Suc*)
**also have** ... = $(p \vdash_n Q)$ ;; $((\bigsqcup i \in \{0..n\} \cdot Q$ ^ $i$ *wp* $p) \vdash_n Q$ ^ *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* ⇒ *logic* ⇒ *logic* ⇒ *logic* ⇒ *logic* (*do* -∈- · - → - *od*)
*-itergcomm* :: *gcomms* ⇒ *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*]:
$IterateD\ A\ g\ P = (\boldsymbol{\mu}_{NDES}\ X \cdot if\ i{\in}A \cdot g(i) \rightarrow P(i)\ ;;\ X\ else\ II_D\ fi)$

**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** $\bigwedge i.\ i \in A \Longrightarrow P\ i\ is\ \mathbf{N}$
**shows** $do\ i{\in}A \cdot g(i) \rightarrow P(i)\ od\ is\ \mathbf{N}$
**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*:
$do\ i{\in}\{\} \cdot g(i) \rightarrow P(i)\ od = II_D$
**by** (*simp add*: *IterateD-def AlternateD-empty normal-design-theory-continuous.LFP-const skip-d-is-H1-H3*)

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

**lemma** *IterateD-singleton*:
**assumes** $P$ *is* **N**
**shows** $do\ b \rightarrow P\ od = do\ i{\in}\{0\} \cdot b \rightarrow P\ od$
**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**
$\bigwedge i.\ P\ i$ *is* **N** $\bigwedge i.\ Q\ i$ *is* **N**
$\bigwedge i.\ P\ i \sqsubseteq Q\ i$
**shows** $(do\ i{\in}A \cdot g(i) \rightarrow P(i)\ od) \sqsubseteq (do\ i{\in}A \cdot g(i) \rightarrow Q(i)\ od)$
**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** $P \sqsubseteq Q$
**shows** $(do\ g \rightarrow P\ od) \sqsubseteq (do\ g \rightarrow Q\ od)$
**oops**

**lemma** *IterateD-refine-intro*:
**fixes** $V$ :: (*nat*, *'a*) *uexpr*
**assumes** *vwb-lens w*
**shows**
$I \vdash_n (w{:}[\lceil I \wedge \neg (\bigvee i{\in}A \cdot g(i))\rceil_{>}]) \sqsubseteq$
$do\ i{\in}A \cdot g(i) \rightarrow (I \wedge g(i)) \vdash_n (w{:}[\lceil I\rceil_{>} \wedge \lceil V\rceil_{>} <_u \lceil V\rceil_{<}])\ od$
**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* $\{0\}$ $\lambda\ i.\ g\ I\ V$, *simplified*, *OF assms*(*1*)])
**oops**

## 4.5 Let and Local Variables

**definition** $LetD :: ('a, '\alpha)\ uexpr \Rightarrow ('a \Rightarrow '\alpha\ hrel\text{-}des) \Rightarrow '\alpha\ hrel\text{-}des$ **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* ($\lambda x.\ e$)

**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*)

## 4.6 Deep Local Variables

**definition** *des-local-state* ::
*'a::countable itself* ⇒ ((*nat*, *'s*) *local-scheme des*, *'s*, *nat*, *'a::countable*) *local-prim* **where**
*des-local-state t* = (| *sstate* = $\Sigma_D$, *sassigns* = *assigns-d*, *inj-local* = *nat-inj-univ* |)

**syntax**
*-des-local-state-type* :: *type* ⇒ *logic* ($\mathcal{L}_D$[-])
*-des-var-scope-type* :: *id* ⇒ *type* ⇒ *logic* ⇒ *logic* (*var*$_D$ - :: - • - [*0*, *0*, *10*] *10*)

**translations**
$\mathcal{L}_D$[*'a*] == *CONST des-local-state TYPE*(*'a*)
*-des-var-scope-type x t P* => *-var-scope-type* (*-des-local-state-type t*) *x t P*

$var_D\ x :: 'a \cdot P <= var[\mathcal{L}_D['a]]\ x \cdot P$

**lemma** *get-rel-local* [*lens-defs*]:
$get_{\mathbf{s}_{\mathcal{L}_D['a::countable]}} = get_{\Sigma_D}$
**by** (*simp add*: *des-local-state-def*)

**lemma** *des-local-state* [*simp*]: *utp-local-state* $\mathcal{L}_D['a::countable]$
**by** (*unfold-locales*, *simp-all add*: *upred-defs assigns-comp des-local-state-def*, *rel-auto*)
(*metis local.cases-scheme*)

**lemma** *sassigns-des-state* [*simp*]: $\langle\sigma\rangle_{\mathcal{L}_D['a::countable]} = \langle\sigma\rangle_D$
**by** (*simp add*: *des-local-state-def*)

**lemma** *des-var-open-H1-H3-closed* [*closure*]:
$open[\mathcal{L}_D['a::countable]]$ *is* **N**
**by** (*simp add*: *utp-local-state.var-open-def closure*)

**lemma** *des-var-close-H1-H3-closed* [*closure*]:
$close[\mathcal{L}_D['a::countable]]$ *is* **N**
**by** (*simp add*: *utp-local-state.var-close-def closure*)

**lemma** *unrest-ok-vtop-des* [*unrest*]: $ok \sharp top[\mathcal{L}_D['a::countable]]$
**by** (*simp add*: *utp-local-state.top-var-def*, *simp add*: *des-local-state-def unrest*)

**lemma** *msubst-H1-H3-closed* [*closure*]:
$[\![\ \$ok \sharp v;\ out\alpha \sharp v;\ (\bigwedge x.\ P\ x\ is\ \mathbf{N})\ ]\!] \Longrightarrow (P(x)[\![x \rightarrow v]\!])\ is\ \mathbf{N}$
**by** (*rel-auto*, *metis+*)

**lemma** *var-block-H1-H3-closed* [*closure*]:
$(\bigwedge x.\ P\ x\ is\ \mathbf{N}) \Longrightarrow \mathcal{V}[\mathcal{L}_D['a::countable], P]\ is\ \mathbf{N}$
**by** (*simp add*: *utp-local-state.var-scope-def closure unrest*)

**lemma** *inj-local-rel* [*simp*]: *inj-local* $R_l = \mathcal{U}_{\mathbb{N}}$
**by** (*simp add*: *rel-local-state-def*)

**lemma** *sstate-rel* [*simp*]: $\mathbf{s}_{R_l} = 1_L$
**by** (*simp add*: *rel-local-state-def*)

**lemma** *inj-local-des* [*simp*]:
*inj-local* $\mathcal{L}_D['a::countable] = \mathcal{U}_{\mathbb{N}}$
**by** (*simp add*: *des-local-state-def*)

**lemma** *sstate-des* [*simp*]: $\mathbf{s}_{\mathcal{L}_D['a::countable]} = \Sigma_D$
**by** (*simp add*: *des-local-state-def*)

**lemma** *ndesign-msubst-top* [*usubst*]:
$(p\ x \vdash_n Q\ x)[\![x \rightarrow \lceil top[\mathcal{L}_D['a::countable]]\rceil_<]\!] = ((p\ x)[\![x \rightarrow top[R_l['a]]]\!] \vdash_n (Q\ x)[\![x \rightarrow \lceil top[R_l['a]]\rceil_<]\!])$
**by** (*rel-auto'*)

First attempt at a law for expanding design variable blocks. Far from adequate at the moment though.

**lemma** *ndesign-local-expand-1* [*ndes-simp*]:
$(var_D\ x :: 'a :: countable \cdot p(x) \vdash_n Q(x)) =$
$(\bigsqcup\ v \cdot (p\ x)[\![x \rightarrow top[R_l]]\!][\![\&store\ \hat{}_u\ \langle \ll v \gg \rangle / store]\!]) \vdash_n$
$(\bigsqcap\ v \cdot store := \&store\ \hat{}_u\ \langle \ll v \gg \rangle\ ;;\ (Q\ x)[\![x \rightarrow \lceil top[R_l]\rceil_<]\!]\ ;;\ store := (front_u(\&store) \triangleleft\ 0 <_u$

$\#_u(\&store) \triangleright \&store))$
**apply** (*simp add*: *utp-local-state.var-scope-def utp-local-state.var-open-def utp-local-state.var-close-def seq-UINF-distr′ usubst*)
**apply** (*simp add*: *ndes-simp wp unrest*)
**apply** (*rel-auto′*)
**done**

**end**

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

**lemma** *seq-hoare-d*:
**assumes** *C is* **N** *D is* **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* :: (*′α*, *′β*) *rel-des* ⇒ *′β cond* ⇒ *′α 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*: $\llbracket$ *P is H1-H3*; *Q is H1-H3*; $\bigwedge r.\ P\ wp_D\ r = Q\ wp_D\ r\ \rrbracket \Longrightarrow P = Q$
 **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* :: *′α 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* :: *′α 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* :: *′α 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* => ⨆ *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* ≡ {&*x*}:[*true*,*true*]$_D$

**lemma** *des-spec-simple-def*:
  *x*:[*pre*,*post*]$_D$ = (*pre* ⊢$_n$ *x*:[⌈*post*⌉$_>$])
  **by** (*rel-auto*)

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

**lemma** *des-spec-skip*: ∅:[*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*:
$\llbracket\ \$ok' \sharp\ P;\ \$ok' \sharp\ Q;\ ok \sharp\ \psi\ \rrbracket \Longrightarrow SIH(\psi)(P \vdash Q) = ((P \wedge \lceil\psi\rceil_<) \vdash (Q \wedge \lceil\psi\rceil_>))$
**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

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