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# 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.

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# 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 λr. (okv r, more r)
apply (unfold-locales)
apply (rule injI)
apply (clarsimp)
done
```

```
interpretation des-vars-rel:
  lens-interp λ(r, r'). (okv r, okv 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**  $'\alpha \text{ des} = '\alpha \text{ des-vars-scheme}$   
**type-synonym**  $(''\alpha, '\beta) \text{ rel-des} = (''\alpha \text{ des}, '\beta \text{ des}) \text{ urel}$   
**type-synonym**  $'\alpha \text{ hrel-des} = (''\alpha \text{ des}) \text{ hrel}$

**translations**

$(\text{type}) '\alpha \text{ des} \leq (\text{type}) '\alpha \text{ des-vars-scheme}$   
 $(\text{type}) '\alpha \text{ des} \leq (\text{type}) '\alpha \text{ des-vars-ext}$   
 $(\text{type}) (''\alpha, '\beta) \text{ rel-des} \leq (\text{type}) (''\alpha \text{ des}, '\beta \text{ des}) \text{ urel}$   
 $(\text{type}) '\alpha \text{ hrel-des} \leq (\text{type}) '\alpha \text{ des hrel}$

**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* ::  $(''\alpha \implies '\beta) \implies (''\alpha \text{ des-vars-scheme} \implies '\beta \text{ des-vars-scheme})$  (*lmap<sub>D</sub>*)  
**where** [*lens-defs*]: *lmap-des-vars* = *lmap*[*des-vars*]

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

**lemma** *lmap-id*: *lmap<sub>D</sub>*  $1_L = 1_L$   
**by** (*simp add: lens-defs fun-eq-iff*)

**lemma** *lmap-comp*: *lmap<sub>D</sub>* ( $f ;_L g$ ) = *lmap<sub>D</sub>*  $f ;_L$  *lmap<sub>D</sub>*  $g$   
**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* ( $[\_ ]_D$ )  
**where**  $[P]_D \equiv P \oplus_p (\Sigma_D \times_L \Sigma_D)$

**abbreviation** *lift-pre-desr* ( $[\_ ]_{D<}$ )  
**where**  $[p]_{D<} \equiv [[p]_{<}]_D$

**abbreviation** *lift-post-desr* ( $[\_ ]_{D>}$ )  
**where**  $[p]_{D>} \equiv [[p]_{>}]_D$

**abbreviation** *drop-desr* ( $[\_ ]_D$ )  
**where**  $[P]_D \equiv P \upharpoonright_e (\Sigma_D \times_L \Sigma_D)$

**abbreviation** *dcond* ::  $(''\alpha, '\beta) \text{ rel-des} \implies '\alpha \text{ upred} \implies (''\alpha, '\beta) \text{ rel-des} \implies (''\alpha, '\beta) \text{ rel-des}$   
 $((\beta \prec \_ \triangleright_D / \_) [52, 0, 53] 52)$   
**where**  $P \prec b \triangleright_D Q \equiv P \prec [b]_{D<} \triangleright Q$

**definition** *design*::('α, 'β) rel-des ⇒ ('α, 'β) rel-des ⇒ ('α, 'β) rel-des (**infixl** ⊢ 60) **where**  
*[upred-defs]*: P ⊢ Q = (\$ok ∧ P ⇒ \$ok' ∧ Q)

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

**definition** *rdesign*::('α, 'β) urel ⇒ ('α, 'β) urel ⇒ ('α, 'β) rel-des (**infixl** ⊢<sub>r</sub> 60) **where**  
*[upred-defs]*: (P ⊢<sub>r</sub> Q) = [P]<sub>D</sub> ⊢ [Q]<sub>D</sub>

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

**definition** *ndesign*::'α cond ⇒ ('α, 'β) urel ⇒ ('α, 'β) rel-des (**infixl** ⊢<sub>n</sub> 60) **where**  
*[upred-defs]*: (p ⊢<sub>n</sub> Q) = ([p]<sub><</sub> ⊢<sub>r</sub> Q)

**definition** *skip-d* :: 'α hrel-des (II<sub>D</sub>) **where**  
*[upred-defs]*: II<sub>D</sub> ≡ (true ⊢<sub>r</sub> II)

**definition** *bot-d* :: ('α, 'β) rel-des (⊥<sub>D</sub>) **where**  
*[upred-defs]*: ⊥<sub>D</sub> = (false ⊢ false)

**definition** *pre-design* :: ('α, 'β) rel-des ⇒ ('α, 'β) urel (pre<sub>D</sub>) **where**  
*[upred-defs]*: pre<sub>D</sub>(P) = [¬ P[[true,false/\$ok,\$ok']]<sub>D</sub>

**definition** *post-design* :: ('α, 'β) rel-des ⇒ ('α, 'β) urel (post<sub>D</sub>) **where**  
*[upred-defs]*: post<sub>D</sub>(P) = [P[[true,true/\$ok,\$ok']]<sub>D</sub>

**syntax**

-ok-f :: logic ⇒ logic (-<sup>f</sup> [1000] 1000)  
 -ok-t :: logic ⇒ logic (-<sup>t</sup> [1000] 1000)  
 -top-d :: logic (⊤<sub>D</sub>)

**translations**

$P^f \equiv \text{CONST usubst (CONST subst-upd CONST id (CONST ovar CONST ok) false) } P$   
 $P^t \equiv \text{CONST usubst (CONST subst-upd CONST id (CONST ovar CONST ok) true) } P$   
 $\top_D \Rightarrow \text{CONST not-upred (CONST utp-expr.var (CONST ivar CONST ok))}$

## 1.2 Lifting, Unrestriction, and Substitution

**lemma** *drop-desr-inv* [*simp*]: [[P]<sub>D</sub>]<sub>D</sub> = P  
**by** (*simp add: prod-mwb-lens*)

**lemma** *lift-desr-inv*:

**fixes** P :: ('α, 'β) rel-des  
**assumes** \$ok # P \$ok' # P  
**shows** [[P]<sub>D</sub>]<sub>D</sub> = P

**proof** –

**have** *bij-lens* (Σ<sub>D</sub> ×<sub>L</sub> Σ<sub>D</sub> +<sub>L</sub> (in-var ok +<sub>L</sub> out-var ok)) :: (-, 'α des-vars-scheme × 'β des-vars-scheme)  
*lens*)

(**is** *bij-lens* (?P))

**proof** –

**have** ?P ≈<sub>L</sub> (ok +<sub>L</sub> Σ<sub>D</sub>) ×<sub>L</sub> (ok +<sub>L</sub> Σ<sub>D</sub>) (**is** ?P ≈<sub>L</sub> ?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 +<sub>L</sub> 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]:  $out\alpha \# p \implies out\alpha \# [p]_D$   
 by (pred-simp)

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

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

**lemma** *lift-des-skip-dr-unit-unrest*:  $\$ok' \# P \implies (P ;; [II]_D) = P$   
 by (rel-auto)

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

**lemma** *design-subst* [usubst]:  
 $\llbracket \$ok \# \sigma; \$ok' \# \sigma \rrbracket \implies \sigma \dagger (P \vdash Q) = (\sigma \dagger P) \vdash (\sigma \dagger Q)$   
 by (simp add: design-def usubst)

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

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

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

**lemma** *ok-post*:  $(\$ok \wedge [post_D(P)]_D) = (\$ok \wedge (P^t))$   
 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*:  $(false \vdash true) = true$   
by (*rel-auto*)

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

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

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

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

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

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

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

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

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

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

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

**lemma** *design-subst-ok-ok'*:  
 $(P \llbracket true/\$ok \rrbracket \vdash Q \llbracket true, true/\$ok, \$ok' \rrbracket) = (P \vdash Q)$

**proof** –  
**have**  $(P \vdash Q) = ((\$ok \wedge P) \vdash (\$ok \wedge \$ok' \wedge Q))$   
by (*pred-auto*)  
**also have**  $\dots = ((\$ok \wedge P \llbracket true/\$ok \rrbracket) \vdash (\$ok \wedge (\$ok' \wedge Q \llbracket true/\$ok' \rrbracket) \llbracket true/\$ok \rrbracket))$   
by (*metis conj-eq-out-var-subst conj-pos-var-subst upred-eq-true utp-pred-laws.inf-commute ok-vwb-lens*)

**also have** ... =  $((\$ok \wedge P[\text{true}/\$ok]) \vdash (\$ok \wedge \$ok' \wedge Q[\text{true}, \text{true}/\$ok, \$ok']))$   
**by** (*simp add: usubst*)  
**also have** ... =  $(P[\text{true}/\$ok] \vdash Q[\text{true}, \text{true}/\$ok, \$ok'])$   
**by** (*pred-auto*)  
**finally show** ?thesis ..  
**qed**

**lemma** *design-subst-ok'*:

$(P \vdash Q[\text{true}/\$ok']) = (P \vdash Q)$

**proof** –

**have**  $(P \vdash Q) = (P \vdash (\$ok' \wedge Q))$

**by** (*pred-auto*)

**also have** ... =  $(P \vdash (\$ok' \wedge Q[\text{true}/\$ok']))$

**by** (*metis conj-eq-out-var-subst upred-eq-true utp-pred-laws.inf-commute ok-vwb-lens*)

**also have** ... =  $(P \vdash Q[\text{true}/\$ok'])$

**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**

$\$ok' \# P1 \ \$ok \# P2$

**shows**  $((P1 \vdash Q1) ;; (P2 \vdash Q2)) =$

$((\neg (\neg P1) ;; \text{true})) \wedge \neg (Q1[\text{true}/\$ok'] ;; (\neg P2)) \vdash (Q1[\text{true}/\$ok'] ;; Q2[\text{true}/\$ok]))$

**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** ...

$= (((P1 \vdash Q1)[\text{false}/\$ok'] ;; (P2 \vdash Q2)[\text{false}/\$ok]) \vee ((P1 \vdash Q1)[\text{true}/\$ok'] ;; (P2 \vdash Q2)[\text{true}/\$ok]))$

**by** (*simp add: true-alt-def false-alt-def, pred-auto*)

**also from** *assms*

**have** ... =  $((\$(ok \wedge P1 \Rightarrow Q1[\text{true}/\$ok']) ;; (P2 \Rightarrow \$ok' \wedge Q2[\text{true}/\$ok])) \vee ((\neg (\$ok \wedge P1)) ;; \text{true}))$

**by** (*simp add: design-def usubst unrest, pred-auto*)

**also have** ... =  $((\neg \$ok ;; \text{true}_h) \vee ((\neg P1) ;; \text{true}) \vee (Q1[\text{true}/\$ok'] ;; (\neg P2)) \vee (\$ok' \wedge (Q1[\text{true}/\$ok'] ;; Q2[\text{true}/\$ok])))$

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

**also have** ... =  $((\neg (\neg P1) ;; \text{true})) \wedge \neg (Q1[\text{true}/\$ok'] ;; (\neg P2)) \vdash (Q1[\text{true}/\$ok'] ;; Q2[\text{true}/\$ok]))$

**by** (*simp add: precond-right-unit design-def unrest, rel-auto*)

**finally show** ?thesis .

**qed**

**theorem** *design-composition*:

**assumes**

$\$ok' \# P1 \ \$ok \# P2 \ \$ok' \# Q1 \ \$ok \# Q2$

**shows**  $((P1 \vdash Q1) ;; (P2 \vdash Q2)) = ((\neg (\neg P1) ;; \text{true})) \wedge \neg (Q1 ;; (\neg P2)) \vdash (Q1 ;; Q2)$

**using** *assms* **by** (*simp add: design-composition-subst usubst*)

**theorem** *design-composition-runrest*:



**assumes**  
 $\$ok' \# P1 \ \$ok \# P2 \ ok \ \#\# \ Q1 \ ok \ \#\# \ Q2$   
**shows**  $((P1 \vdash Q1) ;; (P2 \vdash Q2)) = (((\neg (\neg P1) ;; true)) \wedge \neg (Q1^t ;; (\neg P2))) \vdash (Q1 ;; Q2))$   
**proof** –  
**have**  $(\$ok \wedge \$ok' \wedge (Q1^t ;; Q2[\text{true}/\$ok])) = (\$ok \wedge \$ok' \wedge (Q1 ;; Q2))$   
**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**  $\dots = ((Q1 \wedge \$ok') ;; (\$ok \wedge Q2))$   
**by** *(simp add: assms(3) assms(4) unrest-ident-var)*  
**also have**  $\dots = (Q1^t ;; Q2[\text{true}/\$ok])$   
**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**  $(\neg (\neg P1 ;; true) \wedge \neg (Q1^t ;; (\neg P2))) \vdash (Q1^t ;; Q2[\text{true}/\$ok]) =$   
 $(\neg (\neg P1 ;; true) \wedge \neg (Q1^t ;; (\neg P2))) \vdash (\$ok \wedge \$ok' \wedge (Q1^t ;; Q2[\text{true}/\$ok]))$   
**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**  
 $out\alpha \# p1 \ \$ok \# P2 \ \$ok' \# Q1 \ \$ok \# Q2$   
**shows**  $((p1 \vdash Q1) ;; (P2 \vdash Q2)) = ((p1 \wedge \neg (Q1 ;; (\neg P2))) \vdash (Q1 ;; Q2))$   
**using** *assms*  
**by** *(simp add: design-composition unrest precondition-right-unit)*

**theorem** *rdesign-composition-cond:*

**assumes**  $out\alpha \# p1$   
**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**  
 $ok \# p1 \ ok \# p2$   
 $\$ok \# Q1 \ \$ok' \# Q1 \ \$ok \# Q2 \ \$ok' \# Q2$   
**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**  $(true ;; (P \vdash Q)) = (\exists ok_0 \cdot true[\llcorner ok_0 \gg / \$ok \prime] ;; (P \vdash Q)[\llcorner ok_0 \gg / \$ok])$

**by** (*subst segr-middle*[*of ok*], *simp-all*)

**also have**  $\dots = ((true[\llcorner false / \$ok \prime] ;; (P \vdash Q)[\llcorner false / \$ok]) \vee (true[\llcorner true / \$ok \prime] ;; (P \vdash Q)[\llcorner true / \$ok]))$

**by** (*simp add: disj-comm false-alt-def true-alt-def*)

**also have**  $\dots = ((true[\llcorner false / \$ok \prime] ;; true_h) \vee (true ;; ((P \vdash Q)[\llcorner true / \$ok])))$

**by** (*subst-tac, rel-auto*)

**also have**  $\dots = true$

**by** (*subst-tac, simp add: precondition-right-unit unrest*)

**finally show** *?thesis* .

**qed**

**theorem** *design-left-unit-hom*:

**fixes**  $P Q :: 'a \text{ hrel-des}$

**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**  $\dots = (true \wedge \neg (II ;; (\neg P))) \vdash_r (II ;; Q)$

**proof** –

**have**  $out_\alpha \# true$

**by** *unrest-tac*

**thus** *?thesis*

**using** *rdesign-composition-cond* **by** *blast*

**qed**

**also have**  $\dots = (\neg (\neg P)) \vdash_r Q$

**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**  $out_\alpha \# p$

**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*:  $(\perp_D ;; (P \vdash Q)) = \perp_D$

**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]*:  $pre_D(p \vdash_n Q) = [p]_<$

**by** (*pred-auto*)

**theorem** *ndesign-post [simp]*:  $post_D(p \vdash_n Q) = ([p]_< \Rightarrow Q)$

**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]*:

$$pre_D(P \triangleleft [b]_D \triangleright Q) = (pre_D(P) \triangleleft b \triangleright pre_D(Q))$$

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

**lemma** *design-post-condr [simp]*:

$$post_D(P \triangleleft [b]_D \triangleright Q) = (post_D(P) \triangleleft b \triangleright post_D(Q))$$

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

**lemma** *preD-USUP-mem*:  $pre_D(\bigsqcup_{i \in A} P \ i) = (\bigsqcap_{i \in A} pre_D(P \ i))$

**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*]:

$$(p_1 \vdash_n P_2) \sqcup (q_1 \vdash_n Q_2) = ((p_1 \vee q_1) \vdash_n (([p_1]_{<} \Rightarrow P_2) \wedge ([q_1]_{<} \Rightarrow Q_2)))$$

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  $(\prod i \in A \cdot P(i) \vdash Q(i)) = (\bigsqcup i \in A \cdot P(i) \vdash (\prod i \in A \cdot Q(i)))$   
 using *assms* by (*rel-auto*)

**lemma** *ndesign-UINF-mem* [*ndes-simp*]:

assumes  $A \neq \{\}$   
 shows  $(\prod i \in A \cdot p(i) \vdash_n Q(i)) = (\bigsqcup i \in A \cdot p(i) \vdash_n (\prod i \in A \cdot Q(i)))$   
 using *assms* by (*rel-auto*)

**lemma** *ndesign-UINF-ind* [*ndes-simp*]:

$$(\prod i \cdot p(i) \vdash_n Q(i)) = (\bigsqcup i \cdot p(i) \vdash_n (\prod i \cdot Q(i)))$$

by (*rel-auto*)

**lemma** *design-USUP-mem*:

$$(\bigsqcup i \in A \cdot P(i) \vdash Q(i)) = (\prod i \in A \cdot P(i) \vdash (\bigsqcup i \in A \cdot P(i) \Rightarrow Q(i)))$$

by (*rel-auto*)

**lemma** *ndesign-USUP-mem* [*ndes-simp*]:

$$(\bigsqcup i \in A \cdot p(i) \vdash_n Q(i)) = (\prod i \in A \cdot p(i) \vdash_n (\bigsqcup i \in A \cdot [p(i)]_{<} \Rightarrow Q(i)))$$

by (*rel-auto*)

**lemma** *ndesign-USUP-ind* [*ndes-simp*]:

$(\bigsqcup i \cdot p(i) \vdash_n Q(i)) = (\prod i \cdot p(i)) \vdash_n (\bigsqcup i \cdot [p(i)]_< \Rightarrow Q(i))$   
 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**  
 $\$ok \# P1 \ \$ok' \# P1 \ \$ok \# P2 \ \$ok' \# P2$   
 $\$ok \# Q1 \ \$ok' \# Q1 \ \$ok \# Q2 \ \$ok' \# Q2$   
**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**  $\dots = '(P2 \Rightarrow \$ok' \wedge Q2) \Rightarrow (P1 \Rightarrow \$ok' \wedge Q1)'$   
**by** (*subst subst-bool-split[of in-var ok], simp-all, subst-tac*)

**also with** *assms* **have**  $\dots = '(\neg P2 \Rightarrow \neg P1) \wedge ((P2 \Rightarrow Q2) \Rightarrow P1 \Rightarrow Q1)'$   
**by** (*subst subst-bool-split[of out-var ok], simp-all, subst-tac*)

**also have**  $\dots \longleftrightarrow '(P1 \Rightarrow P2)' \wedge 'P1 \wedge Q2 \Rightarrow Q1'$   
**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**  $P2 \sqsubseteq P1 \ Q1 \sqsubseteq (P1 \wedge Q2)$   
**shows**  $P1 \vdash Q1 \sqsubseteq P2 \vdash Q2$   
**using** *assms design-refine-intro[of P1 P2 Q2 Q1] 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-refine-intro*:

**assumes**  $'p1 \Rightarrow p2' \ '[p1]_< \wedge Q2 \Rightarrow Q1'$

**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*:  
 $\perp_D \sqsubseteq (P \vdash Q)$   
**by** (*rel-auto*)

**lemma** *design-refine-thms*:  
**assumes**  $P \sqsubseteq Q$   
**shows**  $\text{'pre}_D(P) \Rightarrow \text{'pre}_D(Q)$ ,  $\text{'pre}_D(P) \wedge \text{'post}_D(Q) \Rightarrow \text{'post}_D(P)$   
**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* ::  $(\alpha, \beta) \text{ rel-des} \Rightarrow (\alpha, \beta) \text{ rel-des}$  **where**  
 $[\text{upred-defs}]: H1(P) = (\$ok \Rightarrow P)$

**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*:  
 $H1(\text{II}) = \text{II}_D$   
**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**  $\dots = (H1(II) ;; R)$

**by** (*simp add: H1-design-skip*)

**also have**  $\dots = (\$ok \Rightarrow II) ;; R$

**by** (*simp add: H1-def*)

**also have**  $\dots = (((\neg \$ok) ;; R) \vee R)$

**by** (*simp add: impl-alt-def seqr-or-distl*)

**also have**  $\dots = (((\neg \$ok) ;; true_h) ;; R) \vee R$

**by** (*simp add: precond-right-unit unrest*)

**also have**  $\dots = (((\neg \$ok) ;; true_h) \vee R)$

**by** (*metis assms(1) seqr-assoc*)

**also have**  $\dots = (\$ok \Rightarrow R)$

**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**  $\dots = (true ;; (\neg \$ok \vee P))$  (**is**  $- = (?true ;; -)$ )

**by** (*simp add: impl-alt-def*)

**also from** *assms* **have**  $\dots = ((?true ;; (\neg \$ok)) \vee (?true ;; P))$

**using** *seqr-or-distr* **by** *blast*

**also from** *assms* **have**  $\dots = (true \vee (true ;; P))$

**by** (*simp add: nok-not-false precond-left-zero unrest*)

**finally show** *?thesis*

**by** (*simp add: upred-defs urel-defs*)

**qed**

**theorem** *H1-left-unit*:

**fixes**  $P :: 'α \text{ hrel-des}$   
**assumes**  $P \text{ is } H1$   
**shows**  $(II_D ;; P) = P$   
**proof** –  
**have**  $(II_D ;; P) = (\$ok \Rightarrow II) ;; P$   
**by**  $(metis \text{ H1-def H1-design-skip})$   
**also have**  $\dots = (((\neg \$ok) ;; P) \vee P)$   
**by**  $(simp \text{ add: impl-alt-def seqr-or-distl})$   
**also from**  $assms$  **have**  $\dots = (((\neg \$ok) ;; true_h) ;; P) \vee P$   
**by**  $(simp \text{ add: precondition-right-unit unrest})$   
**also have**  $\dots = (((\neg \$ok) ;; (true_h ;; P)) \vee P)$   
**by**  $(simp \text{ add: seqr-assoc})$   
**also from**  $assms$  **have**  $\dots = (\$ok \Rightarrow P)$   
**by**  $(simp \text{ add: H1-left-zero impl-alt-def precondition-right-unit unrest})$   
**finally show**  $?thesis$  **using**  $assms$   
**by**  $(simp \text{ add: H1-def Healthy-def'})$   
**qed**

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

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

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

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

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

**lemma**  $H1\text{-inf-closed}$  [*closure*]:  
 $\llbracket P \text{ is } H1; Q \text{ is } H1 \rrbracket \implies P \sqcup Q \text{ is } H1$   
**by**  $(rel\text{-blast})$

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

shows  $(\sqcap A)$  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  $H1(\sqcup i \in A \cdot P(i)) = (\sqcup i \in A \cdot H1(P(i)))$

by (*rel-auto*)

lemma *H1-Inf* [*closure*]:

assumes  $\forall P \in A. P$  is *H1*

shows  $(\sqcap A)$  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* :: ' $\alpha$  *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 ... =  $(\exists \$ok' \cdot P \wedge \$ok' =_u \text{false})$

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**  $(P ;; (\$ok \wedge ([II]_D \wedge \$ok')))) = (P ;; (\$ok \wedge II))$   
**by** *(rel-auto)*  
**also have**  $\dots = (P^t \wedge \$ok')$   
**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*:  
 $P \text{ is } H2 \iff 'P^f \Rightarrow P^t'$

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

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

**lemma** *H2-design*:  
**assumes**  $\$ok' \# P \ \$ok' \# Q$   
**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 (¬ \$ok) = (¬ \$ok)*

**proof** –

have  $H2 (\neg \$ok) = ((\neg \$ok)^f \vee ((\neg \$ok)^t \wedge \$ok')$

by (*simp add: H2-split*)

also have  $\dots = (\neg \$ok \vee (\neg \$ok) \wedge \$ok')$

by (*subst-tac*)

also have  $\dots = (\neg \$ok)$

by (*pred-auto*)

finally show *?thesis* .

qed

**lemma** *H2-true: H2(true) = true*

by (*rel-auto*)

**lemma** *H2-choice-closed [closure]:*

$\llbracket P \text{ is } H2; Q \text{ is } H2 \rrbracket \implies P \sqcap Q \text{ is } H2$

by (*metis H2-def Healthy-def' disj-upred-def seqr-or-distl*)

**lemma** *H2-inf-closed [closure]:*

assumes  $P \text{ is } H2 \ Q \text{ is } H2$

shows  $P \sqcup Q \text{ is } H2$

**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  $H2(\dots) = \dots$

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  $\dots = ((\neg \$ok \vee P) ;; J)$

by (*rel-auto*)

also have  $\dots = (((\neg \$ok) ;; J) \vee (P ;; J))$

using *seqr-or-distl* by *blast*

also have  $\dots = ((H2 (\neg \$ok)) \vee H2(P))$

by (*simp add: H2-def*)

also have  $\dots = ((\neg \$ok) \vee H2(P))$

by (*simp add: H2-not-okay*)

also have  $\dots = H1(H2(P))$

by (*rel-auto*)

finally show *?thesis* by *simp*

qed

### 2.3 Designs as $H1$ - $H2$ predicates

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

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

**theorem**  $H1-H2\text{-eq-design}$ :

$\mathbf{H}(P) = (\neg P^f) \vdash P^t$

**proof** –

have  $\mathbf{H}(P) = (\$ok \Rightarrow H2(P))$

by (*simp add: H1-def*)

also have  $\dots = (\$ok \Rightarrow (P^f \vee (P^t \wedge \$ok'))$

by (*metis H2-split*)

also have  $\dots = (\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge \$ok \wedge P^t)$

by (*rel-auto*)

also have  $\dots = (\neg P^f) \vdash P^t$

by (*rel-auto*)

finally show *?thesis* .

qed

**theorem**  $H1-H2\text{-is-design}$ :

assumes  $P \text{ is } H1 P \text{ is } H2$

shows  $P = (\neg P^f) \vdash P^t$

using *assms* by (*metis H1-H2-eq-design Healthy-def*)

**theorem**  $H1-H2\text{-eq-rdesign}$ :

$\mathbf{H}(P) = \text{pre}_D(P) \vdash_r \text{post}_D(P)$

**proof** –

have  $\mathbf{H}(P) = (\$ok \Rightarrow H2(P))$

by (*simp add: H1-def Healthy-def'*)

also have  $\dots = (\$ok \Rightarrow (P^f \vee (P^t \wedge \$ok'))$

by (*metis H2-split*)

also have  $\dots = (\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge P^t)$

by (*pred-auto*)

also have  $\dots = (\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge \$ok \wedge P^t)$

by (*pred-auto*)

also have  $\dots = (\$ok \wedge [\text{pre}_D(P)]_D \Rightarrow \$ok' \wedge \$ok \wedge [\text{post}_D(P)]_D)$

by (*simp add: ok-post ok-pre*)

also have  $\dots = (\$ok \wedge [\text{pre}_D(P)]_D \Rightarrow \$ok' \wedge [\text{post}_D(P)]_D)$

by (*pred-auto*)

also have  $\dots = \text{pre}_D(P) \vdash_r \text{post}_D(P)$

by (*simp add: rdesign-def design-def*)

finally show *?thesis* .

qed

**theorem**  $H1-H2\text{-is-rdesign}$ :

assumes  $P \text{ is } H1 P \text{ is } H2$

shows  $P = \text{pre}_D(P) \vdash_r \text{post}_D(P)$

by (*metis H1-H2-eq-rdesign Healthy-def assms(1) assms(2)*)

**lemma**  $H1-H2\text{-refinement}$ :

assumes  $P \text{ is } \mathbf{H} Q \text{ is } \mathbf{H}$

shows  $P \sqsubseteq Q \iff ('pre_D(P) \Rightarrow pre_D(Q))' \wedge 'pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)'$

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* *segr-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*]:

$\llbracket \$ok' \# P; \$ok' \# Q \rrbracket \implies (P \vdash Q)$  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*]:  $\perp_D$  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**  $(\sqcap A)$  is *H1-H2*

**proof** –

**from** *assms* **have**  $A: A = H1-H2 \text{ ' } A$

**by** (*auto* *simp* *add*: *Healthy-def* *rev-image-eqI*)

**also have**  $(\sqcap \dots) = (\sqcap P \in A \cdot H1-H2(P))$

**by** (*simp* *add*: *UINF-as-Sup-collect*)

**also have**  $\dots = (\sqcap P \in A \cdot (\neg P^f) \vdash P^t)$

**by** (*meson* *H1-H2-eq-design*)

also have ... =  $(\bigsqcup P \in A \cdot \neg P^f) \vdash (\prod P \in A \cdot P^t)$

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  $(\prod_D \text{ [900] 900})$  where

$\prod_D A = (\text{if } (A = \{\}) \text{ then } \top_D \text{ else } \prod A)$

**abbreviation** *design-sup* ::  $(\alpha, \beta)$  rel-des set  $\Rightarrow (\alpha, \beta)$  rel-des  $(\bigsqcup_D \text{ [900] 900})$  where

$\bigsqcup_D A \equiv \bigsqcup A$

**lemma** *design-inf-H1-H2-closed*:

assumes  $\forall P \in A. P$  is **H**

shows  $(\prod_D A)$  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]:  $\prod_D \{\} = \top_D$

by (simp add: design-inf-def)

**lemma** *design-sup-non-empty* [simp]:  $A \neq \{\} \Longrightarrow \prod_D A = \prod A$

by (simp add: design-inf-def)

**lemma** *USUP-mem-H1-H2-closed*:

assumes  $\bigwedge i. i \in A \Longrightarrow P i$  is **H**

shows  $(\bigsqcup_{i \in A} P i)$  is **H**

**proof** –

from assms have  $(\bigsqcup_{i \in A} P i) = (\bigsqcup_{i \in A} P i)$

by (auto intro: USUP-cong simp add: Healthy-def)

also have ... =  $(\bigsqcup_{i \in A} \neg (P i)^f) \vdash (P i)^t$

by (meson H1-H2-eq-design)

also have ... =  $(\prod_{i \in A} \neg (P i)^f) \vdash (\bigsqcup_{i \in A} \neg (P i)^f \Rightarrow (P i)^t)$

by (simp add: design-USUP-mem)

also have ... is **H**

by (simp add: design-is-H1-H2 unrest)

finally show ?thesis .

qed

**lemma** *USUP-ind-H1-H2-closed*:

assumes  $\bigwedge i. P i$  is **H**

shows  $(\bigsqcup i \cdot P i)$  is **H**

using assms USUP-mem-H1-H2-closed[of UNIV P] by simp

**lemma** *Inf-H1-H2-closed*:

assumes  $\forall P \in A. P$  is **H**

shows  $(\bigsqcup A)$  is **H**

**proof** –

from assms have  $A: A = \mathbf{H} \text{ ' } A$

by (auto simp add: Healthy-def rev-image-eqI)

also have  $(\bigsqcup \dots) = (\bigsqcup P \in A \cdot \mathbf{H}(P))$

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** ... =  $(\prod P \in A \cdot \neg P^f) \vdash (\bigsqcup P \in A \cdot \neg P^f \Rightarrow P^t)$   
**by** (*simp add: design-USUP-mem*)  
**also have** ... **is** **H**  
**by** (*simp add: design-is-H1-H2 unrest*)  
**finally show** *?thesis* .  
**qed**

**lemma** *rdesign-ref-monos*:

**assumes** *P is H Q is H*  $P \sqsubseteq Q$   
**shows**  $pre_D(Q) \sqsubseteq pre_D(P)$   $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$

**proof** –

**have**  $r: P \sqsubseteq Q \longleftrightarrow ('pre_D(P) \Rightarrow pre_D(Q)' \wedge 'pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)')$   
**by** (*metis H1-H2-eq-rdesign Healthy-if assms(1) assms(2) rdesign-refinement*)  
**from**  $r$  **assms** **show**  $pre_D(Q) \sqsubseteq pre_D(P)$   
**by** (*auto simp add: refBy-order*)  
**from**  $r$  **assms** **show**  $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$   
**by** (*auto simp add: refBy-order*)

**qed**

## 2.4 H3: The design assumption is a precondition

**definition** *H3* ::  $('α, 'β) \text{rel-des} \Rightarrow ('α, 'β) \text{rel-des}$  **where**  
*[upred-defs]: H3* ( $P$ )  $\equiv P ;; \Pi_D$

**theorem** *H3-idem*:

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

**theorem** *H3-mono*:

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

**theorem** *H3-Monotonic*:

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

**theorem** *H3-Continuous*: *Continuous H3*

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

**theorem** *design-condition-is-H3*:

**assumes**  $out\alpha \nmid p$   
**shows**  $(p \vdash Q)$  **is** *H3*

**proof** –

**have**  $((p \vdash Q) ;; \Pi_D) = (\neg ((\neg p) ;; true)) \vdash (Q^t ;; \Pi[true/\$ok])$   
**by** (*simp add: skip-d-alt-def design-composition-subst unrest assms*)  
**also have** ... =  $p \vdash (Q^t ;; \Pi[true/\$ok])$   
**using** *assms precondition-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  $H3 \iff P = (P ;; true)$   
**proof** –  
**have**  $(P \vdash_r Q) ;; II_D = (P \vdash_r Q) ;; (true \vdash_r II)$   
**by** (*simp add: skip-d-def*)  
**also have**  $\dots = (\neg ((\neg P) ;; true) \wedge \neg (Q ;; (\neg true))) \vdash_r (Q ;; II)$   
**by** (*simp add: rdesign-composition*)  
**also have**  $\dots = (\neg ((\neg P) ;; true) \wedge \neg (Q ;; (\neg true))) \vdash_r Q$   
**by** *simp*  
**also have**  $\dots = (\neg ((\neg P) ;; true)) \vdash_r Q$   
**by** (*pred-auto*)  
**finally have**  $P \vdash_r Q$  is  $H3 \iff P \vdash_r Q = (\neg ((\neg P) ;; true)) \vdash_r Q$   
**by** (*metis H3-def Healthy-def'*)  
**also have**  $\dots \iff P = (\neg ((\neg P) ;; true))$   
**by** (*metis rdesign-pre*)  
**thm** *seqr-true-lemma*  
**also have**  $\dots \iff P = (P ;; true)$   
**by** (*simp add: seqr-true-lemma*)  
**finally show** *?thesis* .  
**qed**

**theorem** *design-H3-iff-pre*:  
**assumes**  $\$ok \# P \ \$ok' \# P \ \$ok \# Q \ \$ok' \# Q$   
**shows**  $P \vdash Q$  is  $H3 \iff P = (P ;; true)$   
**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  $H3 \iff \lfloor P \rfloor_D = (\lfloor P \rfloor_D ;; true)$   
**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**  $\dots = (\exists ok_0 \cdot ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D) \llbracket \llcorner ok_0 \gg / \$ok' \rrbracket ;; (true \vdash II) \llbracket \llcorner ok_0 \gg / \$ok \rrbracket$   
**by** (*subst seqr-middle[of ok], simp-all*)  
**also have**  $\dots = (((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D) \llbracket false / \$ok' \rrbracket ;; (true \vdash II) \llbracket false / \$ok \rrbracket$   
 $\vee (((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D) \llbracket true / \$ok' \rrbracket ;; (true \vdash II) \llbracket true / \$ok \rrbracket)$   
**by** (*simp add: disj-comm false-alt-def true-alt-def*)  
**also have**  $\dots = ((\neg \$ok \wedge \lceil II \rceil_D ;; true) \vee (\lceil II \rceil_D ;; \$ok' \wedge \lceil II \rceil_D))$   
**by** (*rel-auto*)  
**also have**  $\dots = II_D$   
**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**  $\$ok \# p \text{ out}\alpha \# p \ \$ok \# Q \ \$ok' \# Q$

**shows**  $H3(p \vdash Q) = p \vdash Q$

**using** *assms*

by (*metis Healthy-def' design-H3-iff-pre precondition-right-unit unrest-out $\alpha$ -var ok-vwb-lens vwb-lens-mwb*)

**theorem** *H3-rdesign-pre*:

**assumes**  $\text{out}\alpha \# p$

**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* ::  $(\alpha, \beta) \text{ rel-des} \Rightarrow (\alpha, \beta) \text{ rel-des } (\mathbf{N})$  **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**  $P = \text{pre}_D(P) \vdash_r \text{post}_D(P)$

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**  $P = \lfloor \text{pre}_D(P) \rfloor_{<} \vdash_n \text{post}_D(P)$

by (*metis H1-H3-is-rdesign assms drop-pre-inv ndesign-def precondition-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 H*  $\text{out}\alpha \# \text{pre}_D(P)$   
 shows *P is N*  
 by (*metis H1-H2-eq-rdesign H1-rdesign H3-rdesign-pre Healthy-def' assms*)

**lemma** *H1-H3-impl-H2 [closure]*:  $P \text{ is } \mathbf{N} \implies P \text{ is } \mathbf{H}$   
 by (*metis H1-H2-commute H1-idem H2-H3-absorb Healthy-def'*)

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

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

**lemma** *H3-unrest-out-alpha-nok [unrest]*:  
 assumes *P is N*  
 shows  $\text{out}\alpha \# P^f$   
**proof** –  
 have  $P = (\neg (P^f ;; \text{true})) \vdash P^t$   
 by (*metis H1-H3-eq-design Healthy-def' assms*)  
 also have  $\text{out}\alpha \# (\dots)^f$   
 by (*simp add: design-def usubst unrest, rel-auto*)  
 finally show *?thesis* .  
**qed**

**lemma** *H3-unrest-out-alpha [unrest]*:  $P \text{ is } \mathbf{N} \implies \text{out}\alpha \# \text{pre}_D(P)$   
 by (*metis H1-H3-commute H1-H3-is-rdesign H1-idem Healthy-def' precond-equiv rdesign-H3-iff-pre*)

**lemma** *ndesign-H1-H3 [closure]*:  $p \vdash_n Q \text{ is } \mathbf{N}$   
 by (*simp add: H1-rdesign H3-def Healthy-def' ndesign-def unrest-pre-out\alpha*)

**lemma** *ndesign-form*:  $P \text{ is } \mathbf{N} \implies ([\text{pre}_D(P)]_< \vdash_n \text{post}_D(P)) = P$   
 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]*:  $\perp_D \text{ is } \mathbf{N}$   
 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]*:  $\top_D \text{ is } \mathbf{N}$

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  $P ;; \top_D = \lfloor pre_D P \rfloor_{<} \vdash_n false$   
**proof** –  
 have  $P ;; \top_D = (\lfloor pre_D(P) \rfloor_{<} \vdash_n post_D(P)) ;; (true \vdash_n false)$   
 by (*simp add: assms ndesign-form ndesign-miracle*)  
 also have  $\dots = \lfloor pre_D P \rfloor_{<} \vdash_n false$   
 by (*simp add: ndesign-composition-wp wp alpha*)  
 finally show *?thesis* .

qed

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

qed

**lemma** *USUP-ind-H1-H3-closed* [*closure*]:  
 $\llbracket \bigwedge i. P i \text{ is } \mathbf{N} \rrbracket \implies (\bigsqcup i \cdot P i) \text{ is } \mathbf{N}$   
 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**  $H_4 :: ('\alpha, '\beta) \text{ rel-des} \Rightarrow ('\alpha, '\beta) \text{ rel-des}$  **where**  
 $[upred-defs]: H_4(P) = ((P ;; true) \Rightarrow P)$

**theorem**  $H_4$ -idem:

$$H_4(H_4(P)) = H_4(P)$$

by (*rel-auto*)

**lemma** *is-H4-alt-def*:

$$P \text{ is } H_4 \iff (P ;; \text{true}) = \text{true}$$

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**  $DES \equiv UTHY(DES, 'α \text{ des})$

**abbreviation**  $NDES \equiv UTHY(NDES, 'α \text{ des})$

**overloading**

$$\text{des-hcond} == \text{utp-hcond} :: (DES, 'α \text{ des}) \text{ uthy} \Rightarrow ('α \text{ des} \times 'α \text{ des}) \text{ health}$$

$$\text{des-unit} == \text{utp-unit} :: (DES, 'α \text{ des}) \text{ uthy} \Rightarrow 'α \text{ hrel-des (unchecked)}$$

$$\text{ndes-hcond} == \text{utp-hcond} :: (NDES, 'α \text{ des}) \text{ uthy} \Rightarrow ('α \text{ des} \times 'α \text{ des}) \text{ health}$$

$$\text{ndes-unit} == \text{utp-unit} :: (NDES, 'α \text{ des}) \text{ uthy} \Rightarrow 'α \text{ hrel-des (unchecked)}$$

**begin**

**definition**  $\text{des-hcond} :: (DES, 'α \text{ des}) \text{ uthy} \Rightarrow ('α \text{ des} \times 'α \text{ des}) \text{ health}$  **where**

[*upred-defs*]:  $\text{des-hcond } t = H1-H2$

**definition**  $\text{des-unit} :: (DES, 'α \text{ des}) \text{ uthy} \Rightarrow 'α \text{ hrel-des}$  **where**

[*upred-defs*]:  $\text{des-unit } t = II_D$

**definition**  $\text{ndes-hcond} :: (NDES, 'α \text{ des}) \text{ uthy} \Rightarrow ('α \text{ des} \times 'α \text{ des}) \text{ health}$  **where**

[*upred-defs*]:  $\text{ndes-hcond } t = H1-H3$

**definition**  $\text{ndes-unit} :: (NDES, 'α \text{ des}) \text{ uthy} \Rightarrow 'α \text{ hrel-des}$  **where**

[*upred-defs*]:  $\text{ndes-unit } t = II_D$

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**  $\bigwedge P. P \in \text{carrier (uthy-order DES)} \longleftrightarrow P \text{ is } \mathbf{H}$   
**and** *carrier (uthy-order DES)  $\rightarrow$  carrier (uthy-order DES)  $\equiv$   $\llbracket \mathbf{H} \rrbracket_H \rightarrow \llbracket \mathbf{H} \rrbracket_H$*   
**and**  *$\llbracket \mathcal{H}_{DES} \rrbracket_H \rightarrow \llbracket \mathcal{H}_{DES} \rrbracket_H \equiv \llbracket \mathbf{H} \rrbracket_H \rightarrow \llbracket \mathbf{H} \rrbracket_H$*   
**and** *le (uthy-order DES) = op  $\sqsubseteq$*   
**and** *eq (uthy-order DES) = op =*  
**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**  $\bigwedge P. P \in \text{carrier (uthy-order NDES)} \longleftrightarrow P \text{ is } \mathbf{N}$   
**and** *carrier (uthy-order NDES)  $\rightarrow$  carrier (uthy-order NDES)  $\equiv$   $\llbracket \mathbf{N} \rrbracket_H \rightarrow \llbracket \mathbf{N} \rrbracket_H$*   
**and**  *$\llbracket \mathcal{H}_{NDES} \rrbracket_H \rightarrow \llbracket \mathcal{H}_{NDES} \rrbracket_H \equiv \llbracket \mathbf{N} \rrbracket_H \rightarrow \llbracket \mathbf{N} \rrbracket_H$*   
**and** *le (uthy-order NDES) = op  $\sqsubseteq$*   
**and**  *$A \subseteq \text{carrier (uthy-order NDES)} \longleftrightarrow A \subseteq \llbracket \mathbf{N} \rrbracket_H$*   
**and** *eq (uthy-order NDES) = op =*  
**by** (*unfold-locales, simp-all add: ndes-hcond-def H1-H3-Continuous utp-order-def*)

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

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

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

**lemma** *ndesign-lat-bottom:  $\perp_{NDES} = \mathbf{N}(\text{true})$*   
**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 COM-PASS deliverable D23.5.

**definition** [*upred-defs*]:  $Des(R) = \mathbf{H}(\llbracket R \rrbracket_D \wedge \$ok')$

**definition** [*upred-defs*]:  $Rel(D) = \llbracket D[\text{true}, \text{true}/\$ok, \$ok'] \rrbracket_D$

**lemma** *Des-design:  $Des(R) = \text{true} \vdash_r R$*   
**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**  
 $\bigwedge x. x \in \text{carrier } \mathcal{X}_{DES \leftarrow \langle Des, Rel \rangle \rightarrow REL} = (x \text{ is } \mathbf{H}) \text{ and}$   
 $\bigwedge x. x \in \text{carrier } \mathcal{Y}_{DES \leftarrow \langle Des, Rel \rangle \rightarrow REL} = \text{True and}$   
 $\pi_{*DES \leftarrow \langle Des, Rel \rangle \rightarrow REL} = Des \text{ and}$   
 $\pi_{*DES \leftarrow \langle Des, Rel \rangle \rightarrow REL} = Rel \text{ and}$   
 $le \mathcal{X}_{DES \leftarrow \langle Des, Rel \rangle \rightarrow REL} = op \sqsubseteq \text{ and}$   
 $le \mathcal{Y}_{DES \leftarrow \langle Des, Rel \rangle \rightarrow REL} = op \sqsubseteq$   
**proof** (*unfold-locales, simp-all add: rel-hcond-def des-hcond-def*)  
**show**  $\bigwedge x. x \text{ is } id$   
**by** (*simp add: Healthy-def*)  
**next**  
**show**  $Rel \in \llbracket \mathbf{H} \rrbracket_H \rightarrow \llbracket id \rrbracket_H$   
**by** (*auto simp add: Rel-def rel-hcond-def Healthy-def*)  
**next**  
**show**  $Des \in \llbracket id \rrbracket_H \rightarrow \llbracket \mathbf{H} \rrbracket_H$   
**by** (*auto simp add: Des-def des-hcond-def Healthy-def H1-H2-commute H1-idem H2-idem*)  
**next**  
**fix**  $R :: 'a \text{ hrel}$   
**show**  $R \sqsubseteq Rel (Des R)$   
**by** (*simp add: Des-design Rel-design*)  
**next**  
**fix**  $R :: 'a \text{ hrel}$  **and**  $D :: 'a \text{ hrel-des}$   
**assume**  $a: D \text{ is } \mathbf{H}$   
**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**  $\dots = 'D_1 \wedge R \Rightarrow D_2'$   
**by** (*simp add: rdesign-refinement*)  
**also have**  $\dots = ((D_1 \Rightarrow D_2) \sqsubseteq R)$   
**by** (*rel-auto*)  
**also have**  $\dots = (Rel D \sqsubseteq R)$   
**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*  $:: ('\alpha \text{ hrel-des} \Rightarrow '\alpha \text{ hrel-des}) \Rightarrow '\alpha \text{ hrel-des } (\mu_D)$  **where**  
 $\mu_D F \equiv \mu_{DES} F$

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

**syntax**

-dmu :: pptrn ⇒ logic ⇒ logic ( $\mu_D$  - · - [0, 10] 10)  
 -dnu :: pptrn ⇒ logic ⇒ logic ( $\nu_D$  - · - [0, 10] 10)

**translations**

$\mu_D X \cdot P == \mu_{CONST\ DES} (\lambda X. P)$   
 $\nu_D X \cdot P == \nu_{CONST\ DES} (\lambda X. P)$

**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' \# C \$ok' \# S (C ⊢ S) ⊆ F(C ⊢ S) 'C ⇒ (μ<sub>D</sub> F ⇔ ν<sub>D</sub> F)'  
**shows** (C ⊢ S) ⊆ μ<sub>D</sub> F

**proof** –

**from** *assms* **have** (C ⊢ S) ⊆ ν<sub>D</sub> 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 ⊢<sub>r</sub> S) ⊆ F(C ⊢<sub>r</sub> S) '[C]<sub>D</sub> ⇒ (μ<sub>D</sub> F ⇔ ν<sub>D</sub> F)'

**shows** (C ⊢<sub>r</sub> S) ⊆ μ<sub>D</sub> F

**using** *assms* **by** (*simp add: rdesign-def design-mu-refine-intro unrest*)

**lemma** *H1-H2-mu-refine-intro*:

**assumes** P is **H** P ⊆ F(P) '[pre<sub>D</sub>(P)]<sub>D</sub> ⇒ (μ<sub>D</sub> F ⇔ ν<sub>D</sub> F)'

**shows** P ⊆ μ<sub>D</sub> 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 ∈ [H]<sub>H</sub> → [H]<sub>H</sub>

**and** *induct-step*:

∧*st*. (P ∧ [e]<sub><</sub> =<sub>u</sub> <st>) ⊢<sub>r</sub> Q ⊆ F ((P ∧ ([e]<sub><</sub>, <st>)<sub>u</sub> ∈<sub>u</sub> <R>) ⊢<sub>r</sub> Q)

**shows** (P ⊢<sub>r</sub> Q) ⊆ μ<sub>D</sub> F

**proof** –

{

**fix** *st*

**have** (P ∧ [e]<sub><</sub> =<sub>u</sub> <st>) ⊢<sub>r</sub> Q ⊆ μ<sub>D</sub> F

**using** WF **proof** (*induction rule: wf-induct-rule*)

**case** (*less st*)

**hence** 0: (P ∧ ([e]<sub><</sub>, <st>)<sub>u</sub> ∈<sub>u</sub> <R>) ⊢<sub>r</sub> Q ⊆ μ<sub>D</sub> F

**by** *rel-blast*

**from** M H *design-theory-continuous.LFP-lemma3 mono-Monotone-utp-order*

**have** 1: μ<sub>D</sub> F ⊆ F (μ<sub>D</sub> F)

**by** *blast*

**from** 0 1 **have** 2: (P ∧ ([e]<sub><</sub>, <st>)<sub>u</sub> ∈<sub>u</sub> <R>) ⊢<sub>r</sub> Q ⊆ F (μ<sub>D</sub> F)

by *simp*  
 have 3:  $F ((P \wedge ([e]_{<}, \ll st \gg)_u \in_u \ll R \gg)) \vdash_r Q \sqsubseteq F (\mu_D F)$   
 by (*simp add: 0 M monoD*)  
 have 4:  $(P \wedge [e]_{<} =_u \ll st \gg) \vdash_r Q \sqsubseteq \dots$   
 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 ∈ [[H]]<sub>H</sub> → [[H]]<sub>H</sub>*  
 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 [p]\_{<} e], simp-all add: alpha*)

**theorem** *ndesign-mu-wf-refine-intro*:  
 assumes *WF: wf R*  
 and *M: Monotonic F*  
 and *H: F ∈ [[N]]<sub>H</sub> → [[N]]<sub>H</sub>*  
 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  $(p \vdash_n Q) \sqsubseteq \mu_{NDES} F$

**proof** –  
 {  
 fix *st*  
 have  $(p \wedge e =_u \ll st \gg) \vdash_n Q \sqsubseteq \mu_{NDES} F$   
 using *WF proof (induction rule: wf-induct-rule)*  
 case (*less st*)  
 hence 0:  $(p \wedge (e, \ll st \gg)_u \in_u \ll R \gg) \vdash_n Q \sqsubseteq \mu_{NDES} F$   
 by *rel-blast*  
 from *M H design-theory-continuous.LFP-lemma3 mono-Monotone-utp-order*  
 have 1:  $\mu_{NDES} F \sqsubseteq F (\mu_{NDES} F)$   
 by (*simp add: mono-Monotone-utp-order normal-design-theory-continuous.LFP-lemma3*)  
 from 0 1 have 2:  $(p \wedge (e, \ll st \gg)_u \in_u \ll R \gg) \vdash_n Q \sqsubseteq F (\mu_{NDES} F)$   
 by *simp*  
 have 3:  $F ((p \wedge (e, \ll st \gg)_u \in_u \ll R \gg) \vdash_n Q) \sqsubseteq F (\mu_{NDES} F)$   
 by (*simp add: 0 M monoD*)  
 have 4:  $(p \wedge e =_u \ll st \gg) \vdash_n Q \sqsubseteq \dots$   
 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:  $\llbracket P \text{ is } \mathbf{N}; Q(\lfloor pre_D(P) \rfloor_{<} \vdash_n post_D(P)) \rrbracket \implies Q(P)$ 
  by (simp add: ndesign-form)

```

```

lemma ndes-ind-elim:  $\llbracket \bigwedge i. P \ i \text{ is } \mathbf{N}; Q(\lambda i. \lfloor pre_D(P \ i) \rfloor_{<} \vdash_n post_D(P \ i)) \rrbracket \implies Q(P)$ 
  by (simp add: ndesign-form)

```

```

lemma ndes-split [ND-elim]:  $\llbracket P \text{ is } \mathbf{N}; \bigwedge pre \ post. Q(pre \vdash_n \ post) \rrbracket \implies Q(P)$ 
  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 ( $\langle \cdot \rangle_D$ ) where
  [upred-defs]: assigns-d  $\sigma$  = (true  $\vdash_r$  assigns-r  $\sigma$ )

```

## syntax

-assignmentd :: svids  $\Rightarrow$  uexprs  $\Rightarrow$  logic (**infixr** :=<sub>D</sub> 72)

## translations

-assignmentd xs vs  $\Rightarrow$  CONST assigns-d (-mk-ustubst (CONST id) xs vs)

-assignmentd x v  $\leq$  CONST assigns-d (CONST subst-upd (CONST id) x v)

-assignmentd x v  $\leq$  -assignmentd (-spvar x) v

x,y :=<sub>D</sub> u,v  $\leq$  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**  $\implies$   $[\sigma \oplus_s \Sigma_D]_s \dagger P$  is **H**

by (metis H1-H2-eq-rdesign Healthy-if rdesign-is-H1-H2 state-subst-design)

**lemma** assigns-d-ndes-def [ndes-simp]:

$\langle \sigma \rangle_D = (\text{true} \vdash_n \langle \sigma \rangle_a)$

by (rel-auto)

**lemma** assigns-d-id [simp]:  $\langle \text{id} \rangle_D = \text{ID}$

by (rel-auto)

**lemma** assign-d-left-comp:

$(\langle f \rangle_D ;; (P \vdash_r Q)) = ([f]_s \dagger P \vdash_r [f]_s \dagger Q)$

by (simp add: assigns-d-def rdesign-composition assigns-r-comp subst-not)

**lemma** assign-d-right-comp:

$((P \vdash_r Q) ;; \langle f \rangle_D) = ((\neg ((\neg P) ;; \text{true})) \vdash_r (Q ;; \langle f \rangle_a))$

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  $(\langle \sigma \rangle_D ;; P) = [\sigma \oplus_s \Sigma_D]_s \dagger P$

**proof** –

have  $\langle \sigma \rangle_D ;; P = \langle \sigma \rangle_D ;; (\text{pre}_D(P) \vdash_r \text{post}_D(P))$

by (metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def' assms)

also have  $\dots = [\sigma]_s \dagger \text{pre}_D(P) \vdash_r [\sigma]_s \dagger \text{post}_D(P)$

by (simp add: assign-d-left-comp)

also have  $\dots = [\sigma \oplus_s \Sigma_D]_s \dagger (\text{pre}_D(P) \vdash_r \text{post}_D(P))$

by (rel-auto)

also have  $\dots = [\sigma \oplus_s \Sigma_D]_s \dagger P$

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]:

$P \text{ is } \mathbf{N} \implies [\sigma \oplus_s \Sigma_D]_s \dagger P \text{ is } \mathbf{N}$

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*:  $\langle \sigma \rangle_D \text{ is } H4$

**proof** –

have  $(\langle \sigma \rangle_D ;; (\text{false} \vdash_r \text{true}_h)) = (\text{false} \vdash_r \text{true})$

by (*simp add: assigns-d-def rdesign-composition assigns-r-feasible*)

moreover have  $\dots = \text{true}$

by (*rel-auto*)

ultimately show *?thesis*

using *is-H4-alt-def* by *auto*

qed

## 4.2 Guarded Commands

**definition** *GrdCommD* ::  $'\alpha \text{ upred} \Rightarrow (''\alpha, '\beta) \text{ rel-des} \Rightarrow (''\alpha, '\beta) \text{ rel-des} \Rightarrow (- \rightarrow_D - [85, 86] 85)$  **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]:  $P \text{ is } \mathbf{N} \implies b \rightarrow_D P \text{ is } \mathbf{N}$

by (*simp add: GrdCommD-def closure*)

**lemma** *GrdCommD-true* [*simp*]:  $\text{true} \rightarrow_D P = P$

by (*rel-auto*)

**lemma** *GrdCommD-false* [*simp*]:  $\text{false} \rightarrow_D P = \top_D$

by (*rel-auto*)

**lemma** *GrdCommD-abort* [*simp*]:  $b \rightarrow_D \text{true} = ((\neg b) \vdash_n \text{false})$

by (*rel-auto*)

## 4.3 Alternation

**consts**

*ualtern* ::  $'a \text{ set} \Rightarrow ('a \Rightarrow 'p) \Rightarrow ('a \Rightarrow 'r) \Rightarrow 'r \Rightarrow 'r$

*ualtern-list* ::  $('a \times 'r) \text{ list} \Rightarrow 'r \Rightarrow 'r$

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

[*upred-defs, ndes-simp*]:

$\text{AlternateD } A \ g \ P \ Q = (\prod_{i \in A} i \cdot g(i) \rightarrow_D P(i)) \sqcap (\bigwedge_{i \in A} i \cdot \neg g(i) \rightarrow_D Q)$

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**  $\bigwedge i. P(i) \text{ is } \mathbf{N}$

**shows**

$AlternateD\ A\ g\ P\ \perp_D =$   
 $((\bigvee i \in A \cdot g(i)) \wedge (\bigwedge i \in A \cdot g(i) \Rightarrow \lfloor pre_D(P\ i) \rfloor_{<})) \vdash_n (\bigvee i \in A \cdot \lfloor g(i) \rfloor_{<} \wedge post_D(P\ i))$   
**proof** (*cases*  $A = \{\}$ )  
**case** *False*  
**have**  $AlternateD\ A\ g\ P\ \perp_D =$   
 $(\prod i \in A \cdot g(i) \rightarrow_D (\lfloor pre_D(P\ i) \rfloor_{<} \vdash_n post_D(P\ i))) \sqcap (\bigwedge i \in A \cdot \neg g(i) \rightarrow_D (false \vdash_n true))$   
**by** (*simp add: AlternateD-def ndesign-form bot-d-ndes-def assms*)  
**also have**  $\dots = ((\bigvee i \in A \cdot g(i)) \wedge (\bigwedge i \in A \cdot g(i) \Rightarrow \lfloor pre_D(P\ i) \rfloor_{<})) \vdash_n (\bigvee i \in A \cdot \lfloor g(i) \rfloor_{<} \wedge post_D(P\ i))$   
*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* ::  $(\alpha\ upred \times (\alpha, \beta)\ rel-des)\ list \Rightarrow (\alpha, \beta)\ rel-des \Rightarrow (\alpha, \beta)\ rel-des$   
**where**

[*upred-defs, ndes-simp*]:

*AlternateD-list*  $xs\ P =$

$AlternateD\ \{0..\<length\ xs\}\ (\lambda\ i.\ map\ fst\ xs\ !\ i)\ (\lambda\ i.\ map\ snd\ xs\ !\ i)\ P$

### adhoc-overloading

*ualtern AlternateD and*

*ualtern-list AlternateD-list*

### nonterminal gcomm and gcomms

#### syntax

*-altind-els* ::  $pttrn \Rightarrow logic \Rightarrow logic \Rightarrow logic \Rightarrow logic \Rightarrow logic \Rightarrow logic$  (*if -∈- · - → - else - fi*)

*-altind* ::  $pttrn \Rightarrow logic \Rightarrow logic \Rightarrow logic \Rightarrow logic \Rightarrow logic$  (*if -∈- · - → - fi*)

*-gcomm* ::  $logic \Rightarrow logic \Rightarrow gcomm$  ( $- \rightarrow -$  [*65, 66*] *65*)

*-gcomm-nil* ::  $gcomm \Rightarrow gcomms$  ( $-$ )

*-gcomm-cons* ::  $gcomm \Rightarrow gcomms \Rightarrow gcomms$  ( $- | -$  [*60, 61*] *61*)

*-gcomm-show* ::  $logic \Rightarrow logic$

*-altgcomm-els* ::  $gcomms \Rightarrow logic \Rightarrow logic$  (*if - else - fi*)

*-altgcomm* ::  $gcomms \Rightarrow logic$  (*if - fi*)

#### translations

*-altind-els*  $x\ A\ g\ P\ Q \Rightarrow CONST\ ualtern\ A\ (\lambda\ x.\ g)\ (\lambda\ x.\ P)\ Q$

*-altind-els*  $x\ A\ g\ P\ Q \Leftarrow CONST\ ualtern\ A\ (\lambda\ x.\ g)\ (\lambda\ x'.\ P)\ Q$

*-altind*  $x\ A\ g\ P \Rightarrow CONST\ ualtern\ A\ (\lambda\ x.\ g)\ (\lambda\ x.\ P)\ (CONST\ Orderings.top)$

*-altind*  $x\ A\ g\ P \Leftarrow CONST\ ualtern\ A\ (\lambda\ x.\ g)\ (\lambda\ x'.\ P)\ (CONST\ Orderings.top)$

*-altgcomm*  $cs \Rightarrow CONST\ ualtern-list\ cs\ (CONST\ Orderings.top)$

*-altgcomm* (*-gcomm-show*  $cs$ )  $\Leftarrow CONST\ ualtern-list\ cs\ (CONST\ Orderings.top)$

*-altgcomm-els*  $cs\ P \Rightarrow CONST\ ualtern-list\ cs\ P$

*-altgcomm-els* (*-gcomm-show*  $cs$ )  $P \Leftarrow CONST\ ualtern-list\ cs\ P$

*-gcomm*  $g\ P \Rightarrow (g, P)$

*-gcomm*  $g\ P \Leftarrow -gcomm-show\ (g, P)$

*-gcomm-cons*  $c\ cs \Rightarrow c\ \#\ cs$

*-gcomm-cons* (*-gcomm-show*  $c$ ) (*-gcomm-show* ( $d\ \#\ cs$ ))  $\Leftarrow -gcomm-show\ (c\ \#\ d\ \#\ cs)$

*-gcomm-nil*  $c \Rightarrow [c]$

*-gcomm-nil* (*-gcomm-show*  $c$ )  $\Leftarrow -gcomm-show\ [c]$

**lemma** *AlternateD-H1-H3-closed* [*closure*]:  
**assumes**  $\bigwedge i. i \in A \implies P \ i \text{ is } \mathbf{N} \ Q \ \text{is } \mathbf{N}$   
**shows**  $\text{if } i \in A \cdot g(i) \rightarrow P(i) \text{ else } Q \ \text{fi is } \mathbf{N}$   
**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*]:  
 $\text{if } i \in A \cdot g(i) \rightarrow (P_1(i) \vdash_n P_2(i)) \text{ else } Q_1 \vdash_n Q_2 \ \text{fi}$   
 $= ((\bigwedge i \in A \cdot g \ i \implies P_1 \ i) \wedge ((\bigwedge i \in A \cdot \neg g \ i) \implies Q_1)) \vdash_n$   
 $((\bigvee i \in A \cdot [g \ i]_{<} \wedge P_2 \ i) \vee (\bigwedge i \in A \cdot \neg [g \ i]_{<} \wedge Q_2))$   
**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**  $(\text{if } i \in A \cdot g(i) \rightarrow P(i) \text{ else } R \ \text{fi}) \sqsubseteq (\text{if } i \in A \cdot g(i) \rightarrow Q(i) \text{ else } S \ \text{fi})$   
**using** *assms* **by** (*rel-auto, meson*)

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

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

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

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

**lemma** *AlernateD-no-ind*:

**assumes**  $A \neq \{\}$   $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } i \in A \cdot b \rightarrow P \text{ else } Q \text{ fi} = \text{if } b \rightarrow P \text{ else } Q \text{ fi}$   
**by** (*ndes-eq cls: assms*)

**lemma** *AlernateD-singleton*:

**assumes**  $P$   $k$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } i \in \{k\} \cdot b(i) \rightarrow P(i) \text{ else } Q \text{ fi} = \text{if } b(k) \rightarrow P(k) \text{ else } Q \text{ fi}$  (**is**  $?lhs = ?rhs$ )

**proof** –

**have**  $?lhs = \text{if } i \in \{k\} \cdot b(k) \rightarrow P(k) \text{ else } Q \text{ fi}$   
**by** (*auto intro: AlternateD-eq simp add: assms ndesign-form*)

**also have**  $\dots = ?rhs$

**by** (*simp add: AlernateD-no-ind assms closure*)

**finally show**  $?thesis$  .

**qed**

**lemma** *AlternateD-commute*:

**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } g_1 \rightarrow P \mid g_2 \rightarrow Q \text{ fi} = \text{if } g_2 \rightarrow Q \mid g_1 \rightarrow P \text{ fi}$   
**by** (*ndes-eq cls: assms*)

**lemma** *AlternateD-dcond*:

**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } g \rightarrow P \text{ else } Q \text{ fi} = P \triangleleft g \triangleright_D Q$   
**by** (*ndes-eq cls: assms*)

**lemma** *AlternateD-cover*:

**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } g \rightarrow P \text{ else } Q \text{ fi} = \text{if } g \rightarrow P \mid (\neg g) \rightarrow Q \text{ fi}$   
**by** (*ndes-eq cls: assms*)

**lemma** *UINF-ndes-expand*:

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

**lemma** *USUP-ndes-expand*:

**assumes**  $\bigwedge i. i \in A \implies P(i)$  is  $\mathbf{N}$   
**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**  $\bigwedge i. i \in A \implies P(i)$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } i \in A \cdot g(i) \rightarrow P(i) \text{ else } Q \text{ fi} =$   
 $\text{if } i \in A \cdot g(i) \rightarrow (\lfloor pre_D(P(i)) \rfloor_{<} \vdash_n post_D(P(i))) \text{ else } \lfloor pre_D(Q) \rfloor_{<} \vdash_n post_D(Q) \text{ fi}$   
**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**  $\bigwedge i. i \in A \implies P(i)$  is  $\mathbf{N}$

**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**  $\bigwedge i. i \in (insert\ x\ A) \implies P(i)$  *is N*  $Q$  *is N*  
**shows**  $if\ i \in (insert\ x\ A) \cdot g(i) \rightarrow P(i)$  *else*  $Q\ fi =$   
 $if\ g(x) \rightarrow P(x) \mid$   
 $(\bigvee i \in A \cdot g(i)) \rightarrow if\ i \in A \cdot g(i) \rightarrow P(i)\ fi$   
 $else\ Q$   
 $fi$  (**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** ... =

$if\ g(x) \rightarrow (\lfloor pre_D(P(x)) \rfloor_{<} \vdash_n post_D(P(x))) \mid$   
 $(\bigvee i \in A \cdot g(i)) \rightarrow if\ i \in A \cdot g(i) \rightarrow \lfloor pre_D(P(i)) \rfloor_{<} \vdash_n post_D(P(i))\ fi$   
 $else\ \lfloor pre_D(Q) \rfloor_{<} \vdash_n post_D(Q)$   
 $fi$

**by** (*ndes-simp cls:assms, rel-auto*)

**also have** ... =  $?rhs$

**by** (*simp add: AlternateD-ndes-expand' ndesign-form assms*)

**finally show**  $?thesis$  .

**qed**

## 4.4 Iteration

**theorem** *ndesign-iteration-wp [ndes-simp]:*

$(p \vdash_n Q) ;; (p \vdash_n Q) \hat{\ } n = ((\bigwedge i \in \{0..n\} \cdot (Q \hat{\ } i)\ wp\ p) \vdash_n Q \hat{\ } Suc\ n)$

**proof** (*induct n*)

**case**  $0$

**then show**  $?case$  **by** (*rel-auto*)

**next**

**case** ( $Suc\ n$ ) **note**  $hyp = this$

**have**  $(p \vdash_n Q) ;; (p \vdash_n Q) \hat{\ } Suc\ n = (p \vdash_n Q) ;; (p \vdash_n Q) ;; (p \vdash_n Q) \hat{\ } n$

**by** (*simp add: upred-semiring.power-Suc*)

**also have** ... =  $(p \vdash_n Q) ;; ((\bigwedge i \in \{0..n\} \cdot Q \hat{\ } i)\ wp\ p) \vdash_n Q \hat{\ } Suc\ n$

**by** (*simp add: hyp*)

**also have** ... =  $(p \wedge Q\ wp\ (\bigwedge i \in \{0..n\} \cdot Q \hat{\ } i)\ wp\ p) \vdash_n (Q ;; Q) ;; Q \hat{\ } n$

**by** (*simp add: upred-semiring.power-Suc ndesign-composition-wp seqr-assoc*)

**also have** ... =  $(p \wedge (\bigwedge i \in \{0..n\} \cdot Q \hat{\ } i)\ wp\ p) \vdash_n (Q ;; Q) ;; Q \hat{\ } n$

**by** (*simp add: upred-semiring.power-Suc wp*)

**also have** ... =  $(p \wedge (\bigwedge i \in \{0..n\} \cdot Q \hat{\ } i)\ wp\ p) \vdash_n (Q ;; Q) ;; Q \hat{\ } n$

**by** (*simp add: USUP-as-Inf-image*)

**also have** ... =  $(p \wedge (\bigwedge i \in \{1..Suc\ n\} \cdot Q \hat{\ } i)\ wp\ p) \vdash_n (Q ;; Q) ;; Q \hat{\ } n$

by (*metis (no-types, lifting) One-nat-def image-Suc-atLeastAtMost image-cong image-image*)  
**also have** ... =  $(Q \hat{=} 0 \text{ wp } p \wedge (\bigsqcup i \in \{1..Suc\ n\}. Q \hat{=} i \text{ wp } p)) \vdash_n (Q ;; Q) ;; Q \hat{=} n$   
 by (*simp add: wp*)  
**also have** ... =  $(\bigsqcup i \in \{0..Suc\ n\}. Q \hat{=} i \text{ wp } p) \vdash_n (Q ;; Q) ;; Q \hat{=} n$   
 by (*simp add: Iic-Suc-eq-insert-0 atLeast0AtMost conj-upred-def image-Suc-atMost*)  
**also have** ... =  $(\bigsqcup i \in \{0..Suc\ n\} \cdot Q \hat{=} i \text{ wp } p) \vdash_n Q \hat{=} Suc\ (Suc\ n)$   
 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* :: pptrn  $\Rightarrow$  logic  $\Rightarrow$  logic  $\Rightarrow$  logic  $\Rightarrow$  logic (do - $\in$ - · -  $\rightarrow$  - od)  
*-itergcomm* :: gcomms  $\Rightarrow$  logic (do - od)

### translations

*-iterind* x A g P  $\Rightarrow$  CONST *uiterate* A ( $\lambda$  x. g) ( $\lambda$  x. P)  
*-iterind* x A g P  $\Leftarrow$  CONST *uiterate* A ( $\lambda$  x. g) ( $\lambda$  x'. P)  
*-itergcomm* cs  $\Rightarrow$  CONST *uiterate-list* cs  
*-itergcomm* (-gcomm-show cs)  $\Leftarrow$  CONST *uiterate-list* cs

**definition** *IterateD* :: 'a set  $\Rightarrow$  ('a  $\Rightarrow$  'α upred)  $\Rightarrow$  ('a  $\Rightarrow$  'α hrel-des)  $\Rightarrow$  'α hrel-des **where**  
 [*upred-defs, ndes-simp*]:

*IterateD* A g P =  $(\mu_{NDES}\ X \cdot \text{if } i \in A \cdot g(i) \rightarrow P(i) ;; X \text{ else } II_D \text{ fi})$

**definition** *IterateD-list* :: ('α upred  $\times$  'α hrel-des) list  $\Rightarrow$  'α hrel-des **where**  
 [*upred-defs, ndes-simp*]:

*IterateD-list* xs = *IterateD* {0..*length* xs} ( $\lambda$  i. *fst* (*nth* xs i)) ( $\lambda$  i. *snd* (*nth* xs i))

### adhoc-overloading

*uiterate* *IterateD* **and**  
*uiterate-list* *IterateD-list*

**lemma** *IterateD-H1-H3-closed* [*closure*]:

**assumes**  $\bigwedge i. i \in A \implies P\ i$  is **N**  
**shows** do  $i \in A \cdot g(i) \rightarrow P(i)$  od is **N**

**proof** (*cases* A = {})

**case** *True*

**then show** ?thesis

by (*simp add: IterateD-def closure assms*)

**next**

**case** *False*

**then show** ?thesis

by (*simp add: IterateD-def closure assms*)

**qed**

**lemma** *IterateD-empty*:

do  $i \in \{\}$  ·  $g(i) \rightarrow P(i)$  od = *II<sub>D</sub>*

by (*simp add: IterateD-def AlternateD-empty normal-design-theory-continuous.LFP-const skip-d-is-H1-H3*)

**lemma** *IterateD-list-single-expand*:



$do\ b \rightarrow P\ od = (\mu_{NDES}\ X \cdot if\ b \rightarrow P\ ;;\ X\ else\ II_D\ fi)$   
**oops**

**lemma** *IterateD-singleton*:

**assumes**  $P\ is\ \mathbf{N}$   
**shows**  $do\ b \rightarrow P\ od = do\ i \in \{0\} \cdot b \rightarrow P\ od$   
**apply** (*simp add: IterateD-list-def IterateD-def Alternated-singleton assms*)  
**apply** (*subst Alternated-singleton*)  
**apply** (*simp*)  
**apply** (*rel-auto*)  
**oops**

**lemma** *IterateD-mono-refine*:

**assumes**  
 $\bigwedge i. P\ i\ is\ \mathbf{N} \wedge i. Q\ i\ is\ \mathbf{N}$   
 $\bigwedge i. P\ i \sqsubseteq Q\ i$   
**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 segr-mono assms*)  
**done**

**lemma** *IterateD-single-refine*:

**assumes**  
 $P\ is\ \mathbf{N}\ Q\ is\ \mathbf{N}\ P \sqsubseteq Q$   
**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: [\![I \wedge \neg (\bigvee i \in A \cdot g(i))\]\!]_{>}) \sqsubseteq$   
 $do\ i \in A \cdot g(i) \rightarrow (I \wedge g(i)) \vdash_n (w: [\![I]\!]_{>} \wedge [\![V]\!]_{>} <_u [\![V]\!]_{<})\ od$   
**proof** (*cases A = {}*)  
**case True**  
**with** *assms* **show** *?thesis*  
**by** (*simp add: IterateD-empty, rel-auto*)  
**next**  
**case False**  
**then** **show** *?thesis*  
**using** *assms*  
**apply** (*simp add: IterateD-def*)  
**apply** (*rule ndesign-mu-wf-refine-intro[where e=V and R={{(x, y). x < y}}*)  
**apply** (*simp-all add: wf closure*)  
**apply** (*simp add: ndes-simp unrest*)  
**apply** (*rule ndesign-refine-intro*)  
**apply** (*rel-auto*)  
**apply** (*rel-auto*)

**apply** (*metis mwb-lens.put-put vwb-lens-mwb*)  
**done**  
**qed**

**lemma** *IterateD-single-refine-intro*:

**fixes**  $V :: (\text{nat}, 'a) \text{ uexpr}$

**assumes** *vwb-lens w*

**shows**

$I \vdash_n (w: \llbracket I \wedge \neg g \rrbracket_{>}) \sqsubseteq$

$\text{do } g \rightarrow ((I \wedge g) \vdash_n (w: \llbracket I \rrbracket_{>} \wedge \llbracket V \rrbracket_{>} <_u \llbracket V \rrbracket_{<})) \text{ od}$

**apply** (*rule order-trans*)

**defer**

**apply** (*rule IterateD-refine-intro[of w {0} λ i. g I V, simplified, OF assms(1)]*)

**oops**

## 4.5 Let and Local Variables

**definition**  $\text{LetD} :: ('a, 'α) \text{ uexpr} \Rightarrow ('a \Rightarrow 'α \text{ hrel-des}) \Rightarrow 'α \text{ hrel-des}$  **where**  
*[upred-defs]:*  $\text{LetD } v P = (P \ x) \llbracket x \rightarrow \llbracket v \rrbracket_{D<} \rrbracket$

**syntax**

$\text{-LetD} \quad :: \llbracket \text{letbinds}, 'a \rrbracket \Rightarrow 'a \quad ((\text{let}_D \ (-) / \text{in } (-)) [0, 10] 10)$

**translations**

$\text{-LetD } (-\text{binds } b \text{ bs}) \ e \ \rightleftharpoons \ \text{-LetD } b \ (\text{-LetD } \text{bs } e)$

$\text{let}_D \ x = a \ \text{in } e \quad \rightleftharpoons \ \text{CONST } \text{LetD } a \ (\lambda x. \ e)$

**lemma** *LetD-ndes-simp [ndes-simp]*:

$\text{LetD } v (\lambda x. \ p(x) \vdash_n Q(x)) = (p(x) \llbracket x \rightarrow v \rrbracket) \vdash_n (Q(x) \llbracket x \rightarrow \llbracket v \rrbracket_{<} \rrbracket)$

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

**lemma** *LetD-H1-H3-closed [closure]*:

$\llbracket \bigwedge x. P(x) \text{ is } \mathbf{N} \rrbracket \Longrightarrow \text{LetD } v P \text{ is } \mathbf{N}$

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

## 4.6 Deep Local Variables

**definition** *des-local-state* ::

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

**syntax**

$\text{-des-local-state-type} :: \text{type} \Rightarrow \text{logic } (\mathcal{L}_D[-])$

$\text{-des-var-scope-type} :: \text{id} \Rightarrow \text{type} \Rightarrow \text{logic} \Rightarrow \text{logic } (\text{var}_D \ - :: - \cdot - [0, 0, 10] 10)$

**translations**

$\mathcal{L}_D['a] == \text{CONST } \text{des-local-state } \text{TYPE}('a)$

$\text{-des-var-scope-type } x \ t \ P \ \Rightarrow \ \text{-var-scope-type } (\text{-des-local-state-type } t) \ x \ t \ P$

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

**lemma** *get-rel-local [lens-defs]*:

$\text{get}_S \ \mathcal{L}_D['a::\text{countable}] = \text{get}_{\Sigma_D}$

**by** (*simp add: des-local-state-def*)

**lemma** *des-local-state [simp]: utp-local-state*  $\mathcal{L}_D['a::\text{countable}]$

**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  $\mathbf{N}$   
 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  $\mathbf{N}$   
 by (simp add: utp-local-state.var-close-def closure)

**lemma** *unrest-ok-vtop-des* [unrest]: ok  $\#$  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]:  
 $\llbracket \$ok \# v; out\alpha \# v; (\bigwedge x. P\ x\ is\ \mathbf{N}) \rrbracket \implies (P(x)\llbracket x \rightarrow v \rrbracket)$  is  $\mathbf{N}$   
 by (rel-auto, metis+)

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

**lemma** *inj-local-rel* [simp]: inj-local  $R_l = \mathcal{U}_{\mathbf{N}}$   
 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  $\mathcal{L}_D['a::countable] = \mathcal{U}_{\mathbf{N}}$   
 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]:  
 $(p\ x \vdash_n Q\ x)\llbracket x \rightarrow \text{top}[\mathcal{L}_D['a::countable]] \rrbracket_{<} = ((p\ x)\llbracket x \rightarrow \text{top}[R_l['a]] \rrbracket \vdash_n (Q\ x)\llbracket x \rightarrow \text{top}[R_l['a]] \rrbracket_{<})$   
 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]:  
 $(var_D\ x :: 'a :: countable \cdot p(x) \vdash_n Q(x)) =$   
 $(\llbracket \sqcup v \cdot (p\ x)\llbracket x \rightarrow \text{top}[R_l] \rrbracket \llbracket \&store \hat{\_u} \langle \llbracket v \rrbracket \rrbracket / store \rrbracket \rrbracket \vdash_n$   
 $(\llbracket \sqcap v \cdot store := \&store \hat{\_u} \langle \llbracket v \rrbracket \rrbracket ;; (Q\ x)\llbracket x \rightarrow \text{top}[R_l] \rrbracket_{<} ;; store := (front_u(\&store) \triangleleft 0 \triangleleft_u$   
 $\#_u(\&store) \triangleright \&store) \rrbracket)$   
 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

## 5 Design Weakest Preconditions

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

**definition** *wp-design* :: (' $\alpha$ , ' $\beta$ ) *rel-des*  $\Rightarrow$  ' $\beta$  *cond*  $\Rightarrow$  ' $\alpha$  *cond* (**infix** *wp<sub>D</sub>* 60) **where**  
[*upred-defs*]:  $Q \text{ wp}_D r = (\lfloor \text{pre}_D(Q) \rfloor ;; \text{true} :: ('\alpha, '\beta) \text{ urel} \rfloor_{<} \wedge (\text{post}_D(Q) \text{ wp } r))$

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

**theorem** *wpd-eq-intro*:  $\llbracket \bigwedge r. (p_1 \vdash_n Q_1) \text{ wp}_D r = (p_2 \vdash_n Q_2) \text{ wp}_D r \rrbracket \Longrightarrow (p_1 \vdash_n Q_1) = (p_2 \vdash_n Q_2)$   
**apply** (*rel-simp robust*; *metis curry-conv*)  
**done**

**theorem** *wpd-H3-eq-intro*:  $\llbracket P \text{ is } H1\text{-}H3; Q \text{ is } H1\text{-}H3; \bigwedge r. P \text{ wp}_D r = Q \text{ wp}_D r \rrbracket \Longrightarrow P = Q$   
**by** (*metis H1-H3-commute H1-H3-is-normal-design H3-idem Healthy-def' wpd-eq-intro*)

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

**theorem** *rdesign-wp* [*wp*]:  
 $(\lfloor p \rfloor_{<} \vdash_r Q) \text{ wp}_D r = (p \wedge Q \text{ wp } r)$   
**by** (*rel-auto*)

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

**theorem** *wpd-seq-r*:  
**fixes**  $Q1 \ Q2 :: '\alpha \text{ hrel}$   
**shows**  $((\lfloor p1 \rfloor_{<} \vdash_r Q1) ;; (\lfloor p2 \rfloor_{<} \vdash_r Q2)) \text{ wp}_D r = (\lfloor p1 \rfloor_{<} \vdash_r Q1) \text{ wp}_D ((\lfloor p2 \rfloor_{<} \vdash_r Q2) \text{ wp}_D r)$   
**apply** (*simp add: wp*)  
**apply** (*subst rdesign-composition-wp*)  
**apply** (*simp only: wp*)  
**apply** (*rel-auto*)  
**done**

**theorem** *wpnd-seq-r* [*wp*]:  
**fixes**  $Q1 \ Q2 :: '\alpha \text{ hrel}$   
**shows**  $((p1 \vdash_n Q1) ;; (p2 \vdash_n Q2)) \text{ wp}_D r = (p1 \vdash_n Q1) \text{ wp}_D ((p2 \vdash_n Q2) \text{ wp}_D r)$   
**by** (*simp add: ndesign-def wpd-seq-r*)

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

**end**

## 6 Refinement Calculus

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

## begin

**definition**  $des-spec :: ('a \Rightarrow 'α) \Rightarrow 'α \text{ upred} \Rightarrow ('α \Rightarrow 'α \text{ upred}) \Rightarrow 'α \text{ hrel-des}$  **where**  
[upred-defs]:  $des-spec\ x\ p\ q = (\sqcup\ v \cdot ((p \wedge \&v =_u \ll v \gg) \vdash_n x: [[q(v)]_{>}]))$

## syntax

-init-var :: logic  
-des-spec ::  $salpha \Rightarrow logic \Rightarrow logic \Rightarrow logic$  ( $:-[-, / -]_D [99, 0, 0] 100$ )  
-des-log-const ::  $pttrn \Rightarrow logic \Rightarrow logic$  ( $con_D - \cdot - [0, 10] 10$ )

## translations

-des-spec  $x\ p\ q \Rightarrow CONST\ des-spec\ x\ p\ (\lambda\ -init-var.\ q)$   
-des-spec  $(-salphaset\ (-salphamk\ x))\ p\ q \Leftarrow CONST\ des-spec\ x\ p\ (\lambda\ iv.\ q)$   
-des-log-const  $x\ P \Rightarrow \sqcup\ x \cdot P$

## parse-translation

$\ll$   
let  
  fun init-var-tr [] = Syntax.free iv  
  | init-var-tr - = raise Match;  
in  
  [(@{syntax-const -init-var}, K init-var-tr)]  
end  
 $\gg$

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

## lemma des-spec-simple-def:

$x: [pre, post]_D = (pre \vdash_n x: [[post]_{>}])$   
**by** (rel-auto)

## lemma des-spec-abort:

$x: [false, post]_D = \perp_D$   
**by** (rel-auto)

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

**by** (rel-auto)

## lemma des-spec-strengthen-post:

**assumes**  $'post' \Rightarrow post'$   
**shows**  $w: [pre, post]_D \sqsubseteq w: [pre, post']_D$   
**using** *assms* **by** (rel-auto)

## lemma des-spec-weaken-pre:

**assumes**  $pre \Rightarrow pre'$   
**shows**  $w: [pre, post]_D \sqsubseteq w: [pre', post]_D$   
**using** *assms* **by** (rel-auto)

## lemma des-spec-refine-skip:

**assumes**  $vwb-lens\ w\ 'pre \Rightarrow post'$   
**shows**  $w: [pre, post]_D \sqsubseteq II_D$   
**using** *assms* **by** (rel-auto)

## lemma rc-iter:

**fixes**  $V :: (nat, 'a)\ uexpr$   
**assumes**  $vwb-lens\ w$

```

shows  $w:[ivr, ivr \wedge \neg (\bigvee_{i \in A} \cdot g(i))]_D$ 
       $\sqsubseteq (do\ i \in A \cdot g(i) \rightarrow \bigsqcup\ iv \cdot w:[ivr \wedge g(i) \wedge \ll iv \gg =_u \&\mathbf{v}, ivr \wedge (V <_u V[\ll iv \gg / \mathbf{v}])]_D\ od)\ (\mathbf{is}$ 
 $\ ?lhs \sqsubseteq\ ?rhs)$ 
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**  $OIH\text{-def}$  [*upred-defs*]

**lemma**  $OIH\text{-design}$ :

```

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  $\dots = ((\$ok \wedge \neg D^f \Rightarrow \$ok' \wedge D^t) \wedge (\$ok \wedge \neg D^f \Rightarrow \psi))$ 
by (simp add: design-def)
also have  $\dots = ((\neg D^f) \vdash (D^t \wedge \psi))$ 
by (pred-auto)
finally show ?thesis .
qed

```

**lemma**  $OIH\text{-idem}$ :

```

assumes  $D$  is H1-H2  $\$ok' \# \psi$ 
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**  $OIH\text{-of-design}$ :

```

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

```

## 7.2 State Invariants

**definition**  $ISH(\psi)(D) = (D \vee (\$ok \wedge \neg D^f \wedge [\psi]_{<} \Rightarrow \$ok' \wedge D^t))$

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

**lemma**  $ISH-design$ :  $ISH(\psi)(D) = (\neg D^f \wedge [\psi]_{<}) \vdash D^t$   
**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**  $ISH-of-design$ :  
 $\llbracket \$ok' \# P; \$ok' \# Q \rrbracket \Longrightarrow ISH(\psi)(P \vdash Q) = ((P \wedge [\psi]_{<}) \vdash Q)$   
**by** (*simp add: ISH-design design-def usubst, pred-auto*)

**definition**  $OSH(\psi)(D) = (D \wedge (\$ok \wedge \neg D^f \wedge [\psi]_{<} \Rightarrow [\psi]_{>}))$

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

**lemma**  $OSH-as-OIH$ :  
 $OSH(\psi)(D) = OIH([\psi]_{<} \Rightarrow [\psi]_{>})(D)$   
**by** (*simp add: OSH-def OIH-def, pred-auto*)

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

**lemma**  $OSH-of-design$ :  
 $\llbracket \$ok' \# P; \$ok' \# Q \rrbracket \Longrightarrow OSH(\psi)(P \vdash Q) = (P \vdash (Q \wedge ([\psi]_{<} \Rightarrow [\psi]_{>})))$   
**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**  $SIH-of-design$ :  
 $\llbracket \$ok' \# P; \$ok' \# Q; ok \# \psi \rrbracket \Longrightarrow SIH(\psi)(P \vdash Q) = ((P \wedge [\psi]_{<}) \vdash (Q \wedge [\psi]_{>}))$   
**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-prog*  
*utp-des-wp*  
*utp-des-refcalc*  
*utp-des-invariants*

begin end

## References

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