

# Isabelle/HOL-NSA — Non-Standard Analysis

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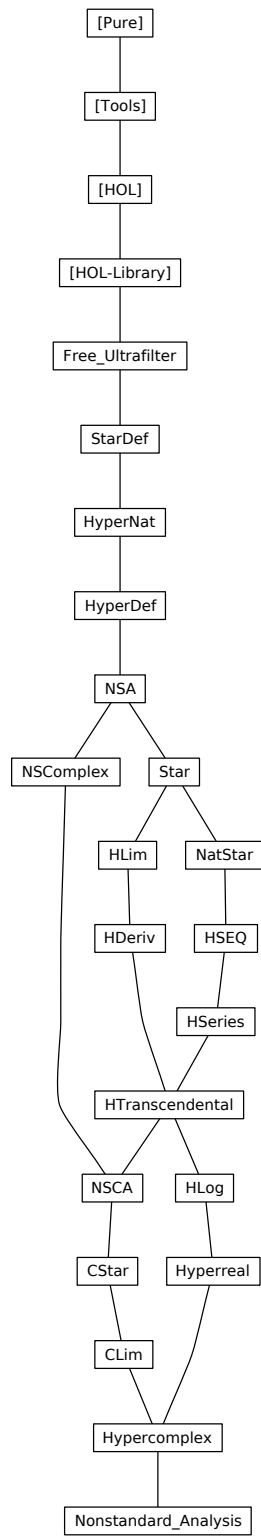
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## 1 Filters and Ultrafilters

```
theory Free-Ultrafilter
  imports HOL-Library.Infinite-Set
begin
```

### 1.1 Definitions and basic properties

#### 1.1.1 Ultrafilters

```
locale ultrafilter =
  fixes F :: 'a filter
  assumes proper: F ≠ bot
  assumes ultra: eventually P F ∨ eventually (λx. ¬ P x) F
begin
```

```
lemma eventually-imp-frequently: frequently P F ⇒ eventually P F
  using ultra[of P] by (simp add: frequently-def)
```

```
lemma frequently-eq-eventually: frequently P F = eventually P F
  using eventually-imp-frequently eventually-frequently[OF proper] ..
```

```
lemma eventually-disj-iff: eventually (λx. P x ∨ Q x) F ↔ eventually P F ∨
  eventually Q F
  unfolding frequently-eq-eventually[symmetric] frequently-disj-iff ..
```

```
lemma eventually-all-iff: eventually (λx. ∀ y. P x y) F = (∀ Y. eventually (λx. P
  x (Y x)) F)
  using frequently-all[of P F] by (simp add: frequently-eq-eventually)
```

```
lemma eventually-imp-iff: eventually (λx. P x → Q x) F ↔ (eventually P F
  → eventually Q F)
  using frequently-imp-iff[of P Q F] by (simp add: frequently-eq-eventually)
```

```
lemma eventually-iff-iff: eventually (λx. P x ↔ Q x) F ↔ (eventually P F
  ↔ eventually Q F)
  unfolding iff-conv-conj-imp eventually-conj-iff eventually-imp-iff by simp
```

```
lemma eventually-not-iff: eventually (λx. ¬ P x) F ↔ ¬ eventually P F
  unfolding not-eventually frequently-eq-eventually ..
```

```
end
```

### 1.2 Maximal filter = Ultrafilter

A filter  $F$  is an ultrafilter iff it is a maximal filter, i.e. whenever  $G$  is a filter and  $F \subseteq G$  then  $F = G$

Lemma that shows existence of an extension to what was assumed to be a maximal filter. Will be used to derive contradiction in proof of property of

ultrafilter.

**lemma** *extend-filter*:  $frequently\ P\ F \implies inf\ F\ (principal\ \{x.\ P\ x\}) \neq bot$   
**by** (*simp add: trivial-limit-def eventually-inf-principal not-eventually*)

**lemma** *max-filter-ultrafilter*:

**assumes**  $F \neq bot$

**assumes** *max*:  $\bigwedge G. G \neq bot \implies G \leq F \implies F = G$

**shows** *ultrafilter*  $F$

**proof**

**show** *eventually*  $P\ F \vee (\forall_F x\ in\ F. \neg P\ x)$  **for**  $P$

**proof** (*rule disjCI*)

**assume**  $\neg (\forall_F x\ in\ F. \neg P\ x)$

**then have**  $inf\ F\ (principal\ \{x.\ P\ x\}) \neq bot$

**by** (*simp add: not-eventually extend-filter*)

**then have**  $F: F = inf\ F\ (principal\ \{x.\ P\ x\})$

**by** (*rule max*) *simp*

**show** *eventually*  $P\ F$

**by** (*subst F*) (*simp add: eventually-inf-principal*)

**qed**

**qed fact**

**lemma** *le-filter-frequently*:  $F \leq G \iff (\forall P. frequently\ P\ F \implies frequently\ P\ G)$

**unfolding** *frequently-def le-filter-def*

**apply** *auto*

**apply** (*erule-tac x= $\lambda x. \neg P\ x$  in allE*)

**apply** *auto*

**done**

**lemma** (*in ultrafilter*) *max-filter*:

**assumes**  $G: G \neq bot$

**and** *sub*:  $G \leq F$

**shows**  $F = G$

**proof** (*rule antisym*)

**show**  $F \leq G$

**using** *sub*

**by** (*auto simp: le-filter-frequently[of F] frequently-eq-eventually le-filter-def[of G]*)

*intro!*: *eventually-frequently G proper*)

**qed fact**

### 1.3 Ultrafilter Theorem

**lemma** *ex-max-ultrafilter*:

**fixes**  $F :: 'a\ filter$

**assumes**  $F: F \neq bot$

**shows**  $\exists U \leq F. ultrafilter\ U$

**proof** –

**let**  $?X = \{G. G \neq bot \wedge G \leq F\}$

**let**  $?R = \{(b, a). a \neq bot \wedge a \leq b \wedge b \leq F\}$



```

have bot-notin-R:  $c \in \text{Chains } ?R \implies \text{bot} \notin c$  for  $c$ 
  by (auto simp: Chains-def)

have [simp]:  $\text{Field } ?R = ?X$ 
  by (auto simp: Field-def bot-unique)

have  $\exists m \in \text{Field } ?R. \forall a \in \text{Field } ?R. (m, a) \in ?R \implies a = m$  (is  $\exists m \in ?A. ?B m$ )
proof (rule Zorns-po-lemma)
  show Partial-order  $?R$ 
    by (auto simp: partial-order-on-def preorder-on-def
      antisym-def refl-on-def trans-def Field-def bot-unique)
  show  $\exists u \in \text{Field } ?R. \forall a \in C. (a, u) \in ?R$  if  $C: C \in \text{Chains } ?R$  for  $C$ 
proof (simp, intro exI conjI ballI)
  have Inf-C:  $\text{Inf } C \neq \text{bot} \implies \text{Inf } C \leq F$  if  $C \neq \{\}$ 
    proof –
    from  $C$  that have  $\text{Inf } C = \text{bot} \iff (\exists x \in C. x = \text{bot})$ 
      unfolding trivial-limit-def by (intro eventually-Inf-base) (auto simp:
Chains-def)
    with  $C$  show  $\text{Inf } C \neq \text{bot}$ 
      by (simp add: bot-notin-R)
    from  $C$  obtain  $x$  where  $x \in C$  by auto
    with  $C$  show  $\text{Inf } C \leq F$ 
      by (auto intro!: Inf-lower2[of  $x$ ] simp: Chains-def)
    qed
  then have [simp]:  $\text{inf } F (\text{Inf } C) = (\text{if } C = \{\} \text{ then } F \text{ else } \text{Inf } C)$ 
    using  $C$  by (auto simp add: inf-absorb2)
  from  $C$  show  $\text{inf } F (\text{Inf } C) \neq \text{bot}$ 
    by (simp add: F Inf-C)
  from  $C$  show  $\text{inf } F (\text{Inf } C) \leq F$ 
    by (simp add: Chains-def Inf-C F)
  with  $C$  show  $\text{inf } F (\text{Inf } C) \leq x \wedge x \leq F$  if  $x \in C$  for  $x$ 
    using  $C$  that by (auto intro: Inf-lower simp: Chains-def)
  qed
qed
then obtain  $U$  where  $U: U \in ?A \wedge ?B U$  ..
show ?thesis
proof
  from  $U$  show  $U \leq F \wedge \text{ultrafilter } U$ 
    by (auto intro!: max-filter-ultrafilter)
qed
qed

```

### 1.3.1 Free Ultrafilters

There exists a free ultrafilter on any infinite set.

```

locale freeultrafilter = ultrafilter +
  assumes infinite: eventually  $P F \implies \text{infinite } \{x. P x\}$ 
begin

```

```

lemma finite: finite {x. P x}  $\implies \neg$  eventually P F
  by (erule contrapos-pn) (erule infinite)

lemma finite': finite {x.  $\neg P x$ }  $\implies$  eventually P F
  by (drule finite) (simp add: not-eventually frequently-eq-eventually)

lemma le-cofinite:  $F \leq$  cofinite
  by (intro filter-leI)
  (auto simp add: eventually-cofinite not-eventually frequently-eq-eventually dest!: finite)

lemma singleton:  $\neg$  eventually ( $\lambda x. x = a$ ) F
  by (rule finite) simp

lemma singleton':  $\neg$  eventually ( $(=) a$ ) F
  by (rule finite) simp

lemma ultrafilter: ultrafilter F ..

end

lemma freeultrafilter-Ex:
  assumes [simp]: infinite (UNIV :: 'a set)
  shows  $\exists U :: 'a$  filter. freeultrafilter U
proof –
  from ex-max-ultrafilter[of cofinite :: 'a filter]
  obtain U :: 'a filter where  $U \leq$  cofinite ultrafilter U
  by auto
  interpret ultrafilter U by fact
  have freeultrafilter U
  proof
  fix P
  assume eventually P U
  with proper have frequently P U
  by (rule eventually-frequently)
  then have frequently P cofinite
  using  $\langle U \leq$  cofinite  $\rangle$  by (simp add: le-filter-frequently)
  then show infinite {x. P x}
  by (simp add: frequently-cofinite)
  qed
  then show ?thesis ..
qed

end

```

## 2 Construction of Star Types Using Ultrafilters

**theory** *StarDef*

```

imports Free-Ultrafilter
begin

```

## 2.1 A Free Ultrafilter over the Naturals

```

definition FreeUltrafilterNat :: nat filter (⟨U⟩)
  where U = (SOME U. freeultrafilter U)

```

```

lemma freeultrafilter-FreeUltrafilterNat: freeultrafilter U
  unfolding FreeUltrafilterNat-def
  by (simp add: freeultrafilter-Ex someI-ex)

```

```

interpretation FreeUltrafilterNat: freeultrafilter U
  by (rule freeultrafilter-FreeUltrafilterNat)

```

## 2.2 Definition of *star* type constructor

```

definition starrel :: ((nat ⇒ 'a) × (nat ⇒ 'a)) set
  where starrel = {(X, Y). eventually (λn. X n = Y n) U}

```

```

definition star = (UNIV :: (nat ⇒ 'a) set) // starrel

```

```

typedef 'a star = star :: (nat ⇒ 'a) set set
  by (auto simp: star-def intro: quotientI)

```

```

definition star-n :: (nat ⇒ 'a) ⇒ 'a star
  where star-n X = Abs-star (starrel “ {X})

```

```

theorem star-cases [case-names star-n, cases type: star]:
  obtains X where x = star-n X
  by (cases x) (auto simp: star-n-def star-def elim: quotientE)

```

```

lemma all-star-eq: (∀ x. P x) ⟷ (∀ X. P (star-n X))
  by (metis star-cases)

```

```

lemma ex-star-eq: (∃ x. P x) ⟷ (∃ X. P (star-n X))
  by (metis star-cases)

```

Proving that *starrel* is an equivalence relation.

```

lemma starrel-iff [iff]: (X, Y) ∈ starrel ⟷ eventually (λn. X n = Y n) U
  by (simp add: starrel-def)

```

```

lemma equiv-starrel: equiv UNIV starrel

```

```

proof (rule equivI)
  show refl starrel by (simp add: refl-on-def)
  show sym starrel by (simp add: sym-def eq-commute)
  show trans starrel by (intro transI) (auto elim: eventually-elim2)
qed

```

**lemmas** *equiv-starrel-iff* = *eq-equiv-class-iff* [*OF equiv-starrel UNIV-I UNIV-I*]

**lemma** *starrel-in-star*: *starrel*“ $\{x\} \in \text{star}$ ”  
**by** (*simp add: star-def quotientI*)

**lemma** *star-n-eq-iff*: *star-n*  $X = \text{star-n } Y \iff \text{eventually } (\lambda n. X\ n = Y\ n) \mathcal{U}$   
**by** (*simp add: star-n-def Abs-star-inject starrel-in-star equiv-starrel-iff*)

### 2.3 Transfer principle

This introduction rule starts each transfer proof.

**lemma** *transfer-start*:  $P \equiv \text{eventually } (\lambda n. Q) \mathcal{U} \implies \text{Trueprop } P \equiv \text{Trueprop } Q$   
**by** (*simp add: FreeUltrafilterNat.proper*)

Standard principles that play a central role in the transfer tactic.

**definition** *Ifun* ::  $(\text{'a} \Rightarrow \text{'b}) \text{ star} \Rightarrow \text{'a star} \Rightarrow \text{'b star} \langle (- \star / -) \rangle$  [*300, 301*] *300*)  
**where** *Ifun*  $f \equiv$   
 $\lambda x. \text{Abs-star } (\bigcup F \in \text{Rep-star } f. \bigcup X \in \text{Rep-star } x. \text{starrel} \text{“}\{\lambda n. F\ n (X\ n)\}\text{”})$

**lemma** *Ifun-congruent2*: *congruent2* *starrel* *starrel*  $(\lambda F\ X. \text{starrel} \text{“}\{\lambda n. F\ n (X\ n)\}\text{”})$   
**by** (*auto simp add: congruent2-def equiv-starrel-iff elim!: eventually-rev-mp*)

**lemma** *Ifun-star-n*: *star-n*  $F \star \text{star-n } X = \text{star-n } (\lambda n. F\ n (X\ n))$   
**by** (*simp add: Ifun-def star-n-def Abs-star-inverse starrel-in-star UN-equiv-class2 [OF equiv-starrel equiv-starrel Ifun-congruent2]*)

**lemma** *transfer-Ifun*:  $f \equiv \text{star-n } F \implies x \equiv \text{star-n } X \implies f \star x \equiv \text{star-n } (\lambda n. F\ n (X\ n))$   
**by** (*simp only: Ifun-star-n*)

**definition** *star-of* ::  $\text{'a} \Rightarrow \text{'a star}$   
**where** *star-of*  $x \equiv \text{star-n } (\lambda n. x)$

Initialize transfer tactic.

**ML-file**  $\langle \text{transfer-principle.ML} \rangle$

**method-setup** *transfer* =  
 $\langle \text{Attrib.thms} \rangle \rangle (\text{fn } \text{ths} \Rightarrow \text{fn } \text{ctxt} \Rightarrow \text{SIMPLE-METHOD}' (\text{Transfer-Principle.transfer-tac } \text{ctxt } \text{ths}))$   
*transfer principle*

Transfer introduction rules.

**lemma** *transfer-ex* [*transfer-intro*]:  
 $(\bigwedge X. p (\text{star-n } X) \equiv \text{eventually } (\lambda n. P\ n (X\ n)) \mathcal{U}) \implies$   
 $\exists x :: \text{'a star}. p\ x \equiv \text{eventually } (\lambda n. \exists x. P\ n\ x) \mathcal{U}$   
**by** (*simp only: ex-star-eq eventually-ex*)

**lemma** *transfer-all* [*transfer-intro*]:

$$\begin{aligned} & (\bigwedge X. p \text{ (star-n } X) \equiv \text{eventually } (\lambda n. P n (X n)) \mathcal{U}) \implies \\ & \quad \forall x::'a \text{ star. } p x \equiv \text{eventually } (\lambda n. \forall x. P n x) \mathcal{U} \\ & \text{by (simp only: all-star-eq FreeUltrafilterNat.eventually-all-iff)} \end{aligned}$$

**lemma** *transfer-not* [*transfer-intro*]:  $p \equiv \text{eventually } P \mathcal{U} \implies \neg p \equiv \text{eventually } (\lambda n. \neg P n) \mathcal{U}$

**by** (*simp only: FreeUltrafilterNat.eventually-not-iff*)

**lemma** *transfer-conj* [*transfer-intro*]:

$$p \equiv \text{eventually } P \mathcal{U} \implies q \equiv \text{eventually } Q \mathcal{U} \implies p \wedge q \equiv \text{eventually } (\lambda n. P n \wedge Q n) \mathcal{U}$$

**by** (*simp only: eventually-conj-iff*)

**lemma** *transfer-disj* [*transfer-intro*]:

$$p \equiv \text{eventually } P \mathcal{U} \implies q \equiv \text{eventually } Q \mathcal{U} \implies p \vee q \equiv \text{eventually } (\lambda n. P n \vee Q n) \mathcal{U}$$

**by** (*simp only: FreeUltrafilterNat.eventually-disj-iff*)

**lemma** *transfer-imp* [*transfer-intro*]:

$$p \equiv \text{eventually } P \mathcal{U} \implies q \equiv \text{eventually } Q \mathcal{U} \implies p \longrightarrow q \equiv \text{eventually } (\lambda n. P n \longrightarrow Q n) \mathcal{U}$$

**by** (*simp only: FreeUltrafilterNat.eventually-imp-iff*)

**lemma** *transfer-iff* [*transfer-intro*]:

$$p \equiv \text{eventually } P \mathcal{U} \implies q \equiv \text{eventually } Q \mathcal{U} \implies p = q \equiv \text{eventually } (\lambda n. P n = Q n) \mathcal{U}$$

**by** (*simp only: FreeUltrafilterNat.eventually-iff-iff*)

**lemma** *transfer-if-bool* [*transfer-intro*]:

$$p \equiv \text{eventually } P \mathcal{U} \implies x \equiv \text{eventually } X \mathcal{U} \implies y \equiv \text{eventually } Y \mathcal{U} \implies$$

$$(if p then x else y) \equiv \text{eventually } (\lambda n. if P n then X n else Y n) \mathcal{U}$$

**by** (*simp only: if-bool-eq-conj transfer-conj transfer-imp transfer-not*)

**lemma** *transfer-eq* [*transfer-intro*]:

$$x \equiv \text{star-n } X \implies y \equiv \text{star-n } Y \implies x = y \equiv \text{eventually } (\lambda n. X n = Y n) \mathcal{U}$$

**by** (*simp only: star-n-eq-iff*)

**lemma** *transfer-if* [*transfer-intro*]:

$$p \equiv \text{eventually } (\lambda n. P n) \mathcal{U} \implies x \equiv \text{star-n } X \implies y \equiv \text{star-n } Y \implies$$

$$(if p then x else y) \equiv \text{star-n } (\lambda n. if P n then X n else Y n)$$

**by** (*rule eq-reflection*) (*auto simp: star-n-eq-iff transfer-not elim!: eventually-mono*)

**lemma** *transfer-fun-eq* [*transfer-intro*]:

$$(\bigwedge X. f \text{ (star-n } X) = g \text{ (star-n } X) \equiv \text{eventually } (\lambda n. F n (X n) = G n (X n)) \mathcal{U}) \implies$$

$$f = g \equiv \text{eventually } (\lambda n. F n = G n) \mathcal{U}$$

**by** (*simp only: fun-eq-iff transfer-all*)

**lemma** *transfer-star-n* [*transfer-intro*]:  $star\text{-}n\ X \equiv star\text{-}n\ (\lambda n. X\ n)$   
**by** (*rule reflexive*)

**lemma** *transfer-bool* [*transfer-intro*]:  $p \equiv eventually\ (\lambda n. p)\ \mathcal{U}$   
**by** (*simp add: FreeUltrafilterNat.proper*)

## 2.4 Standard elements

**definition** *Standard* :: 'a star set  
**where** *Standard* = *range star-of*

Transfer tactic should remove occurrences of *star-of*.

**setup** <*Transfer-Principle.add-const const-name* <*star-of*>>

**lemma** *star-of-inject*:  $star\text{-}of\ x = star\text{-}of\ y \longleftrightarrow x = y$   
**by** *transfer (rule refl)*

**lemma** *Standard-star-of* [*simp*]:  $star\text{-}of\ x \in Standard$   
**by** (*simp add: Standard-def*)

## 2.5 Internal functions

Transfer tactic should remove occurrences of *Ifun*.

**setup** <*Transfer-Principle.add-const const-name* <*Ifun*>>

**lemma** *Ifun-star-of* [*simp*]:  $star\text{-}of\ f \star star\text{-}of\ x = star\text{-}of\ (f\ x)$   
**by** *transfer (rule refl)*

**lemma** *Standard-Ifun* [*simp*]:  $f \in Standard \implies x \in Standard \implies f \star x \in Standard$   
**by** (*auto simp add: Standard-def*)

Nonstandard extensions of functions.

**definition** *starfun* :: ('a  $\Rightarrow$  'b)  $\Rightarrow$  'a star  $\Rightarrow$  'b star (*<f\* -> [80] 80*)  
**where** *starfun* *f*  $\equiv \lambda x. star\text{-}of\ f \star x$

**definition** *starfun2* :: ('a  $\Rightarrow$  'b  $\Rightarrow$  'c)  $\Rightarrow$  'a star  $\Rightarrow$  'b star  $\Rightarrow$  'c star (*<f2\* -> [80] 80*)  
**where** *starfun2* *f*  $\equiv \lambda x\ y. star\text{-}of\ f \star x \star y$

**declare** *starfun-def* [*transfer-unfold*]  
**declare** *starfun2-def* [*transfer-unfold*]

**lemma** *starfun-star-n*:  $(\star f) (star\text{-}n\ X) = star\text{-}n\ (\lambda n. f\ (X\ n))$   
**by** (*simp only: starfun-def star-of-def Ifun-star-n*)

**lemma** *starfun2-star-n*:  $(\star f2) (star\text{-}n\ X) (star\text{-}n\ Y) = star\text{-}n\ (\lambda n. f\ (X\ n)\ (Y\ n))$   
**by** (*simp only: starfun2-def star-of-def Ifun-star-n*)

**lemma** *starfun-star-of* [*simp*]:  $( *f* f ) ( \text{star-of } x ) = \text{star-of } ( f x )$   
**by** *transfer* (*rule refl*)

**lemma** *starfun2-star-of* [*simp*]:  $( *f2* f ) ( \text{star-of } x ) = *f* f x$   
**by** *transfer* (*rule refl*)

**lemma** *Standard-starfun* [*simp*]:  $x \in \text{Standard} \implies \text{starfun } f x \in \text{Standard}$   
**by** (*simp add: starfun-def*)

**lemma** *Standard-starfun2* [*simp*]:  $x \in \text{Standard} \implies y \in \text{Standard} \implies \text{starfun2 } f x y \in \text{Standard}$   
**by** (*simp add: starfun2-def*)

**lemma** *Standard-starfun-iff*:  
**assumes** *inj*:  $\bigwedge x y. f x = f y \implies x = y$   
**shows**  $\text{starfun } f x \in \text{Standard} \longleftrightarrow x \in \text{Standard}$   
**proof**  
**assume**  $x \in \text{Standard}$   
**then show**  $\text{starfun } f x \in \text{Standard}$  **by** *simp*  
**next**  
**from** *inj* **have** *inj'*:  $\bigwedge x y. \text{starfun } f x = \text{starfun } f y \implies x = y$   
**by** *transfer*  
**assume**  $\text{starfun } f x \in \text{Standard}$   
**then obtain** *b* **where**  $b: \text{starfun } f x = \text{star-of } b$   
**unfolding** *Standard-def* ..  
**then have**  $\exists x. \text{starfun } f x = \text{star-of } b$  ..  
**then have**  $\exists a. f a = b$  **by** *transfer*  
**then obtain** *a* **where**  $f a = b$  ..  
**then have**  $\text{starfun } f (\text{star-of } a) = \text{star-of } b$  **by** *transfer*  
**with** *b* **have**  $\text{starfun } f x = \text{starfun } f (\text{star-of } a)$  **by** *simp*  
**then have**  $x = \text{star-of } a$  **by** (*rule inj'*)  
**then show**  $x \in \text{Standard}$  **by** (*simp add: Standard-def*)  
**qed**

**lemma** *Standard-starfun2-iff*:  
**assumes** *inj*:  $\bigwedge a b a' b'. f a b = f a' b' \implies a = a' \wedge b = b'$   
**shows**  $\text{starfun2 } f x y \in \text{Standard} \longleftrightarrow x \in \text{Standard} \wedge y \in \text{Standard}$   
**proof**  
**assume**  $x \in \text{Standard} \wedge y \in \text{Standard}$   
**then show**  $\text{starfun2 } f x y \in \text{Standard}$  **by** *simp*  
**next**  
**have** *inj'*:  $\bigwedge x y z w. \text{starfun2 } f x y = \text{starfun2 } f z w \implies x = z \wedge y = w$   
**using** *inj* **by** *transfer*  
**assume**  $\text{starfun2 } f x y \in \text{Standard}$   
**then obtain** *c* **where**  $c: \text{starfun2 } f x y = \text{star-of } c$   
**unfolding** *Standard-def* ..  
**then have**  $\exists x y. \text{starfun2 } f x y = \text{star-of } c$  **by** *auto*  
**then have**  $\exists a b. f a b = c$  **by** *transfer*

**then obtain**  $a \ b$  **where**  $f \ a \ b = c$  **by** *auto*  
**then have**  $\text{starfun2 } f \ (\text{star-of } a) \ (\text{star-of } b) = \text{star-of } c$  **by** *transfer*  
**with**  $c$  **have**  $\text{starfun2 } f \ x \ y = \text{starfun2 } f \ (\text{star-of } a) \ (\text{star-of } b)$  **by** *simp*  
**then have**  $x = \text{star-of } a \ \wedge \ y = \text{star-of } b$  **by** (*rule inj'*)  
**then show**  $x \in \text{Standard} \ \wedge \ y \in \text{Standard}$  **by** (*simp add: Standard-def*)  
**qed**

## 2.6 Internal predicates

**definition**  $\text{unstar} :: \text{bool} \ \text{star} \Rightarrow \text{bool}$   
**where**  $\text{unstar } b \iff b = \text{star-of } \text{True}$

**lemma**  $\text{unstar-star-n}$ :  $\text{unstar} \ (\text{star-n } P) \iff \text{eventually } P \ \mathcal{U}$   
**by** (*simp add: unstar-def star-of-def star-n-eq-iff*)

**lemma**  $\text{unstar-star-of}$  [*simp*]:  $\text{unstar} \ (\text{star-of } p) = p$   
**by** (*simp add: unstar-def star-of-inject*)

Transfer tactic should remove occurrences of *unstar*.

**setup**  $\langle \text{Transfer-Principle.add-const } \mathbf{const-name} \ \langle \text{unstar} \rangle \rangle$

**lemma**  $\text{transfer-unstar}$  [*transfer-intro*]:  $p \equiv \text{star-n } P \implies \text{unstar } p \equiv \text{eventually } P \ \mathcal{U}$   
**by** (*simp only: unstar-star-n*)

**definition**  $\text{starP} :: ('a \Rightarrow \text{bool}) \Rightarrow 'a \ \text{star} \Rightarrow \text{bool}$  ( $\langle *p* \ \rightarrow \ [80] \ 80 \rangle$ )  
**where**  $*p* \ P = (\lambda x. \text{unstar} \ (\text{star-of } P \ \star \ x))$

**definition**  $\text{starP2} :: ('a \Rightarrow 'b \Rightarrow \text{bool}) \Rightarrow 'a \ \text{star} \Rightarrow 'b \ \text{star} \Rightarrow \text{bool}$  ( $\langle *p2* \ \rightarrow \ [80] \ 80 \rangle$ )  
**where**  $*p2* \ P = (\lambda x \ y. \text{unstar} \ (\text{star-of } P \ \star \ x \ \star \ y))$

**declare**  $\text{starP-def}$  [*transfer-unfold*]  
**declare**  $\text{starP2-def}$  [*transfer-unfold*]

**lemma**  $\text{starP-star-n}$ :  $( *p* \ P) \ (\text{star-n } X) = \text{eventually} \ (\lambda n. \ P \ (X \ n)) \ \mathcal{U}$   
**by** (*simp only: starP-def star-of-def Ifun-star-n unstar-star-n*)

**lemma**  $\text{starP2-star-n}$ :  $( *p2* \ P) \ (\text{star-n } X) \ (\text{star-n } Y) = (\text{eventually} \ (\lambda n. \ P \ (X \ n) \ (Y \ n))) \ \mathcal{U}$   
**by** (*simp only: starP2-def star-of-def Ifun-star-n unstar-star-n*)

**lemma**  $\text{starP-star-of}$  [*simp*]:  $( *p* \ P) \ (\text{star-of } x) = P \ x$   
**by** *transfer (rule refl)*

**lemma**  $\text{starP2-star-of}$  [*simp*]:  $( *p2* \ P) \ (\text{star-of } x) = *p2* \ P \ x$   
**by** *transfer (rule refl)*



## 2.7 Internal sets

**definition**  $Iset :: 'a \text{ set } \text{star} \Rightarrow 'a \text{ star set}$   
**where**  $Iset A = \{x. (*p2* (\in)) x A\}$

**lemma**  $Iset\text{-star-}n$ :  $(\text{star-}n X \in Iset (\text{star-}n A)) = (\text{eventually } (\lambda n. X n \in A n) \mathcal{U})$

**by** ( $\text{simp add: } Iset\text{-def } \text{star}P2\text{-star-}n$ )

Transfer tactic should remove occurrences of  $Iset$ .

**setup**  $\langle \text{Transfer-Principle.add-const } \mathbf{const-name} \langle Iset \rangle \rangle$

**lemma**  $\text{transfer-mem}$  [ $\text{transfer-intro}$ ]:

$x \equiv \text{star-}n X \Longrightarrow a \equiv Iset (\text{star-}n A) \Longrightarrow x \in a \equiv \text{eventually } (\lambda n. X n \in A n) \mathcal{U}$

**by** ( $\text{simp only: } Iset\text{-star-}n$ )

**lemma**  $\text{transfer-Collect}$  [ $\text{transfer-intro}$ ]:

$(\bigwedge X. p (\text{star-}n X) \equiv \text{eventually } (\lambda n. P n (X n)) \mathcal{U}) \Longrightarrow$   
 $\text{Collect } p \equiv Iset (\text{star-}n (\lambda n. \text{Collect } (P n)))$

**by** ( $\text{simp add: } \text{atomize-eq } \text{set-eq-iff } \text{all-star-eq } Iset\text{-star-}n$ )

**lemma**  $\text{transfer-set-eq}$  [ $\text{transfer-intro}$ ]:

$a \equiv Iset (\text{star-}n A) \Longrightarrow b \equiv Iset (\text{star-}n B) \Longrightarrow a = b \equiv \text{eventually } (\lambda n. A n = B n) \mathcal{U}$

**by** ( $\text{simp only: } \text{set-eq-iff } \text{transfer-all } \text{transfer-iff } \text{transfer-mem}$ )

**lemma**  $\text{transfer-ball}$  [ $\text{transfer-intro}$ ]:

$a \equiv Iset (\text{star-}n A) \Longrightarrow (\bigwedge X. p (\text{star-}n X) \equiv \text{eventually } (\lambda n. P n (X n)) \mathcal{U}) \Longrightarrow$   
 $\forall x \in a. p x \equiv \text{eventually } (\lambda n. \forall x \in A n. P n x) \mathcal{U}$

**by** ( $\text{simp only: } \text{Ball-def } \text{transfer-all } \text{transfer-imp } \text{transfer-mem}$ )

**lemma**  $\text{transfer-bex}$  [ $\text{transfer-intro}$ ]:

$a \equiv Iset (\text{star-}n A) \Longrightarrow (\bigwedge X. p (\text{star-}n X) \equiv \text{eventually } (\lambda n. P n (X n)) \mathcal{U}) \Longrightarrow$   
 $\exists x \in a. p x \equiv \text{eventually } (\lambda n. \exists x \in A n. P n x) \mathcal{U}$

**by** ( $\text{simp only: } \text{Bex-def } \text{transfer-ex } \text{transfer-conj } \text{transfer-mem}$ )

**lemma**  $\text{transfer-Iset}$  [ $\text{transfer-intro}$ ]:  $a \equiv \text{star-}n A \Longrightarrow Iset a \equiv Iset (\text{star-}n (\lambda n. A n))$

**by**  $\text{simp}$

Nonstandard extensions of sets.

**definition**  $\text{starset} :: 'a \text{ set} \Rightarrow 'a \text{ star set}$  ( $\langle *s* \rightarrow [80] 80$ )

**where**  $\text{starset } A = Iset (\text{star-of } A)$

**declare**  $\text{starset-def}$  [ $\text{transfer-unfold}$ ]

**lemma**  $\text{starset-mem}$ :  $\text{star-of } x \in *s* A \longleftrightarrow x \in A$

**by**  $\text{transfer (rule refl)}$

**lemma** *starset-UNIV*:  $*s* (UNIV::'a set) = (UNIV::'a star set)$   
**by** (*transfer UNIV-def*) (*rule refl*)

**lemma** *starset-empty*:  $*s* \{\} = \{\}$   
**by** (*transfer empty-def*) (*rule refl*)

**lemma** *starset-insert*:  $*s* (insert x A) = insert (star-of x) (*s* A)$   
**by** (*transfer insert-def Un-def*) (*rule refl*)

**lemma** *starset-Un*:  $*s* (A \cup B) = *s* A \cup *s* B$   
**by** (*transfer Un-def*) (*rule refl*)

**lemma** *starset-Int*:  $*s* (A \cap B) = *s* A \cap *s* B$   
**by** (*transfer Int-def*) (*rule refl*)

**lemma** *starset-Compl*:  $*s* -A = -( *s* A)$   
**by** (*transfer Compl-eq*) (*rule refl*)

**lemma** *starset-diff*:  $*s* (A - B) = *s* A - *s* B$   
**by** (*transfer set-diff-eq*) (*rule refl*)

**lemma** *starset-image*:  $*s* (f ` A) = (*f* f) ` (*s* A)$   
**by** (*transfer image-def*) (*rule refl*)

**lemma** *starset-vimage*:  $*s* (f -` A) = (*f* f) -` (*s* A)$   
**by** (*transfer vimage-def*) (*rule refl*)

**lemma** *starset-subset*:  $(*s* A \subseteq *s* B) \longleftrightarrow A \subseteq B$   
**by** (*transfer subset-eq*) (*rule refl*)

**lemma** *starset-eq*:  $(*s* A = *s* B) \longleftrightarrow A = B$   
**by** *transfer* (*rule refl*)

**lemmas** *starset-simps* [*simp*] =  
*starset-mem starset-UNIV*  
*starset-empty starset-insert*  
*starset-Un starset-Int*  
*starset-Compl starset-diff*  
*starset-image starset-vimage*  
*starset-subset starset-eq*

## 2.8 Syntactic classes

**instantiation** *star* :: (*zero*) *zero*

**begin**

**definition** *star-zero-def*:  $0 \equiv star-of 0$

**instance** ..

**end**

```

instantiation star :: (one) one
begin
  definition star-one-def:  $1 \equiv \text{star-of } 1$ 
  instance ..
end

instantiation star :: (plus) plus
begin
  definition star-add-def:  $(+) \equiv \text{*f2* } (+)$ 
  instance ..
end

instantiation star :: (times) times
begin
  definition star-mult-def:  $((*)) \equiv \text{*f2* } ((*))$ 
  instance ..
end

instantiation star :: (uminus) uminus
begin
  definition star-minus-def: uminus  $\equiv \text{*f* } \text{uminus}$ 
  instance ..
end

instantiation star :: (minus) minus
begin
  definition star-diff-def:  $(-) \equiv \text{*f2* } (-)$ 
  instance ..
end

instantiation star :: (abs) abs
begin
  definition star-abs-def: abs  $\equiv \text{*f* } \text{abs}$ 
  instance ..
end

instantiation star :: (sgn) sgn
begin
  definition star-sgn-def: sgn  $\equiv \text{*f* } \text{sgn}$ 
  instance ..
end

instantiation star :: (divide) divide
begin
  definition star-divide-def: divide  $\equiv \text{*f2* } \text{divide}$ 
  instance ..
end

instantiation star :: (inverse) inverse

```

```

begin
  definition star-inverse-def: inverse  $\equiv$  *f* inverse
  instance ..
end

instance star :: (Rings.dvd) Rings.dvd ..

instantiation star :: (modulo) modulo
begin
  definition star-mod-def: (mod)  $\equiv$  *f2* (mod)
  instance ..
end

instantiation star :: (ord) ord
begin
  definition star-le-def: ( $\leq$ )  $\equiv$  *p2* ( $\leq$ )
  definition star-less-def: (<)  $\equiv$  *p2* (<)
  instance ..
end

lemmas star-class-defs [transfer-unfold] =
  star-zero-def   star-one-def
  star-add-def   star-diff-def   star-minus-def
  star-mult-def  star-divide-def  star-inverse-def
  star-le-def    star-less-def   star-abs-def   star-sgn-def
  star-mod-def

Class operations preserve standard elements.

lemma Standard-zero: 0  $\in$  Standard
  by (simp add: star-zero-def)

lemma Standard-one: 1  $\in$  Standard
  by (simp add: star-one-def)

lemma Standard-add: x  $\in$  Standard  $\implies$  y  $\in$  Standard  $\implies$  x + y  $\in$  Standard
  by (simp add: star-add-def)

lemma Standard-diff: x  $\in$  Standard  $\implies$  y  $\in$  Standard  $\implies$  x - y  $\in$  Standard
  by (simp add: star-diff-def)

lemma Standard-minus: x  $\in$  Standard  $\implies$  - x  $\in$  Standard
  by (simp add: star-minus-def)

lemma Standard-mult: x  $\in$  Standard  $\implies$  y  $\in$  Standard  $\implies$  x * y  $\in$  Standard
  by (simp add: star-mult-def)

lemma Standard-divide: x  $\in$  Standard  $\implies$  y  $\in$  Standard  $\implies$  x / y  $\in$  Standard
  by (simp add: star-divide-def)

```

**lemma** *Standard-inverse*:  $x \in \text{Standard} \implies \text{inverse } x \in \text{Standard}$   
**by** (*simp add: star-inverse-def*)

**lemma** *Standard-abs*:  $x \in \text{Standard} \implies |x| \in \text{Standard}$   
**by** (*simp add: star-abs-def*)

**lemma** *Standard-mod*:  $x \in \text{Standard} \implies y \in \text{Standard} \implies x \text{ mod } y \in \text{Standard}$   
**by** (*simp add: star-mod-def*)

**lemmas** *Standard-simps* [*simp*] =  
*Standard-zero Standard-one*  
*Standard-add Standard-diff Standard-minus*  
*Standard-mult Standard-divide Standard-inverse*  
*Standard-abs Standard-mod*

*star-of* preserves class operations.

**lemma** *star-of-add*:  $\text{star-of } (x + y) = \text{star-of } x + \text{star-of } y$   
**by** *transfer (rule refl)*

**lemma** *star-of-diff*:  $\text{star-of } (x - y) = \text{star-of } x - \text{star-of } y$   
**by** *transfer (rule refl)*

**lemma** *star-of-minus*:  $\text{star-of } (-x) = - \text{star-of } x$   
**by** *transfer (rule refl)*

**lemma** *star-of-mult*:  $\text{star-of } (x * y) = \text{star-of } x * \text{star-of } y$   
**by** *transfer (rule refl)*

**lemma** *star-of-divide*:  $\text{star-of } (x / y) = \text{star-of } x / \text{star-of } y$   
**by** *transfer (rule refl)*

**lemma** *star-of-inverse*:  $\text{star-of } (\text{inverse } x) = \text{inverse } (\text{star-of } x)$   
**by** *transfer (rule refl)*

**lemma** *star-of-mod*:  $\text{star-of } (x \text{ mod } y) = \text{star-of } x \text{ mod } \text{star-of } y$   
**by** *transfer (rule refl)*

**lemma** *star-of-abs*:  $\text{star-of } |x| = |\text{star-of } x|$   
**by** *transfer (rule refl)*

*star-of* preserves numerals.

**lemma** *star-of-zero*:  $\text{star-of } 0 = 0$   
**by** *transfer (rule refl)*

**lemma** *star-of-one*:  $\text{star-of } 1 = 1$   
**by** *transfer (rule refl)*

*star-of* preserves orderings.

**lemma** *star-of-less*:  $(\text{star-of } x < \text{star-of } y) = (x < y)$

by *transfer* (rule *refl*)

**lemma** *star-of-le*:  $(\text{star-of } x \leq \text{star-of } y) = (x \leq y)$   
by *transfer* (rule *refl*)

**lemma** *star-of-eq*:  $(\text{star-of } x = \text{star-of } y) = (x = y)$   
by *transfer* (rule *refl*)

As above, for 0.

**lemmas** *star-of-0-less* = *star-of-less* [*of 0, simplified star-of-zero*]

**lemmas** *star-of-0-le* = *star-of-le* [*of 0, simplified star-of-zero*]

**lemmas** *star-of-0-eq* = *star-of-eq* [*of 0, simplified star-of-zero*]

**lemmas** *star-of-less-0* = *star-of-less* [*of - 0, simplified star-of-zero*]

**lemmas** *star-of-le-0* = *star-of-le* [*of - 0, simplified star-of-zero*]

**lemmas** *star-of-eq-0* = *star-of-eq* [*of - 0, simplified star-of-zero*]

As above, for 1.

**lemmas** *star-of-1-less* = *star-of-less* [*of 1, simplified star-of-one*]

**lemmas** *star-of-1-le* = *star-of-le* [*of 1, simplified star-of-one*]

**lemmas** *star-of-1-eq* = *star-of-eq* [*of 1, simplified star-of-one*]

**lemmas** *star-of-less-1* = *star-of-less* [*of - 1, simplified star-of-one*]

**lemmas** *star-of-le-1* = *star-of-le* [*of - 1, simplified star-of-one*]

**lemmas** *star-of-eq-1* = *star-of-eq* [*of - 1, simplified star-of-one*]

**lemmas** *star-of-simps* [*simp*] =  
*star-of-add*   *star-of-diff*   *star-of-minus*  
*star-of-mult*   *star-of-divide*   *star-of-inverse*  
*star-of-mod*   *star-of-abs*  
*star-of-zero*   *star-of-one*  
*star-of-less*   *star-of-le*   *star-of-eq*  
*star-of-0-less*   *star-of-0-le*   *star-of-0-eq*  
*star-of-less-0*   *star-of-le-0*   *star-of-eq-0*  
*star-of-1-less*   *star-of-1-le*   *star-of-1-eq*  
*star-of-less-1*   *star-of-le-1*   *star-of-eq-1*

## 2.9 Ordering and lattice classes

**instance** *star* :: (order) order

**proof**

**show**  $\bigwedge x y :: 'a \text{ star. } (x < y) = (x \leq y \wedge \neg y \leq x)$

by *transfer* (rule *less-le-not-le*)

**show**  $\bigwedge x :: 'a \text{ star. } x \leq x$

by *transfer* (rule *order-refl*)

**show**  $\bigwedge x y z :: 'a \text{ star. } \llbracket x \leq y; y \leq z \rrbracket \implies x \leq z$

by *transfer* (rule *order-trans*)

**show**  $\bigwedge x y :: 'a \text{ star. } \llbracket x \leq y; y \leq x \rrbracket \implies x = y$

by *transfer* (rule *order-antisym*)

qed

**instantiation** *star* :: (*semilattice-inf*) *semilattice-inf*  
**begin**  
  **definition** *star-inf-def* [*transfer-unfold*]:  $inf \equiv *f2* inf$   
  **instance** by (*standard*; *transfer*) *auto*  
**end**

**instantiation** *star* :: (*semilattice-sup*) *semilattice-sup*  
**begin**  
  **definition** *star-sup-def* [*transfer-unfold*]:  $sup \equiv *f2* sup$   
  **instance** by (*standard*; *transfer*) *auto*  
**end**

**instance** *star* :: (*lattice*) *lattice* ..

**instance** *star* :: (*distrib-lattice*) *distrib-lattice*  
  by (*standard*; *transfer*) (*auto simp add: sup-inf-distrib1*)

**lemma** *Standard-inf* [*simp*]:  $x \in Standard \implies y \in Standard \implies inf\ x\ y \in Standard$   
  by (*simp add: star-inf-def*)

**lemma** *Standard-sup* [*simp*]:  $x \in Standard \implies y \in Standard \implies sup\ x\ y \in Standard$   
  by (*simp add: star-sup-def*)

**lemma** *star-of-inf* [*simp*]:  $star-of\ (inf\ x\ y) = inf\ (star-of\ x)\ (star-of\ y)$   
  by *transfer (rule refl)*

**lemma** *star-of-sup* [*simp*]:  $star-of\ (sup\ x\ y) = sup\ (star-of\ x)\ (star-of\ y)$   
  by *transfer (rule refl)*

**instance** *star* :: (*linorder*) *linorder*  
  by (*intro-classes, transfer, rule linorder-linear*)

**lemma** *star-max-def* [*transfer-unfold*]:  $max = *f2* max$   
  **unfolding** *max-def*  
  by (*intro ext, transfer, simp*)

**lemma** *star-min-def* [*transfer-unfold*]:  $min = *f2* min$   
  **unfolding** *min-def*  
  by (*intro ext, transfer, simp*)

**lemma** *Standard-max* [*simp*]:  $x \in Standard \implies y \in Standard \implies max\ x\ y \in Standard$   
  by (*simp add: star-max-def*)

**lemma** *Standard-min* [*simp*]:  $x \in Standard \implies y \in Standard \implies min\ x\ y \in Standard$

by (*simp add: star-min-def*)

**lemma** *star-of-max* [*simp*]: *star-of* (*max* *x* *y*) = *max* (*star-of* *x*) (*star-of* *y*)  
by *transfer* (*rule refl*)

**lemma** *star-of-min* [*simp*]: *star-of* (*min* *x* *y*) = *min* (*star-of* *x*) (*star-of* *y*)  
by *transfer* (*rule refl*)

## 2.10 Ordered group classes

**instance** *star* :: (*semigroup-add*) *semigroup-add*  
by (*intro-classes, transfer, rule add.assoc*)

**instance** *star* :: (*ab-semigroup-add*) *ab-semigroup-add*  
by (*intro-classes, transfer, rule add.commute*)

**instance** *star* :: (*semigroup-mult*) *semigroup-mult*  
by (*intro-classes, transfer, rule mult.assoc*)

**instance** *star* :: (*ab-semigroup-mult*) *ab-semigroup-mult*  
by (*intro-classes, transfer, rule mult.commute*)

**instance** *star* :: (*comm-monoid-add*) *comm-monoid-add*  
by (*intro-classes, transfer, rule comm-monoid-add-class.add-0*)

**instance** *star* :: (*monoid-mult*) *monoid-mult*  
apply *intro-classes*  
  apply (*transfer, rule mult-1-left*)  
  apply (*transfer, rule mult-1-right*)  
done

**instance** *star* :: (*power*) *power* ..

**instance** *star* :: (*comm-monoid-mult*) *comm-monoid-mult*  
by (*intro-classes, transfer, rule mult-1*)

**instance** *star* :: (*cancel-semigroup-add*) *cancel-semigroup-add*  
apply *intro-classes*  
  apply (*transfer, erule add-left-imp-eq*)  
  apply (*transfer, erule add-right-imp-eq*)  
done

**instance** *star* :: (*cancel-ab-semigroup-add*) *cancel-ab-semigroup-add*  
by *intro-classes* (*transfer, simp add: diff-diff-eq*)+

**instance** *star* :: (*cancel-comm-monoid-add*) *cancel-comm-monoid-add* ..

**instance** *star* :: (*ab-group-add*) *ab-group-add*  
apply *intro-classes*



```

apply (transfer, rule left-minus)
apply (transfer, rule diff-conv-add-uminus)
done

instance star :: (ordered-ab-semigroup-add) ordered-ab-semigroup-add
  by (intro-classes, transfer, rule add-left-mono)

instance star :: (ordered-cancel-ab-semigroup-add) ordered-cancel-ab-semigroup-add
..

instance star :: (ordered-ab-semigroup-add-imp-le) ordered-ab-semigroup-add-imp-le
  by (intro-classes, transfer, rule add-le-imp-le-left)

instance star :: (ordered-comm-monoid-add) ordered-comm-monoid-add ..
instance star :: (ordered-ab-semigroup-monoid-add-imp-le) ordered-ab-semigroup-monoid-add-imp-le
..
instance star :: (ordered-cancel-comm-monoid-add) ordered-cancel-comm-monoid-add
..
instance star :: (ordered-ab-group-add) ordered-ab-group-add ..

instance star :: (ordered-ab-group-add-abs) ordered-ab-group-add-abs
  by intro-classes (transfer, simp add: abs-ge-self abs-leI abs-triangle-ineq)+

instance star :: (linordered-cancel-ab-semigroup-add) linordered-cancel-ab-semigroup-add
..

2.11 Ring and field classes

instance star :: (semiring) semiring
  by (intro-classes; transfer) (fact distrib-right distrib-left)+

instance star :: (semiring-0) semiring-0
  by (intro-classes; transfer) simp-all

instance star :: (semiring-0-cancel) semiring-0-cancel ..

instance star :: (comm-semiring) comm-semiring
  by (intro-classes; transfer) (fact distrib-right)

instance star :: (comm-semiring-0) comm-semiring-0 ..
instance star :: (comm-semiring-0-cancel) comm-semiring-0-cancel ..

instance star :: (zero-neq-one) zero-neq-one
  by (intro-classes; transfer) (fact zero-neq-one)

instance star :: (semiring-1) semiring-1 ..
instance star :: (comm-semiring-1) comm-semiring-1 ..

declare dvd-def [transfer-refold]

```

```

instance star :: (comm-semiring-1-cancel) comm-semiring-1-cancel
  by (intro-classes; transfer) (fact right-diff-distrib')

instance star :: (semiring-no-zero-divisors) semiring-no-zero-divisors
  by (intro-classes; transfer) (fact no-zero-divisors)

instance star :: (semiring-1-no-zero-divisors) semiring-1-no-zero-divisors ..

instance star :: (semiring-no-zero-divisors-cancel) semiring-no-zero-divisors-cancel
  by (intro-classes; transfer) simp-all

instance star :: (semiring-1-cancel) semiring-1-cancel ..
instance star :: (ring) ring ..
instance star :: (comm-ring) comm-ring ..
instance star :: (ring-1) ring-1 ..
instance star :: (comm-ring-1) comm-ring-1 ..
instance star :: (semidom) semidom ..

instance star :: (semidom-divide) semidom-divide
  by (intro-classes; transfer) simp-all

instance star :: (ring-no-zero-divisors) ring-no-zero-divisors ..
instance star :: (ring-1-no-zero-divisors) ring-1-no-zero-divisors ..
instance star :: (idom) idom ..
instance star :: (idom-divide) idom-divide ..

instance star :: (division-ring) division-ring
  by (intro-classes; transfer) (simp-all add: divide-inverse)

instance star :: (field) field
  by (intro-classes; transfer) (simp-all add: divide-inverse)

instance star :: (ordered-semiring) ordered-semiring
  by (intro-classes; transfer) (fact mult-left-mono mult-right-mono)+

instance star :: (ordered-cancel-semiring) ordered-cancel-semiring ..

instance star :: (linordered-semiring-strict) linordered-semiring-strict
  by (intro-classes; transfer) (fact mult-strict-left-mono mult-strict-right-mono)+

instance star :: (ordered-comm-semiring) ordered-comm-semiring
  by (intro-classes; transfer) (fact mult-left-mono)

instance star :: (ordered-cancel-comm-semiring) ordered-cancel-comm-semiring ..

instance star :: (linordered-comm-semiring-strict) linordered-comm-semiring-strict
  by (intro-classes; transfer) (fact mult-strict-left-mono)

```

```

instance star :: (ordered-ring) ordered-ring ..

instance star :: (ordered-ring-abs) ordered-ring-abs
  by (intro-classes; transfer) (fact abs-eq-mult)

instance star :: (abs-if) abs-if
  by (intro-classes; transfer) (fact abs-if)

instance star :: (linordered-ring-strict) linordered-ring-strict ..
instance star :: (ordered-comm-ring) ordered-comm-ring ..

instance star :: (linordered-semidom) linordered-semidom
  by (intro-classes; transfer) (fact zero-less-one le-add-diff-inverse2)+

instance star :: (linordered-idom) linordered-idom
  by (intro-classes; transfer) (fact sgn-if)

instance star :: (linordered-field) linordered-field ..

instance star :: (algebraic-semidom) algebraic-semidom ..

instantiation star :: (normalization-semidom) normalization-semidom
begin

definition unit-factor-star :: 'a star  $\Rightarrow$  'a star
  where [transfer-unfold]: unit-factor-star = *f* unit-factor

definition normalize-star :: 'a star  $\Rightarrow$  'a star
  where [transfer-unfold]: normalize-star = *f* normalize

instance
  by standard (transfer; simp add: is-unit-unit-factor unit-factor-mult)+

end

instance star :: (semidom-modulo) semidom-modulo
  by standard (transfer; simp)

```

## 2.12 Power

```

lemma star-power-def [transfer-unfold]: ( $\wedge$ )  $\equiv$   $\lambda x n. ( *f* (\lambda x. x \wedge n)) x$ 
proof (rule eq-reflection, rule ext, rule ext)
  show  $x \wedge n = ( *f* (\lambda x. x \wedge n)) x$  for  $n :: \text{nat}$  and  $x :: 'a \text{ star}$ 
  proof (induct n arbitrary: x)
    case 0
    have  $\bigwedge x :: 'a \text{ star}. ( *f* (\lambda x. 1)) x = 1$ 
      by transfer simp
    then show ?case by simp
  next

```

```

case (Suc n)
have  $\bigwedge x::'a$  star.  $x * (*f* (\lambda x::'a. x \wedge n)) x = (*f* (\lambda x::'a. x * x \wedge n)) x$ 
  by transfer simp
with Suc show ?case by simp
qed
qed

```

**lemma** *Standard-power* [simp]:  $x \in \text{Standard} \implies x \wedge n \in \text{Standard}$   
**by** (simp add: star-power-def)

**lemma** *star-of-power* [simp]:  $\text{star-of } (x \wedge n) = \text{star-of } x \wedge n$   
**by** transfer (rule refl)

## 2.13 Number classes

**instance** star :: (numeral) numeral ..

**lemma** *star-numeral-def* [transfer-unfold]: numeral  $k = \text{star-of } (\text{numeral } k)$   
**by** (induct k) (simp-all only: numeral.simps star-of-one star-of-add)

**lemma** *Standard-numeral* [simp]: numeral  $k \in \text{Standard}$   
**by** (simp add: star-numeral-def)

**lemma** *star-of-numeral* [simp]:  $\text{star-of } (\text{numeral } k) = \text{numeral } k$   
**by** transfer (rule refl)

**lemma** *star-of-nat-def* [transfer-unfold]:  $\text{of-nat } n = \text{star-of } (\text{of-nat } n)$   
**by** (induct n) simp-all

**lemmas** *star-of-compare-numeral* [simp] =  
 star-of-less [of numeral k, simplified star-of-numeral]  
 star-of-le [of numeral k, simplified star-of-numeral]  
 star-of-eq [of numeral k, simplified star-of-numeral]  
 star-of-less [of - numeral k, simplified star-of-numeral]  
 star-of-le [of - numeral k, simplified star-of-numeral]  
 star-of-eq [of - numeral k, simplified star-of-numeral]  
 star-of-less [of - numeral k, simplified star-of-numeral]  
 star-of-le [of - numeral k, simplified star-of-numeral]  
 star-of-eq [of - numeral k, simplified star-of-numeral]  
 star-of-less [of - numeral k, simplified star-of-numeral]  
 star-of-le [of - numeral k, simplified star-of-numeral]  
 star-of-eq [of - numeral k, simplified star-of-numeral] **for** k

**lemma** *Standard-of-nat* [simp]:  $\text{of-nat } n \in \text{Standard}$   
**by** (simp add: star-of-nat-def)

**lemma** *star-of-of-nat* [simp]:  $\text{star-of } (\text{of-nat } n) = \text{of-nat } n$   
**by** transfer (rule refl)

**lemma** *star-of-int-def* [*transfer-unfold*]:  $of\text{-}int\ z = star\text{-}of\ (of\text{-}int\ z)$   
**by** (*rule int-diff-cases* [*of z*]) *simp*

**lemma** *Standard-of-int* [*simp*]:  $of\text{-}int\ z \in Standard$   
**by** (*simp add: star-of-int-def*)

**lemma** *star-of-of-int* [*simp*]:  $star\text{-}of\ (of\text{-}int\ z) = of\text{-}int\ z$   
**by** *transfer* (*rule refl*)

**instance** *star* :: (*semiring-char-0*) *semiring-char-0*

**proof**

**have** *inj* (*star-of* ::  $'a \Rightarrow 'a\ star$ )

**by** (*rule injI*) *simp*

**then have** *inj* ( $star\text{-}of \circ of\text{-}nat :: nat \Rightarrow 'a\ star$ )

**using** *inj-of-nat* **by** (*rule inj-compose*)

**then show** *inj* ( $of\text{-}nat :: nat \Rightarrow 'a\ star$ )

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

**qed**

**instance** *star* :: (*ring-char-0*) *ring-char-0* ..

## 2.14 Finite class

**lemma** *starset-finite*:  $finite\ A \Longrightarrow *s* A = star\text{-}of\ 'A$   
**by** (*erule finite-induct*) *simp-all*

**instance** *star* :: (*finite*) *finite*

**proof** *intro-classes*

**show** *finite* ( $UNIV :: 'a\ star\ set$ )

**by** (*metis starset-UNIV finite finite-imageI starset-finite*)

**qed**

**end**

## 3 Hypernatural numbers

**theory** *HyperNat*

**imports** *StarDef*

**begin**

**type-synonym** *hypnat* = *nat star*

**abbreviation** *hypnat-of-nat* ::  $nat \Rightarrow nat\ star$

**where**  $hypnat\text{-}of\text{-}nat \equiv star\text{-}of$

**definition** *hSuc* ::  $hypnat \Rightarrow hypnat$

**where** *hSuc-def* [*transfer-unfold*]:  $hSuc = *f* Suc$

### 3.1 Properties Transferred from Naturals

**lemma** *hSuc-not-zero* [iff]:  $\bigwedge m. \text{hSuc } m \neq 0$   
 by *transfer* (rule *Suc-not-Zero*)

**lemma** *zero-not-hSuc* [iff]:  $\bigwedge m. 0 \neq \text{hSuc } m$   
 by *transfer* (rule *Zero-not-Suc*)

**lemma** *hSuc-hSuc-eq* [iff]:  $\bigwedge m n. \text{hSuc } m = \text{hSuc } n \longleftrightarrow m = n$   
 by *transfer* (rule *nat.inject*)

**lemma** *zero-less-hSuc* [iff]:  $\bigwedge n. 0 < \text{hSuc } n$   
 by *transfer* (rule *zero-less-Suc*)

**lemma** *hypnat-minus-zero* [simp]:  $\bigwedge z::\text{hypnat}. z - z = 0$   
 by *transfer* (rule *diff-self-eq-0*)

**lemma** *hypnat-diff-0-eq-0* [simp]:  $\bigwedge n::\text{hypnat}. 0 - n = 0$   
 by *transfer* (rule *diff-0-eq-0*)

**lemma** *hypnat-add-is-0* [iff]:  $\bigwedge m n::\text{hypnat}. m + n = 0 \longleftrightarrow m = 0 \wedge n = 0$   
 by *transfer* (rule *add-is-0*)

**lemma** *hypnat-diff-diff-left*:  $\bigwedge i j k::\text{hypnat}. i - j - k = i - (j + k)$   
 by *transfer* (rule *diff-diff-left*)

**lemma** *hypnat-diff-commute*:  $\bigwedge i j k::\text{hypnat}. i - j - k = i - k - j$   
 by *transfer* (rule *diff-commute*)

**lemma** *hypnat-diff-add-inverse* [simp]:  $\bigwedge m n::\text{hypnat}. n + m - n = m$   
 by *transfer* (rule *diff-add-inverse*)

**lemma** *hypnat-diff-add-inverse2* [simp]:  $\bigwedge m n::\text{hypnat}. m + n - n = m$   
 by *transfer* (rule *diff-add-inverse2*)

**lemma** *hypnat-diff-cancel* [simp]:  $\bigwedge k m n::\text{hypnat}. (k + m) - (k + n) = m - n$   
 by *transfer* (rule *diff-cancel*)

**lemma** *hypnat-diff-cancel2* [simp]:  $\bigwedge k m n::\text{hypnat}. (m + k) - (n + k) = m - n$   
 by *transfer* (rule *diff-cancel2*)

**lemma** *hypnat-diff-add-0* [simp]:  $\bigwedge m n::\text{hypnat}. n - (n + m) = 0$   
 by *transfer* (rule *diff-add-0*)

**lemma** *hypnat-diff-mult-distrib*:  $\bigwedge k m n::\text{hypnat}. (m - n) * k = (m * k) - (n * k)$   
 by *transfer* (rule *diff-mult-distrib*)

**lemma** *hypnat-diff-mult-distrib2*:  $\bigwedge k m n::\text{hypnat}. k * (m - n) = (k * m) - (k * n)$

by *transfer* (rule *diff-mult-distrib2*)

**lemma** *hypnat-le-zero-cancel* [*iff*]:  $\bigwedge n::\text{hypnat}. n \leq 0 \longleftrightarrow n = 0$   
by *transfer* (rule *le-0-eq*)

**lemma** *hypnat-mult-is-0* [*simp*]:  $\bigwedge m n::\text{hypnat}. m * n = 0 \longleftrightarrow m = 0 \vee n = 0$   
by *transfer* (rule *mult-is-0*)

**lemma** *hypnat-diff-is-0-eq* [*simp*]:  $\bigwedge m n::\text{hypnat}. m - n = 0 \longleftrightarrow m \leq n$   
by *transfer* (rule *diff-is-0-eq*)

**lemma** *hypnat-not-less0* [*iff*]:  $\bigwedge n::\text{hypnat}. \neg n < 0$   
by *transfer* (rule *not-less0*)

**lemma** *hypnat-less-one* [*iff*]:  $\bigwedge n::\text{hypnat}. n < 1 \longleftrightarrow n = 0$   
by *transfer* (rule *less-one*)

**lemma** *hypnat-add-diff-inverse*:  $\bigwedge m n::\text{hypnat}. \neg m < n \implies n + (m - n) = m$   
by *transfer* (rule *add-diff-inverse*)

**lemma** *hypnat-le-add-diff-inverse* [*simp*]:  $\bigwedge m n::\text{hypnat}. n \leq m \implies n + (m - n) = m$   
by *transfer* (rule *le-add-diff-inverse*)

**lemma** *hypnat-le-add-diff-inverse2* [*simp*]:  $\bigwedge m n::\text{hypnat}. n \leq m \implies (m - n) + n = m$   
by *transfer* (rule *le-add-diff-inverse2*)

**declare** *hypnat-le-add-diff-inverse2* [*OF order-less-imp-le*]

**lemma** *hypnat-le0* [*iff*]:  $\bigwedge n::\text{hypnat}. 0 \leq n$   
by *transfer* (rule *le0*)

**lemma** *hypnat-le-add1* [*simp*]:  $\bigwedge x n::\text{hypnat}. x \leq x + n$   
by *transfer* (rule *le-add1*)

**lemma** *hypnat-add-self-le* [*simp*]:  $\bigwedge x n::\text{hypnat}. x \leq n + x$   
by *transfer* (rule *le-add2*)

**lemma** *hypnat-add-one-self-less* [*simp*]:  $x < x + 1$  **for**  $x :: \text{hypnat}$   
by (*fact less-add-one*)

**lemma** *hypnat-neq0-conv* [*iff*]:  $\bigwedge n::\text{hypnat}. n \neq 0 \longleftrightarrow 0 < n$   
by *transfer* (rule *neq0-conv*)

**lemma** *hypnat-gt-zero-iff*:  $0 < n \longleftrightarrow 1 \leq n$  **for**  $n :: \text{hypnat}$   
by (*auto simp add: linorder-not-less [symmetric]*)

**lemma** *hypnat-gt-zero-iff2*:  $0 < n \longleftrightarrow (\exists m. n = m + 1)$  **for**  $n :: \text{hypnat}$

by (auto intro!: add-nonneg-pos exI[of - n - 1] simp: hypnat-gt-zero-iff)

**lemma** hypnat-add-self-not-less:  $\neg x + y < x$  for  $x y :: \text{hypnat}$   
 by (simp add: linorder-not-le [symmetric] add commute [of x])

**lemma** hypnat-diff-split:  $P (a - b) \longleftrightarrow (a < b \longrightarrow P 0) \wedge (\forall d. a = b + d \longrightarrow P d)$

for  $a b :: \text{hypnat}$   
 — elimination of  $-$  on  $\text{hypnat}$

**proof** (cases  $a < b$  rule: case-split)

case True

then show ?thesis

by (auto simp add: hypnat-add-self-not-less order-less-imp-le hypnat-diff-is-0-eq [THEN iffD2])

next

case False

then show ?thesis

by (auto simp add: linorder-not-less dest: order-le-less-trans)

qed

### 3.2 Properties of the set of embedded natural numbers

**lemma** of-nat-eq-star-of [simp]:  $\text{of-nat} = \text{star-of}$

**proof**

show  $\text{of-nat } n = \text{star-of } n$  for  $n$

by transfer simp

qed

**lemma** Nats-eq-Standard:  $(\text{Nats} :: \text{nat star set}) = \text{Standard}$

by (auto simp: Nats-def Standard-def)

**lemma** hypnat-of-nat-mem-Nats [simp]:  $\text{hypnat-of-nat } n \in \text{Nats}$

by (simp add: Nats-eq-Standard)

**lemma** hypnat-of-nat-one [simp]:  $\text{hypnat-of-nat } (\text{Suc } 0) = 1$

by transfer simp

**lemma** hypnat-of-nat-Suc [simp]:  $\text{hypnat-of-nat } (\text{Suc } n) = \text{hypnat-of-nat } n + 1$

by transfer simp

**lemma** of-nat-eq-add:

fixes  $d :: \text{hypnat}$

shows  $\text{of-nat } m = \text{of-nat } n + d \implies d \in \text{range of-nat}$

**proof** (induct  $n$  arbitrary:  $d$ )

case (Suc  $n$ )

then show ?case

by (metis Nats-def Nats-eq-Standard Standard-simps(4) hypnat-diff-add-inverse of-nat-in-Nats)

qed auto



**lemma** *Nats-diff* [*simp*]:  $a \in \text{Nats} \implies b \in \text{Nats} \implies a - b \in \text{Nats}$  **for**  $a\ b :: \text{hypnat}$   
**by** (*simp add: Nats-eq-Standard*)

### 3.3 Infinite Hypernatural Numbers – *HNatInfinite*

The set of infinite hypernatural numbers.

**definition** *HNatInfinite* :: *hypnat set*  
**where**  $\text{HNatInfinite} = \{n. n \notin \text{Nats}\}$

**lemma** *Nats-not-HNatInfinite-iff*:  $x \in \text{Nats} \longleftrightarrow x \notin \text{HNatInfinite}$   
**by** (*simp add: HNatInfinite-def*)

**lemma** *HNatInfinite-not-Nats-iff*:  $x \in \text{HNatInfinite} \longleftrightarrow x \notin \text{Nats}$   
**by** (*simp add: HNatInfinite-def*)

**lemma** *star-of-neq-HNatInfinite*:  $N \in \text{HNatInfinite} \implies \text{star-of } n \neq N$   
**by** (*auto simp add: HNatInfinite-def Nats-eq-Standard*)

**lemma** *star-of-Suc-lessI*:  $\bigwedge N. \text{star-of } n < N \implies \text{star-of } (\text{Suc } n) \neq N \implies \text{star-of } (\text{Suc } n) < N$   
**by** *transfer (rule Suc-lessI)*

**lemma** *star-of-less-HNatInfinite*:  
**assumes**  $N: N \in \text{HNatInfinite}$   
**shows**  $\text{star-of } n < N$

**proof** (*induct n*)

**case**  $0$

**from**  $N$  **have**  $\text{star-of } 0 \neq N$

**by** (*rule star-of-neq-HNatInfinite*)

**then show** *?case* **by** *simp*

**next**

**case**  $(\text{Suc } n)$

**from**  $N$  **have**  $\text{star-of } (\text{Suc } n) \neq N$

**by** (*rule star-of-neq-HNatInfinite*)

**with**  $\text{Suc}$  **show** *?case*

**by** (*rule star-of-Suc-lessI*)

**qed**

**lemma** *star-of-le-HNatInfinite*:  $N \in \text{HNatInfinite} \implies \text{star-of } n \leq N$   
**by** (*rule star-of-less-HNatInfinite [THEN order-less-imp-le]*)

#### 3.3.1 Closure Rules

**lemma** *Nats-less-HNatInfinite*:  $x \in \text{Nats} \implies y \in \text{HNatInfinite} \implies x < y$   
**by** (*auto simp add: Nats-def star-of-less-HNatInfinite*)

**lemma** *Nats-le-HNatInfinite*:  $x \in \text{Nats} \implies y \in \text{HNatInfinite} \implies x \leq y$

**by** (*rule Nats-less-HNatInfinite* [THEN *order-less-imp-le*])

**lemma** *zero-less-HNatInfinite*:  $x \in \text{HNatInfinite} \implies 0 < x$   
**by** (*simp add: Nats-less-HNatInfinite*)

**lemma** *one-less-HNatInfinite*:  $x \in \text{HNatInfinite} \implies 1 < x$   
**by** (*simp add: Nats-less-HNatInfinite*)

**lemma** *one-le-HNatInfinite*:  $x \in \text{HNatInfinite} \implies 1 \leq x$   
**by** (*simp add: Nats-le-HNatInfinite*)

**lemma** *zero-not-mem-HNatInfinite* [*simp*]:  $0 \notin \text{HNatInfinite}$   
**by** (*simp add: HNatInfinite-def*)

**lemma** *Nats-downward-closed*:  $x \in \text{Nats} \implies y \leq x \implies y \in \text{Nats}$  **for**  $x\ y :: \text{hypnat}$   
**using** *HNatInfinite-not-Nats-iff Nats-le-HNatInfinite* **by** *fastforce*

**lemma** *HNatInfinite-upward-closed*:  $x \in \text{HNatInfinite} \implies x \leq y \implies y \in \text{HNatInfinite}$   
**using** *HNatInfinite-not-Nats-iff Nats-downward-closed* **by** *blast*

**lemma** *HNatInfinite-add*:  $x \in \text{HNatInfinite} \implies x + y \in \text{HNatInfinite}$   
**using** *HNatInfinite-upward-closed hypnat-le-add1* **by** *blast*

**lemma** *HNatInfinite-diff*:  $\llbracket x \in \text{HNatInfinite}; y \in \text{Nats} \rrbracket \implies x - y \in \text{HNatInfinite}$   
**by** (*metis HNatInfinite-not-Nats-iff Nats-add Nats-le-HNatInfinite le-add-diff-inverse*)

**lemma** *HNatInfinite-is-Suc*:  $x \in \text{HNatInfinite} \implies \exists y. x = y + 1$  **for**  $x :: \text{hypnat}$   
**using** *hypnat-gt-zero-iff2 zero-less-HNatInfinite* **by** *blast*

### 3.4 Existence of an infinite hypernatural number

$\omega$  is in fact an infinite hypernatural number = [ $\langle 1, 2, 3, \dots \rangle$ ]

**definition** *whn* :: *hypnat*

**where** *hypnat-omega-def*:  $\text{whn} = \text{star-}n\ (\lambda n::\text{nat}. n)$

**lemma** *hypnat-of-nat-neq-whn*:  $\text{hypnat-of-nat } n \neq \text{whn}$   
**by** (*simp add: FreeUltrafilterNat.singleton' hypnat-omega-def star-of-def star-n-eq-iff*)

**lemma** *whn-neq-hypnat-of-nat*:  $\text{whn} \neq \text{hypnat-of-nat } n$   
**by** (*simp add: FreeUltrafilterNat.singleton hypnat-omega-def star-of-def star-n-eq-iff*)

**lemma** *whn-not-Nats* [*simp*]:  $\text{whn} \notin \text{Nats}$   
**by** (*simp add: Nats-def image-def whn-neq-hypnat-of-nat*)

**lemma** *HNatInfinite-whn* [*simp*]:  $\text{whn} \in \text{HNatInfinite}$   
**by** (*simp add: HNatInfinite-def*)

**lemma** *lemma-unbounded-set* [*simp*]: *eventually*  $(\lambda n::\text{nat}. m < n)\ \mathcal{U}$

**by** (*rule filter-leD*[*OF FreeUltrafilterNat.le-cofinite*])  
 (*auto simp add: cofinite-eq-sequentially-eventually-at-top-dense*)

**lemma** *hypnat-of-nat-eq*:  $\text{hypnat-of-nat } m = \text{star-n } (\lambda n::\text{nat. } m)$   
**by** (*simp add: star-of-def*)

**lemma** *SHNat-eq*:  $\text{Nats} = \{n. \exists N. n = \text{hypnat-of-nat } N\}$   
**by** (*simp add: Nats-def image-def*)

**lemma** *Nats-less-whn*:  $n \in \text{Nats} \implies n < \text{whn}$   
**by** (*simp add: Nats-less-HNatInfinite*)

**lemma** *Nats-le-whn*:  $n \in \text{Nats} \implies n \leq \text{whn}$   
**by** (*simp add: Nats-le-HNatInfinite*)

**lemma** *hypnat-of-nat-less-whn* [*simp*]:  $\text{hypnat-of-nat } n < \text{whn}$   
**by** (*simp add: Nats-less-whn*)

**lemma** *hypnat-of-nat-le-whn* [*simp*]:  $\text{hypnat-of-nat } n \leq \text{whn}$   
**by** (*simp add: Nats-le-whn*)

**lemma** *hypnat-zero-less-hypnat-omega* [*simp*]:  $0 < \text{whn}$   
**by** (*simp add: Nats-less-whn*)

**lemma** *hypnat-one-less-hypnat-omega* [*simp*]:  $1 < \text{whn}$   
**by** (*simp add: Nats-less-whn*)

### 3.4.1 Alternative characterization of the set of infinite hypernaturals

$\text{HNatInfinite} = \{N. \forall n \in \mathbb{N}. n < N\}$

unused, but possibly interesting

**lemma** *HNatInfinite-FreeUltrafilterNat-eventually*:

**assumes**  $\bigwedge k::\text{nat. eventually } (\lambda n. f n \neq k) \mathcal{U}$

**shows**  $\text{eventually } (\lambda n. m < f n) \mathcal{U}$

**proof** (*induct m*)

**case** 0

**then show** *?case*

**using** *assms eventually-mono* **by** *fastforce*

**next**

**case** (*Suc m*)

**then show** *?case*

**using** *assms [of Suc m] eventually-elim2* **by** *fastforce*

**qed**

**lemma** *HNatInfinite-iff*:  $\text{HNatInfinite} = \{N. \forall n \in \text{Nats. } n < N\}$   
**using** *HNatInfinite-def Nats-less-HNatInfinite* **by** *auto*

### 3.4.2 Alternative Characterization of $HNatInfinite$ using Free Ultrafilter

**lemma**  $HNatInfinite$ -FreeUltrafilterNat:

$star\text{-}n\ X \in HNatInfinite \implies \forall u. eventually\ (\lambda n. u < X\ n)\ \mathcal{U}$

**by** (*metis (full-types) starP2-star-of-starP-star-n star-less-def star-of-less-HNatInfinite*)

**lemma** FreeUltrafilterNat- $HNatInfinite$ :

$\forall u. eventually\ (\lambda n. u < X\ n)\ \mathcal{U} \implies star\text{-}n\ X \in HNatInfinite$

**by** (*auto simp add: star-less-def starP2-star-n HNatInfinite-iff SHNat-eq hypnat-of-nat-eq*)

**lemma**  $HNatInfinite$ -FreeUltrafilterNat-iff:

$(star\text{-}n\ X \in HNatInfinite) = (\forall u. eventually\ (\lambda n. u < X\ n)\ \mathcal{U})$

**by** (*rule iffI [OF HNatInfinite-FreeUltrafilterNat FreeUltrafilterNat- $HNatInfinite$ ]*)

### 3.5 Embedding of the Hypernaturals into other types

**definition**  $of\ hypnat :: hypnat \Rightarrow 'a::semiring\text{-}1\text{-cancel}\ star$

**where**  $of\ hypnat\text{-}def$  [*transfer-unfold*]:  $of\ hypnat = *f* of\ nat$

**lemma**  $of\ hypnat\text{-}0$  [*simp*]:  $of\ hypnat\ 0 = 0$

**by** *transfer (rule of-nat-0)*

**lemma**  $of\ hypnat\text{-}1$  [*simp*]:  $of\ hypnat\ 1 = 1$

**by** *transfer (rule of-nat-1)*

**lemma**  $of\ hypnat\text{-}hSuc$ :  $\bigwedge m. of\ hypnat\ (hSuc\ m) = 1 + of\ hypnat\ m$

**by** *transfer (rule of-nat-Suc)*

**lemma**  $of\ hypnat\text{-}add$  [*simp*]:  $\bigwedge m\ n. of\ hypnat\ (m + n) = of\ hypnat\ m + of\ hypnat\ n$

**by** *transfer (rule of-nat-add)*

**lemma**  $of\ hypnat\text{-}mult$  [*simp*]:  $\bigwedge m\ n. of\ hypnat\ (m * n) = of\ hypnat\ m * of\ hypnat\ n$

**by** *transfer (rule of-nat-mult)*

**lemma**  $of\ hypnat\text{-}less\text{-}iff$  [*simp*]:

$\bigwedge m\ n. of\ hypnat\ m < (of\ hypnat\ n :: 'a::linordered\text{-}semidom\ star) \iff m < n$

**by** *transfer (rule of-nat-less-iff)*

**lemma**  $of\ hypnat\text{-}0\text{-}less\text{-}iff$  [*simp*]:

$\bigwedge n. 0 < (of\ hypnat\ n :: 'a::linordered\text{-}semidom\ star) \iff 0 < n$

**by** *transfer (rule of-nat-0-less-iff)*

**lemma**  $of\ hypnat\text{-}less\text{-}0\text{-}iff$  [*simp*]:  $\bigwedge m. \neg (of\ hypnat\ m :: 'a::linordered\text{-}semidom\ star) < 0$

**by** *transfer (rule of-nat-less-0-iff)*

**lemma** *of-hypnat-le-iff* [simp]:

$\bigwedge m n. \text{of-hypnat } m \leq (\text{of-hypnat } n :: 'a :: \text{linordered-semidom star}) \longleftrightarrow m \leq n$   
**by** *transfer* (*rule of-nat-le-iff*)

**lemma** *of-hypnat-0-le-iff* [simp]:  $\bigwedge n. 0 \leq (\text{of-hypnat } n :: 'a :: \text{linordered-semidom star})$

**by** *transfer* (*rule of-nat-0-le-iff*)

**lemma** *of-hypnat-le-0-iff* [simp]:  $\bigwedge m. (\text{of-hypnat } m :: 'a :: \text{linordered-semidom star}) \leq 0 \longleftrightarrow m = 0$

**by** *transfer* (*rule of-nat-le-0-iff*)

**lemma** *of-hypnat-eq-iff* [simp]:

$\bigwedge m n. \text{of-hypnat } m = (\text{of-hypnat } n :: 'a :: \text{linordered-semidom star}) \longleftrightarrow m = n$   
**by** *transfer* (*rule of-nat-eq-iff*)

**lemma** *of-hypnat-eq-0-iff* [simp]:  $\bigwedge m. (\text{of-hypnat } m :: 'a :: \text{linordered-semidom star}) = 0 \longleftrightarrow m = 0$

**by** *transfer* (*rule of-nat-eq-0-iff*)

**lemma** *HNatInfinite-of-hypnat-gt-zero*:

$N \in \text{HNatInfinite} \implies (0 :: 'a :: \text{linordered-semidom star}) < \text{of-hypnat } N$   
**by** (*rule ccontr*) (*simp add: linorder-not-less*)

**end**

## 4 Construction of Hyperreals Using Ultrafilters

**theory** *HyperDef*

**imports** *Complex-Main HyperNat*

**begin**

**type-synonym** *hypreal* = *real star*

**abbreviation** *hypreal-of-real* :: *real*  $\Rightarrow$  *real star*

**where** *hypreal-of-real*  $\equiv$  *star-of*

**abbreviation** *hypreal-of-hypnat* :: *hypnat*  $\Rightarrow$  *hypreal*

**where** *hypreal-of-hypnat*  $\equiv$  *of-hypnat*

**definition** *omega* :: *hypreal* ( $\omega$ )

**where**  $\omega = \text{star-n } (\lambda n. \text{real } (\text{Suc } n))$

— an infinite number = [ $<1, 2, 3, \dots>$ ]

**definition** *epsilon* :: *hypreal* ( $\varepsilon$ )

**where**  $\varepsilon = \text{star-n } (\lambda n. \text{inverse } (\text{real } (\text{Suc } n)))$

— an infinitesimal number = [ $<1, 1/2, 1/3, \dots>$ ]

#### 4.1 Real vector class instances

**instantiation** *star* :: (*scaleR*) *scaleR*

**begin**

**definition** *star-scaleR-def* [*transfer-unfold*]: *scaleR* *r*  $\equiv$  *scaleR* *r*

**instance** ..

**end**

**lemma** *Standard-scaleR* [*simp*]:  $x \in \text{Standard} \implies \text{scaleR } r \ x \in \text{Standard}$

**by** (*simp add: star-scaleR-def*)

**lemma** *star-of-scaleR* [*simp*]:  $\text{star-of } (\text{scaleR } r \ x) = \text{scaleR } r \ (\text{star-of } x)$

**by** *transfer (rule refl)*

**instance** *star* :: (*real-vector*) *real-vector*

**proof**

**fix** *a b* :: *real*

**show**  $\bigwedge x y :: 'a \ \text{star}. \ \text{scaleR } a \ (x + y) = \text{scaleR } a \ x + \text{scaleR } a \ y$

**by** *transfer (rule scaleR-right-distrib)*

**show**  $\bigwedge x :: 'a \ \text{star}. \ \text{scaleR } (a + b) \ x = \text{scaleR } a \ x + \text{scaleR } b \ x$

**by** *transfer (rule scaleR-left-distrib)*

**show**  $\bigwedge x :: 'a \ \text{star}. \ \text{scaleR } a \ (\text{scaleR } b \ x) = \text{scaleR } (a * b) \ x$

**by** *transfer (rule scaleR-scaleR)*

**show**  $\bigwedge x :: 'a \ \text{star}. \ \text{scaleR } 1 \ x = x$

**by** *transfer (rule scaleR-one)*

**qed**

**instance** *star* :: (*real-algebra*) *real-algebra*

**proof**

**fix** *a* :: *real*

**show**  $\bigwedge x y :: 'a \ \text{star}. \ \text{scaleR } a \ x * y = \text{scaleR } a \ (x * y)$

**by** *transfer (rule mult-scaleR-left)*

**show**  $\bigwedge x y :: 'a \ \text{star}. \ x * \text{scaleR } a \ y = \text{scaleR } a \ (x * y)$

**by** *transfer (rule mult-scaleR-right)*

**qed**

**instance** *star* :: (*real-algebra-1*) *real-algebra-1* ..

**instance** *star* :: (*real-div-algebra*) *real-div-algebra* ..

**instance** *star* :: (*field-char-0*) *field-char-0* ..

**instance** *star* :: (*real-field*) *real-field* ..

**lemma** *star-of-real-def* [*transfer-unfold*]:  $\text{of-real } r = \text{star-of } (\text{of-real } r)$

**by** (*unfold of-real-def, transfer, rule refl*)

**lemma** *Standard-of-real* [*simp*]:  $\text{of-real } r \in \text{Standard}$

**by** (*simp add: star-of-real-def*)

**lemma** *star-of-of-real* [simp]:  $\text{star-of (of-real } r) = \text{of-real } r$   
**by** *transfer (rule refl)*

**lemma** *of-real-eq-star-of* [simp]:  $\text{of-real} = \text{star-of}$   
**proof**  
**show**  $\text{of-real } r = \text{star-of } r$  **for**  $r :: \text{real}$   
**by** *transfer simp*  
**qed**

**lemma** *Reals-eq-Standard*:  $(\mathbb{R} :: \text{hypreal set}) = \text{Standard}$   
**by** (*simp add: Reals-def Standard-def*)

## 4.2 Injection from hypreal

**definition** *of-hypreal* ::  $\text{hypreal} \Rightarrow 'a::\text{real-algebra-1 star}$   
**where** [*transfer-unfold*]:  $\text{of-hypreal} = *f* \text{ of-real}$

**lemma** *Standard-of-hypreal* [simp]:  $r \in \text{Standard} \implies \text{of-hypreal } r \in \text{Standard}$   
**by** (*simp add: of-hypreal-def*)

**lemma** *of-hypreal-0* [simp]:  $\text{of-hypreal } 0 = 0$   
**by** *transfer (rule of-real-0)*

**lemma** *of-hypreal-1* [simp]:  $\text{of-hypreal } 1 = 1$   
**by** *transfer (rule of-real-1)*

**lemma** *of-hypreal-add* [simp]:  $\bigwedge x y. \text{of-hypreal } (x + y) = \text{of-hypreal } x + \text{of-hypreal } y$   
**by** *transfer (rule of-real-add)*

**lemma** *of-hypreal-minus* [simp]:  $\bigwedge x. \text{of-hypreal } (- x) = - \text{of-hypreal } x$   
**by** *transfer (rule of-real-minus)*

**lemma** *of-hypreal-diff* [simp]:  $\bigwedge x y. \text{of-hypreal } (x - y) = \text{of-hypreal } x - \text{of-hypreal } y$   
**by** *transfer (rule of-real-diff)*

**lemma** *of-hypreal-mult* [simp]:  $\bigwedge x y. \text{of-hypreal } (x * y) = \text{of-hypreal } x * \text{of-hypreal } y$   
**by** *transfer (rule of-real-mult)*

**lemma** *of-hypreal-inverse* [simp]:  
 $\bigwedge x. \text{of-hypreal } (\text{inverse } x) =$   
 $\text{inverse (of-hypreal } x :: 'a::\{\text{real-div-algebra, division-ring}\} \text{star})$   
**by** *transfer (rule of-real-inverse)*

**lemma** *of-hypreal-divide* [simp]:  
 $\bigwedge x y. \text{of-hypreal } (x / y) =$   
 $(\text{of-hypreal } x / \text{of-hypreal } y :: 'a::\{\text{real-field, field}\} \text{star})$

by *transfer (rule of-real-divide)*

**lemma** *of-hypreal-eq-iff* [*simp*]:  $\bigwedge x y. (\text{of-hypreal } x = \text{of-hypreal } y) = (x = y)$   
by *transfer (rule of-real-eq-iff)*

**lemma** *of-hypreal-eq-0-iff* [*simp*]:  $\bigwedge x. (\text{of-hypreal } x = 0) = (x = 0)$   
by *transfer (rule of-real-eq-0-iff)*

### 4.3 Properties of *starrel*

**lemma** *lemma-starrel-refl* [*simp*]:  $x \in \text{starrel} \text{ “ } \{x\}$   
by (*simp add: starrel-def*)

**lemma** *starrel-in-hypreal* [*simp*]:  $\text{starrel} \text{ “ } \{x\} \in \text{star}$   
by (*simp add: star-def starrel-def quotient-def, blast*)

**declare** *Abs-star-inject* [*simp*] *Abs-star-inverse* [*simp*]  
**declare** *equiv-starrel* [*THEN eq-equiv-class-iff, simp*]

### 4.4 *hypreal-of-real*: the Injection from *real* to *hypreal*

**lemma** *inj-star-of*: *inj star-of*  
by (*rule inj-onI*) *simp*

**lemma** *mem-Rep-star-iff*:  $X \in \text{Rep-star } x \longleftrightarrow x = \text{star-n } X$   
by (*cases x*) (*simp add: star-n-def*)

**lemma** *Rep-star-star-n-iff* [*simp*]:  $X \in \text{Rep-star } (\text{star-n } Y) \longleftrightarrow \text{eventually } (\lambda n. Y n = X n) \mathcal{U}$   
by (*simp add: star-n-def*)

**lemma** *Rep-star-star-n*:  $X \in \text{Rep-star } (\text{star-n } X)$   
by *simp*

### 4.5 Properties of *star-n*

**lemma** *star-n-add*:  $\text{star-n } X + \text{star-n } Y = \text{star-n } (\lambda n. X n + Y n)$   
by (*simp only: star-add-def starfun2-star-n*)

**lemma** *star-n-minus*:  $-\text{star-n } X = \text{star-n } (\lambda n. -(X n))$   
by (*simp only: star-minus-def starfun-star-n*)

**lemma** *star-n-diff*:  $\text{star-n } X - \text{star-n } Y = \text{star-n } (\lambda n. X n - Y n)$   
by (*simp only: star-diff-def starfun2-star-n*)

**lemma** *star-n-mult*:  $\text{star-n } X * \text{star-n } Y = \text{star-n } (\lambda n. X n * Y n)$   
by (*simp only: star-mult-def starfun2-star-n*)

**lemma** *star-n-inverse*:  $\text{inverse } (\text{star-n } X) = \text{star-n } (\lambda n. \text{inverse } (X n))$   
by (*simp only: star-inverse-def starfun-star-n*)



**lemma** *star-n-le*:  $star-n\ X \leq star-n\ Y = eventually\ (\lambda n. X\ n \leq Y\ n)\ \mathcal{U}$   
**by** (*simp only*: *star-le-def starP2-star-n*)

**lemma** *star-n-less*:  $star-n\ X < star-n\ Y = eventually\ (\lambda n. X\ n < Y\ n)\ \mathcal{U}$   
**by** (*simp only*: *star-less-def starP2-star-n*)

**lemma** *star-n-zero-num*:  $0 = star-n\ (\lambda n. 0)$   
**by** (*simp only*: *star-zero-def star-of-def*)

**lemma** *star-n-one-num*:  $1 = star-n\ (\lambda n. 1)$   
**by** (*simp only*: *star-one-def star-of-def*)

**lemma** *star-n-abs*:  $|star-n\ X| = star-n\ (\lambda n. |X\ n|)$   
**by** (*simp only*: *star-abs-def starfun-star-n*)

**lemma** *hypreal-omega-gt-zero* [*simp*]:  $0 < \omega$   
**by** (*simp add*: *omega-def star-n-zero-num star-n-less*)

## 4.6 Existence of Infinite Hyperreal Number

Existence of infinite number not corresponding to any real number. Use assumption that member  $\mathcal{U}$  is not finite.

**lemma** *hypreal-of-real-not-eq-omega*: *hypreal-of-real*  $x \neq \omega$

**proof** –

**have** *False* **if**  $\forall_F\ n\ in\ \mathcal{U}. x = 1 + real\ n$  **for**  $x$

**proof** –

**have** *finite*  $\{n::nat. x = 1 + real\ n\}$

**by** (*simp add*: *finite-nat-set-iff-bounded-le*) (*metis add.commute nat-le-linear nat-le-real-less*)

**then show** *False*

**using** *FreeUltrafilterNat.finite* **that** **by** *blast*

**qed**

**then show** *?thesis*

**by** (*auto simp add*: *omega-def star-of-def star-n-eq-iff*)

**qed**

Existence of infinitesimal number also not corresponding to any real number.

**lemma** *hypreal-of-real-not-eq-epsilon*: *hypreal-of-real*  $x \neq \varepsilon$

**proof** –

**have** *False* **if**  $\forall_F\ n\ in\ \mathcal{U}. x = inverse\ (1 + real\ n)$  **for**  $x$

**proof** –

**have** *finite*  $\{n::nat. x = inverse\ (1 + real\ n)\}$

**by** (*simp add*: *finite-nat-set-iff-bounded-le*) (*metis add.commute inverse-inverse-eq linear nat-le-real-less of-nat-Suc*)

**then show** *False*

**using** *FreeUltrafilterNat.finite* **that** **by** *blast*

**qed**

**then show** *?thesis*  
**by** (*auto simp: epsilon-def star-of-def star-n-eq-iff*)  
**qed**

**lemma** *epsilon-ge-zero* [*simp*]:  $0 \leq \varepsilon$   
**by** (*simp add: epsilon-def star-n-zero-num star-n-le*)

**lemma** *epsilon-not-zero*:  $\varepsilon \neq 0$   
**using** *hypreal-of-real-not-eq-epsilon* **by force**

**lemma** *epsilon-inverse-omega*:  $\varepsilon = \text{inverse } \omega$   
**by** (*simp add: epsilon-def omega-def star-n-inverse*)

**lemma** *epsilon-gt-zero*:  $0 < \varepsilon$   
**by** (*simp add: epsilon-inverse-omega*)

## 4.7 Embedding the Naturals into the Hyperreals

**abbreviation** *hypreal-of-nat* ::  $\text{nat} \Rightarrow \text{hypreal}$   
**where** *hypreal-of-nat*  $\equiv$  *of-nat*

**lemma** *SNat-eq*:  $\text{Nats} = \{n. \exists N. n = \text{hypreal-of-nat } N\}$   
**by** (*simp add: Nats-def image-def*)

Naturals embedded in hyperreals: is a hyperreal c.f. NS extension.

**lemma** *hypreal-of-nat*:  $\text{hypreal-of-nat } m = \text{star-n } (\lambda n. \text{real } m)$   
**by** (*simp add: star-of-def [symmetric]*)

**declaration**  $\langle$   
*K* (*Lin-Arith.add-simps* @{*thms star-of-zero star-of-one*  
*star-of-numeral star-of-add*  
*star-of-minus star-of-diff star-of-mult*}  
#> *Lin-Arith.add-inj-thms* @{*thms star-of-le [THEN iffD2]*  
*star-of-less [THEN iffD2] star-of-eq [THEN iffD2]*}  
#> *Lin-Arith.add-inj-const* (**const-name**  $\langle \text{StarDef.star-of} \rangle$ , **typ**  $\langle \text{real} \Rightarrow \text{hypreal} \rangle$ )  
 $\rangle$

**simproc-setup** *fast-arith-hypreal*  $((m::\text{hypreal}) < n \mid (m::\text{hypreal}) \leq n \mid (m::\text{hypreal}) = n) =$   
 $\langle K \text{ Lin-Arith.simproc} \rangle$

## 4.8 Exponentials on the Hyperreals

**lemma** *hpowr-0* [*simp*]:  $r \wedge 0 = (1::\text{hypreal})$   
**for**  $r :: \text{hypreal}$   
**by** (*rule power-0*)

**lemma** *hpowr-Suc* [*simp*]:  $r \wedge (\text{Suc } n) = r * (r \wedge n)$   
**for**  $r :: \text{hypreal}$

by (rule power-Suc)

**lemma** hrealpow:  $\text{star-n } X \hat{=} m = \text{star-n } (\lambda n. (X \text{ n}::\text{real}) \hat{=} m)$   
 by (induct m) (auto simp: star-n-one-num star-n-mult)

**lemma** hrealpow-sum-square-expand:

$(x + y) \hat{=} \text{Suc } (\text{Suc } 0) =$   
 $x \hat{=} \text{Suc } (\text{Suc } 0) + y \hat{=} \text{Suc } (\text{Suc } 0) + (\text{hyreal-of-nat } (\text{Suc } (\text{Suc } 0))) * x * y$   
 for  $x \ y :: \text{hyreal}$   
 by (simp add: distrib-left distrib-right)

**lemma** power-hyreal-of-real-numeral:

$(\text{numeral } v :: \text{hyreal}) \hat{=} n = \text{hyreal-of-real } ((\text{numeral } v) \hat{=} n)$   
 by simp  
**declare** power-hyreal-of-real-numeral [of - numeral w, simp] for w

**lemma** power-hyreal-of-real-neg-numeral:

$(-\text{ numeral } v :: \text{hyreal}) \hat{=} n = \text{hyreal-of-real } ((-\text{ numeral } v) \hat{=} n)$   
 by simp  
**declare** power-hyreal-of-real-neg-numeral [of - numeral w, simp] for w

## 4.9 Powers with Hypernatural Exponents

Hypernatural powers of hyperreals.

**definition** pow :: 'a::power star  $\Rightarrow$  nat star  $\Rightarrow$  'a star (infixr pow 80)  
 where hyperpow-def [transfer-unfold]:  $R \text{ pow } N = (*f2* (\hat{=})) R N$

**lemma** Standard-hyperpow [simp]:  $r \in \text{Standard} \Longrightarrow n \in \text{Standard} \Longrightarrow r \text{ pow } n \in \text{Standard}$   
 by (simp add: hyperpow-def)

**lemma** hyperpow:  $\text{star-n } X \text{ pow } \text{star-n } Y = \text{star-n } (\lambda n. X \text{ n} \hat{=} Y \text{ n})$   
 by (simp add: hyperpow-def starfun2-star-n)

**lemma** hyperpow-zero [simp]:  $\bigwedge n. (0::'a::\{\text{power,semiring-0}\} \text{star}) \text{ pow } (n + (1::\text{hypnat})) = 0$   
 by transfer simp

**lemma** hyperpow-not-zero:  $\bigwedge r \ n. r \neq (0::'a::\{\text{field}\} \text{star}) \Longrightarrow r \text{ pow } n \neq 0$   
 by transfer (rule power-not-zero)

**lemma** hyperpow-inverse:  $\bigwedge r \ n. r \neq (0::'a::\text{field } \text{star}) \Longrightarrow \text{inverse } (r \text{ pow } n) = (\text{inverse } r) \text{ pow } n$   
 by transfer (rule power-inverse [symmetric])

**lemma** hyperpow-hrabs:  $\bigwedge r \ n. |r::'a::\{\text{linordered-idom}\} \text{star}| \text{ pow } n = |r \text{ pow } n|$   
 by transfer (rule power-abs [symmetric])

**lemma** hyperpow-add:  $\bigwedge r \ n \ m. (r::'a::\text{monoid-mult } \text{star}) \text{ pow } (n + m) = (r \text{ pow } n) \text{ pow } m$

$n) * (r \text{ pow } m)$   
**by** *transfer* (*rule power-add*)

**lemma** *hyperpow-one* [*simp*]:  $\bigwedge r. (r::'a::\text{monoid-mult star}) \text{ pow } (1::\text{hypnat}) = r$   
**by** *transfer* (*rule power-one-right*)

**lemma** *hyperpow-two*:  $\bigwedge r. (r::'a::\text{monoid-mult star}) \text{ pow } (2::\text{hypnat}) = r * r$   
**by** *transfer* (*rule power2-eq-square*)

**lemma** *hyperpow-gt-zero*:  $\bigwedge r n. (0::'a::\{\text{linordered-semidom}\} \text{ star}) < r \implies 0 < r \text{ pow } n$   
**by** *transfer* (*rule zero-less-power*)

**lemma** *hyperpow-ge-zero*:  $\bigwedge r n. (0::'a::\{\text{linordered-semidom}\} \text{ star}) \leq r \implies 0 \leq r \text{ pow } n$   
**by** *transfer* (*rule zero-le-power*)

**lemma** *hyperpow-le*:  $\bigwedge x y n. (0::'a::\{\text{linordered-semidom}\} \text{ star}) < x \implies x \leq y \implies x \text{ pow } n \leq y \text{ pow } n$   
**by** *transfer* (*rule power-mono [OF - order-less-imp-le]*)

**lemma** *hyperpow-eq-one* [*simp*]:  $\bigwedge n. 1 \text{ pow } n = (1::'a::\text{monoid-mult star})$   
**by** *transfer* (*rule power-one*)

**lemma** *hrabs-hyperpow-minus* [*simp*]:  $\bigwedge (a::'a::\text{linordered-idom star}) n. |(-a) \text{ pow } n| = |a \text{ pow } n|$   
**by** *transfer* (*rule abs-power-minus*)

**lemma** *hyperpow-mult*:  $\bigwedge r s n. (r * s::'a::\text{comm-monoid-mult star}) \text{ pow } n = (r \text{ pow } n) * (s \text{ pow } n)$   
**by** *transfer* (*rule power-mult-distrib*)

**lemma** *hyperpow-two-le* [*simp*]:  $\bigwedge r. (0::'a::\{\text{monoid-mult, linordered-ring-strict}\} \text{ star}) \leq r \text{ pow } 2$   
**by** (*auto simp add: hyperpow-two zero-le-mult-iff*)

**lemma** *hyperpow-two-hrabs* [*simp*]:  $|x::'a::\text{linordered-idom star}| \text{ pow } 2 = x \text{ pow } 2$   
**by** (*simp add: hyperpow-hrabs*)

**lemma** *hyperpow-two-gt-one*:  $\bigwedge r::'a::\text{linordered-semidom star}. 1 < r \implies 1 < r \text{ pow } 2$   
**by** *transfer simp*

**lemma** *hyperpow-two-ge-one*:  $\bigwedge r::'a::\text{linordered-semidom star}. 1 \leq r \implies 1 \leq r \text{ pow } 2$   
**by** *transfer* (*rule one-le-power*)

**lemma** *two-hyperpow-ge-one* [*simp*]:  $(1::\text{hypreal}) \leq 2 \text{ pow } n$   
**by** (*metis hyperpow-eq-one hyperpow-le one-le-numeral zero-less-one*)

**lemma** *hyperpow-minus-one2* [simp]:  $\bigwedge n. (-1) \text{ pow } (2 * n) = (1::\text{hypreal})$   
**by** *transfer (rule power-minus1-even)*

**lemma** *hyperpow-less-le*:  $\bigwedge r n N. (0::\text{hypreal}) \leq r \implies r \leq 1 \implies n < N \implies r \text{ pow } N \leq r \text{ pow } n$   
**by** *transfer (rule power-decreasing [OF order-less-imp-le])*

**lemma** *hyperpow-SHNat-le*:  
 $0 \leq r \implies r \leq (1::\text{hypreal}) \implies N \in \text{HNatInfinite} \implies \forall n \in \text{Nats}. r \text{ pow } N \leq r \text{ pow } n$   
**by** *(auto intro!: hyperpow-less-le simp: HNatInfinite-iff)*

**lemma** *hyperpow-realpow*:  $(\text{hypreal-of-real } r) \text{ pow } (\text{hypnat-of-nat } n) = \text{hypreal-of-real } (r \hat{\ } n)$   
**by** *transfer (rule refl)*

**lemma** *hyperpow-SReal* [simp]:  $(\text{hypreal-of-real } r) \text{ pow } (\text{hypnat-of-nat } n) \in \mathbb{R}$   
**by** *(simp add: Reals-eq-Standard)*

**lemma** *hyperpow-zero-HNatInfinite* [simp]:  $N \in \text{HNatInfinite} \implies (0::\text{hypreal}) \text{ pow } N = 0$   
**by** *(drule HNatInfinite-is-Suc, auto)*

**lemma** *hyperpow-le-le*:  $(0::\text{hypreal}) \leq r \implies r \leq 1 \implies n \leq N \implies r \text{ pow } N \leq r \text{ pow } n$   
**by** *(metis hyperpow-less-le le-less)*

**lemma** *hyperpow-Suc-le-self2*:  $(0::\text{hypreal}) \leq r \implies r < 1 \implies r \text{ pow } (n + (1::\text{hypnat})) \leq r$   
**by** *(metis hyperpow-less-le hyperpow-one hypnat-add-self-le le-less)*

**lemma** *hyperpow-hypnat-of-nat*:  $\bigwedge x. x \text{ pow } \text{hypnat-of-nat } n = x \hat{\ } n$   
**by** *transfer (rule refl)*

**lemma** *of-hypreal-hyperpow*:  
 $\bigwedge x n. \text{of-hypreal } (x \text{ pow } n) = (\text{of-hypreal } x::'a::\{\text{real-algebra-1}\} \text{ star}) \text{ pow } n$   
**by** *transfer (rule of-real-power)*

**end**

## 5 Infinite Numbers, Infinitesimals, Infinitely Close Relation

**theory** *NSA*  
**imports** *HyperDef HOL-Library.Lub-Glb*  
**begin**

**definition**  $hnorm :: 'a::real-normed-vector\ star \Rightarrow real\ star$   
**where**  $[transfer-unfold]: hnorm = *f* norm$

**definition**  $Infinitesimal :: ('a::real-normed-vector)\ star\ set$   
**where**  $Infinitesimal = \{x. \forall r \in Reals. 0 < r \longrightarrow hnorm\ x < r\}$

**definition**  $HFinite :: ('a::real-normed-vector)\ star\ set$   
**where**  $HFinite = \{x. \exists r \in Reals. hnorm\ x < r\}$

**definition**  $HInfinite :: ('a::real-normed-vector)\ star\ set$   
**where**  $HInfinite = \{x. \forall r \in Reals. r < hnorm\ x\}$

**definition**  $approx :: 'a::real-normed-vector\ star \Rightarrow 'a\ star \Rightarrow bool$  (**infixl**  $\approx 50$ )  
**where**  $x \approx y \longleftrightarrow x - y \in Infinitesimal$   
— the “infinitely close” relation

**definition**  $st :: hypreal \Rightarrow hypreal$   
**where**  $st = (\lambda x. SOME\ r. x \in HFinite \wedge r \in \mathbb{R} \wedge r \approx x)$   
— the standard part of a hyperreal

**definition**  $monad :: 'a::real-normed-vector\ star \Rightarrow 'a\ star\ set$   
**where**  $monad\ x = \{y. x \approx y\}$

**definition**  $galaxy :: 'a::real-normed-vector\ star \Rightarrow 'a\ star\ set$   
**where**  $galaxy\ x = \{y. (x + -y) \in HFinite\}$

**lemma**  $SReal-def: \mathbb{R} \equiv \{x. \exists r. x = hypreal-of-real\ r\}$   
**by**  $(simp\ add: Reals-def\ image-def)$

## 5.1 Nonstandard Extension of the Norm Function

**definition**  $scaleHR :: real\ star \Rightarrow 'a\ star \Rightarrow 'a::real-normed-vector\ star$   
**where**  $[transfer-unfold]: scaleHR = starfun2\ scaleR$

**lemma**  $Standard-hnorm [simp]: x \in Standard \Longrightarrow hnorm\ x \in Standard$   
**by**  $(simp\ add: hnorm-def)$

**lemma**  $star-of-norm [simp]: star-of\ (norm\ x) = hnorm\ (star-of\ x)$   
**by**  $transfer\ (rule\ refl)$

**lemma**  $hnorm-ge-zero [simp]: \bigwedge x::'a::real-normed-vector\ star. 0 \leq hnorm\ x$   
**by**  $transfer\ (rule\ norm-ge-zero)$

**lemma**  $hnorm-eq-zero [simp]: \bigwedge x::'a::real-normed-vector\ star. hnorm\ x = 0 \longleftrightarrow x = 0$   
**by**  $transfer\ (rule\ norm-eq-zero)$

**lemma**  $hnorm-triangle-ineq: \bigwedge x\ y::'a::real-normed-vector\ star. hnorm\ (x + y) \leq hnorm\ x + hnorm\ y$

**by** *transfer* (*rule norm-triangle-ineq*)

**lemma** *hnorm-triangle-ineq3*:  $\bigwedge x y :: 'a :: \text{real-normed-vector star. } | \text{hnorm } x - \text{hnorm } y | \leq \text{hnorm } (x - y)$

**by** *transfer* (*rule norm-triangle-ineq3*)

**lemma** *hnorm-scaleR*:  $\bigwedge x :: 'a :: \text{real-normed-vector star. } \text{hnorm } (a *_{\mathbb{R}} x) = | \text{star-of } a | * \text{hnorm } x$

**by** *transfer* (*rule norm-scaleR*)

**lemma** *hnorm-scaleHR*:  $\bigwedge a (x :: 'a :: \text{real-normed-vector star}). \text{hnorm } (\text{scaleHR } a x) = |a| * \text{hnorm } x$

**by** *transfer* (*rule norm-scaleR*)

**lemma** *hnorm-mult-ineq*:  $\bigwedge x y :: 'a :: \text{real-normed-algebra star. } \text{hnorm } (x * y) \leq \text{hnorm } x * \text{hnorm } y$

**by** *transfer* (*rule norm-mult-ineq*)

**lemma** *hnorm-mult*:  $\bigwedge x y :: 'a :: \text{real-normed-div-algebra star. } \text{hnorm } (x * y) = \text{hnorm } x * \text{hnorm } y$

**by** *transfer* (*rule norm-mult*)

**lemma** *hnorm-hyperpow*:  $\bigwedge (x :: 'a :: \{\text{real-normed-div-algebra}\} \text{ star}) n. \text{hnorm } (x \text{ pow } n) = \text{hnorm } x \text{ pow } n$

**by** *transfer* (*rule norm-power*)

**lemma** *hnorm-one* [*simp*]:  $\text{hnorm } (1 :: 'a :: \text{real-normed-div-algebra star}) = 1$

**by** *transfer* (*rule norm-one*)

**lemma** *hnorm-zero* [*simp*]:  $\text{hnorm } (0 :: 'a :: \text{real-normed-vector star}) = 0$

**by** *transfer* (*rule norm-zero*)

**lemma** *zero-less-hnorm-iff* [*simp*]:  $\bigwedge x :: 'a :: \text{real-normed-vector star. } 0 < \text{hnorm } x \iff x \neq 0$

**by** *transfer* (*rule zero-less-norm-iff*)

**lemma** *hnorm-minus-cancel* [*simp*]:  $\bigwedge x :: 'a :: \text{real-normed-vector star. } \text{hnorm } (- x) = \text{hnorm } x$

**by** *transfer* (*rule norm-minus-cancel*)

**lemma** *hnorm-minus-commute*:  $\bigwedge a b :: 'a :: \text{real-normed-vector star. } \text{hnorm } (a - b) = \text{hnorm } (b - a)$

**by** *transfer* (*rule norm-minus-commute*)

**lemma** *hnorm-triangle-ineq2*:  $\bigwedge a b :: 'a :: \text{real-normed-vector star. } \text{hnorm } a - \text{hnorm } b \leq \text{hnorm } (a - b)$

**by** *transfer* (*rule norm-triangle-ineq2*)

**lemma** *hnorm-triangle-ineq4*:  $\bigwedge a b :: 'a :: \text{real-normed-vector star. } \text{hnorm } (a - b) \leq$

$hnorm\ a + hnorm\ b$   
**by** *transfer (rule norm-triangle-ineq4)*

**lemma** *abs-hnorm-cancel [simp]*:  $\bigwedge a::'a::real-normed-vector\ star. |hnorm\ a| = hnorm\ a$   
**by** *transfer (rule abs-norm-cancel)*

**lemma** *hnorm-of-hypreal [simp]*:  $\bigwedge r. hnorm\ (of-hypreal\ r::'a::real-normed-algebra-1\ star) = |r|$   
**by** *transfer (rule norm-of-real)*

**lemma** *nonzero-hnorm-inverse*:  
 $\bigwedge a::'a::real-normed-div-algebra\ star. a \neq 0 \implies hnorm\ (inverse\ a) = inverse\ (hnorm\ a)$   
**by** *transfer (rule nonzero-norm-inverse)*

**lemma** *hnorm-inverse*:  
 $\bigwedge a::'a::\{real-normed-div-algebra, division-ring\}\ star. hnorm\ (inverse\ a) = inverse\ (hnorm\ a)$   
**by** *transfer (rule norm-inverse)*

**lemma** *hnorm-divide*:  $\bigwedge a\ b::'a::\{real-normed-field, field\}\ star. hnorm\ (a / b) = hnorm\ a / hnorm\ b$   
**by** *transfer (rule norm-divide)*

**lemma** *hypreal-hnorm-def [simp]*:  $\bigwedge r::hypreal. hnorm\ r = |r|$   
**by** *transfer (rule real-norm-def)*

**lemma** *hnorm-add-less*:  
 $\bigwedge (x::'a::real-normed-vector\ star)\ y\ r\ s. hnorm\ x < r \implies hnorm\ y < s \implies hnorm\ (x + y) < r + s$   
**by** *transfer (rule norm-add-less)*

**lemma** *hnorm-mult-less*:  
 $\bigwedge (x::'a::real-normed-algebra\ star)\ y\ r\ s. hnorm\ x < r \implies hnorm\ y < s \implies hnorm\ (x * y) < r * s$   
**by** *transfer (rule norm-mult-less)*

**lemma** *hnorm-scaleHR-less*:  $|x| < r \implies hnorm\ y < s \implies hnorm\ (scaleHR\ x\ y) < r * s$   
**by** *(simp only: hnorm-scaleHR) (simp add: mult-strict-mono')*

## 5.2 Closure Laws for the Standard Reals

**lemma** *Reals-add-cancel*:  $x + y \in \mathbb{R} \implies y \in \mathbb{R} \implies x \in \mathbb{R}$   
**by** *(drule (1) Reals-diff) simp*

**lemma** *SReal-hrabs*:  $x \in \mathbb{R} \implies |x| \in \mathbb{R}$   
**for**  $x :: hypreal$



by (simp add: Reals-eq-Standard)

**lemma** *SReal-hypreal-of-real* [simp]: *hypreal-of-real*  $x \in \mathbb{R}$   
by (simp add: Reals-eq-Standard)

**lemma** *SReal-divide-numeral*:  $r \in \mathbb{R} \implies r / (\text{numeral } w::\text{hypreal}) \in \mathbb{R}$   
by simp

$\varepsilon$  is not in Reals because it is an infinitesimal

**lemma** *SReal-epsilon-not-mem*:  $\varepsilon \notin \mathbb{R}$   
by (auto simp: SReal-def hypreal-of-real-not-eq-epsilon [symmetric])

**lemma** *SReal-omega-not-mem*:  $\omega \notin \mathbb{R}$   
by (auto simp: SReal-def hypreal-of-real-not-eq-omega [symmetric])

**lemma** *SReal-UNIV-real*:  $\{x. \text{hypreal-of-real } x \in \mathbb{R}\} = (\text{UNIV}::\text{real set})$   
by simp

**lemma** *SReal-iff*:  $x \in \mathbb{R} \longleftrightarrow (\exists y. x = \text{hypreal-of-real } y)$   
by (simp add: SReal-def)

**lemma** *hypreal-of-real-image*: *hypreal-of-real* ‘ $(\text{UNIV}::\text{real set})$ ’ =  $\mathbb{R}$   
by (simp add: Reals-eq-Standard Standard-def)

**lemma** *inv-hypreal-of-real-image*: *inv hypreal-of-real* ‘ $\mathbb{R}$ ’ = *UNIV*  
by (simp add: Reals-eq-Standard Standard-def inj-star-of)

**lemma** *SReal-dense*:  $x \in \mathbb{R} \implies y \in \mathbb{R} \implies x < y \implies \exists r \in \text{Reals}. x < r \wedge r < y$   
for  $x y :: \text{hypreal}$   
using dense by (fastforce simp add: SReal-def)

### 5.3 Set of Finite Elements is a Subring of the Extended Reals

**lemma** *HFinite-add*:  $x \in \text{HFinite} \implies y \in \text{HFinite} \implies x + y \in \text{HFinite}$   
unfolding *HFinite-def* by (blast intro!: Reals-add hnorm-add-less)

**lemma** *HFinite-mult*:  $x \in \text{HFinite} \implies y \in \text{HFinite} \implies x * y \in \text{HFinite}$   
for  $x y :: 'a::\text{real-normed-algebra star}$   
unfolding *HFinite-def* by (blast intro!: Reals-mult hnorm-mult-less)

**lemma** *HFinite-scaleHR*:  $x \in \text{HFinite} \implies y \in \text{HFinite} \implies \text{scaleHR } x y \in \text{HFinite}$   
by (auto simp: HFinite-def intro!: Reals-mult hnorm-scaleHR-less)

**lemma** *HFinite-minus-iff*:  $-x \in \text{HFinite} \longleftrightarrow x \in \text{HFinite}$   
by (simp add: HFinite-def)

**lemma** *HFinite-star-of* [simp]: *star-of*  $x \in \text{HFinite}$   
by (simp add: HFinite-def) (*metis* *SReal-hypreal-of-real gt-ex star-of-less star-of-norm*)

**lemma** *SReal-subset-HFinite*:  $(\mathbf{R}::\text{hypreal set}) \subseteq \text{HFinite}$   
**by** (*auto simp add: SReal-def*)

**lemma** *HFiniteD*:  $x \in \text{HFinite} \implies \exists t \in \text{Reals}. \text{hnorm } x < t$   
**by** (*simp add: HFinite-def*)

**lemma** *HFinite-hrabs-iff* [*iff*]:  $|x| \in \text{HFinite} \longleftrightarrow x \in \text{HFinite}$   
**for**  $x :: \text{hypreal}$   
**by** (*simp add: HFinite-def*)

**lemma** *HFinite-hnorm-iff* [*iff*]:  $\text{hnorm } x \in \text{HFinite} \longleftrightarrow x \in \text{HFinite}$   
**for**  $x :: \text{hypreal}$   
**by** (*simp add: HFinite-def*)

**lemma** *HFinite-numeral* [*simp*]: *numeral*  $w \in \text{HFinite}$   
**unfolding** *star-numeral-def* **by** (*rule HFinite-star-of*)

As always with numerals,  $0$  and  $1$  are special cases.

**lemma** *HFinite-0* [*simp*]:  $0 \in \text{HFinite}$   
**unfolding** *star-zero-def* **by** (*rule HFinite-star-of*)

**lemma** *HFinite-1* [*simp*]:  $1 \in \text{HFinite}$   
**unfolding** *star-one-def* **by** (*rule HFinite-star-of*)

**lemma** *hrealpow-HFinite*:  $x \in \text{HFinite} \implies x \hat{=} n \in \text{HFinite}$   
**for**  $x :: 'a::\{\text{real-normed-algebra, monoid-mult}\}$  *star*  
**by** (*induct n*) (*auto intro: HFinite-mult*)

**lemma** *HFinite-bounded*:  
**fixes**  $x y :: \text{hypreal}$   
**assumes**  $x \in \text{HFinite}$  **and**  $y: y \leq x$   $0 \leq y$  **shows**  $y \in \text{HFinite}$   
**proof** (*cases*  $x \leq 0$ )  
**case** *True*  
**then have**  $y = 0$   
**using**  $y$  **by** *auto*  
**then show** *?thesis*  
**by** *simp*  
**next**  
**case** *False*  
**then show** *?thesis*  
**using** *assms le-less-trans* **by** (*auto simp: HFinite-def*)  
**qed**

## 5.4 Set of Infinitesimals is a Subring of the Hyperreals

**lemma** *InfinitesimalI*:  $(\bigwedge r. r \in \mathbf{R} \implies 0 < r \implies \text{hnorm } x < r) \implies x \in \text{Infinitesimal}$   
**by** (*simp add: Infinitesimal-def*)

**lemma** *InfinesimalD*:  $x \in \text{Infinesimal} \implies \forall r \in \text{Reals}. 0 < r \implies \text{hnorm } x < r$   
**by** (*simp add: Infinesimal-def*)

**lemma** *InfinesimalI2*:  $(\bigwedge r. 0 < r \implies \text{hnorm } x < \text{star-of } r) \implies x \in \text{Infinesimal}$   
**by** (*auto simp add: Infinesimal-def SReal-def*)

**lemma** *InfinesimalD2*:  $x \in \text{Infinesimal} \implies 0 < r \implies \text{hnorm } x < \text{star-of } r$   
**by** (*auto simp add: Infinesimal-def SReal-def*)

**lemma** *Infinesimal-zero [iff]*:  $0 \in \text{Infinesimal}$   
**by** (*simp add: Infinesimal-def*)

**lemma** *Infinesimal-add*:

**assumes**  $x \in \text{Infinesimal } y \in \text{Infinesimal}$

**shows**  $x + y \in \text{Infinesimal}$

**proof** (*rule InfinesimalI*)

**show**  $\text{hnorm } (x + y) < r$

**if**  $r \in \mathbb{R}$  **and**  $0 < r$  **for**  $r :: \text{real star}$

**proof** –

**have**  $\text{hnorm } x < r/2$   $\text{hnorm } y < r/2$

**using** *InfinesimalD SReal-divide-numeral assms half-gt-zero* **that** **by** *blast+*

**then show** *?thesis*

**using** *hnorm-add-less* **by** *fastforce*

**qed**

**qed**

**lemma** *Infinesimal-minus-iff [simp]*:  $-x \in \text{Infinesimal} \longleftrightarrow x \in \text{Infinesimal}$   
**by** (*simp add: Infinesimal-def*)

**lemma** *Infinesimal-hnorm-iff*:  $\text{hnorm } x \in \text{Infinesimal} \longleftrightarrow x \in \text{Infinesimal}$   
**by** (*simp add: Infinesimal-def*)

**lemma** *Infinesimal-hrabs-iff [iff]*:  $|x| \in \text{Infinesimal} \longleftrightarrow x \in \text{Infinesimal}$   
**for**  $x :: \text{hypreal}$   
**by** (*simp add: abs-if*)

**lemma** *Infinesimal-of-hypreal-iff [simp]*:

(*of-hypreal x::'a::real-normed-algebra-1 star*)  $\in \text{Infinesimal} \longleftrightarrow x \in \text{Infinesimal}$

**by** (*subst Infinesimal-hnorm-iff [symmetric]*) *simp*

**lemma** *Infinesimal-diff*:  $x \in \text{Infinesimal} \implies y \in \text{Infinesimal} \implies x - y \in \text{Infinesimal}$

**using** *Infinesimal-add [of x - y]* **by** *simp*

**lemma** *Infinesimal-mult*:

**fixes**  $x y :: 'a::\text{real-normed-algebra star}$

**assumes**  $x \in \text{Infinesimal } y \in \text{Infinesimal}$

**shows**  $x * y \in \text{Infinesimal}$

**proof** (*rule InfinesimalI*)

```

show  $hnorm\ (x * y) < r$ 
  if  $r \in \mathbb{R}$  and  $0 < r$  for  $r :: real\ star$ 
proof –
  have  $hnorm\ x < 1\ hnorm\ y < r$ 
    using assms that by (auto simp add: InfinitesimalD)
  then show ?thesis
    using hnorm-mult-less by fastforce
qed
qed

```

**lemma** *Infinitesimal-HFinite-mult:*

```

fixes  $x\ y :: 'a::real-normed-algebra\ star$ 
assumes  $x \in Infinitesimal\ y \in HFinite$ 
shows  $x * y \in Infinitesimal$ 
proof (rule InfinitesimalI)
  obtain  $t$  where  $hnorm\ y < t\ t \in Reals$ 
    using HFiniteD  $\langle y \in HFinite \rangle$  by blast
  then have  $t > 0$ 
    using hnorm-ge-zero le-less-trans by blast
  show  $hnorm\ (x * y) < r$ 
    if  $r \in \mathbb{R}$  and  $0 < r$  for  $r :: real\ star$ 
  proof –
    have  $hnorm\ x < r/t$ 
      by (meson InfinitesimalD Reals-divide  $\langle hnorm\ y < t \rangle \langle t \in \mathbb{R} \rangle$  assms(1))
    divide-pos-pos hnorm-ge-zero le-less-trans that
    then have  $hnorm\ (x * y) < (r / t) * t$ 
      using  $\langle hnorm\ y < t \rangle$  hnorm-mult-less by blast
    then show ?thesis
      using  $\langle 0 < t \rangle$  by auto
  qed
qed

```

**lemma** *Infinitesimal-HFinite-scaleHR:*

```

assumes  $x \in Infinitesimal\ y \in HFinite$ 
shows  $scaleHR\ x\ y \in Infinitesimal$ 
proof (rule InfinitesimalI)
  obtain  $t$  where  $hnorm\ y < t\ t \in Reals$ 
    using HFiniteD  $\langle y \in HFinite \rangle$  by blast
  then have  $t > 0$ 
    using hnorm-ge-zero le-less-trans by blast
  show  $hnorm\ (scaleHR\ x\ y) < r$ 
    if  $r \in \mathbb{R}$  and  $0 < r$  for  $r :: real\ star$ 
  proof –
    have  $|x| * hnorm\ y < (r / t) * t$ 
      by (metis InfinitesimalD Reals-divide  $\langle 0 < t \rangle \langle hnorm\ y < t \rangle \langle t \in \mathbb{R} \rangle$  assms(1))
    divide-pos-pos hnorm-ge-zero hypreal-hnorm-def mult-strict-mono' that
    then show ?thesis
      by (simp add:  $\langle 0 < t \rangle$  hnorm-scaleHR less-imp-not-eq2)
  qed
qed

```

qed

**lemma** *Infinesimal-HFinite-mult2*:

**fixes**  $x\ y :: 'a::\text{real-normed-algebra star}$

**assumes**  $x \in \text{Infinesimal } y \in \text{HFinite}$

**shows**  $y * x \in \text{Infinesimal}$

**proof** (rule *InfinesimalI*)

**obtain**  $t$  **where**  $\text{hnorm } y < t \ t \in \text{Reals}$

**using** *HFiniteD*  $\langle y \in \text{HFinite} \rangle$  **by** *blast*

**then have**  $t > 0$

**using** *hnorm-ge-zero le-less-trans* **by** *blast*

**show**  $\text{hnorm } (y * x) < r$

**if**  $r \in \mathbb{R}$  **and**  $0 < r$  **for**  $r :: \text{real star}$

**proof** –

**have**  $\text{hnorm } x < r/t$

**by** (meson *InfinesimalD Reals-divide*  $\langle \text{hnorm } y < t \rangle \langle t \in \mathbb{R} \rangle$  *assms(1)*)

*divide-pos-pos hnorm-ge-zero le-less-trans* **that**)

**then have**  $\text{hnorm } (y * x) < t * (r / t)$

**using**  $\langle \text{hnorm } y < t \rangle$  *hnorm-mult-less* **by** *blast*

**then show** *?thesis*

**using**  $\langle 0 < t \rangle$  **by** *auto*

qed

qed

**lemma** *Infinesimal-scaleR2*:

**assumes**  $x \in \text{Infinesimal}$  **shows**  $a *_R x \in \text{Infinesimal}$

**by** (metis *HFinite-star-of Infinesimal-HFinite-mult2 Infinesimal-hnorm-iff* *assms hnorm-scaleR hypreal-hnorm-def star-of-norm*)

**lemma** *Compl-HFinite*:  $-\text{HFinite} = \text{HInfinite}$

**proof** –

**have**  $r < \text{hnorm } x$  **if**  $*$ :  $\bigwedge s. s \in \mathbb{R} \implies s \leq \text{hnorm } x$  **and**  $r \in \mathbb{R}$

**for**  $x :: 'a \text{ star}$  **and**  $r :: \text{hypreal}$

**using**  $*$   $[of\ r+1]$   $\langle r \in \mathbb{R} \rangle$  **by** *auto*

**then show** *?thesis*

**by** (*auto simp add: HInfinite-def HFinite-def linorder-not-less*)

qed

**lemma** *HInfinite-inverse-Infinesimal*:

$x \in \text{HInfinite} \implies \text{inverse } x \in \text{Infinesimal}$

**for**  $x :: 'a::\text{real-normed-div-algebra star}$

**by** (*simp add: HInfinite-def InfinesimalI hnorm-inverse inverse-less-imp-less*)

**lemma** *inverse-Infinesimal-iff-HInfinite*:

$x \neq 0 \implies \text{inverse } x \in \text{Infinesimal} \iff x \in \text{HInfinite}$

**for**  $x :: 'a::\text{real-normed-div-algebra star}$

**by** (metis *Compl-HFinite Compl-iff HInfinite-inverse-Infinesimal InfinesimalD* *Infinesimal-HFinite-mult Reals-1 hnorm-one left-inverse less-irrefl zero-less-one*)

**lemma** *HInfiniteI*:  $(\bigwedge r. r \in \mathbf{R} \implies r < \text{hnorm } x) \implies x \in \text{HInfinite}$   
**by** (*simp add: HInfinite-def*)

**lemma** *HInfiniteD*:  $x \in \text{HInfinite} \implies r \in \mathbf{R} \implies r < \text{hnorm } x$   
**by** (*simp add: HInfinite-def*)

**lemma** *HInfinite-mult*:

**fixes**  $x\ y :: 'a::\text{real-normed-div-algebra star}$

**assumes**  $x \in \text{HInfinite}\ y \in \text{HInfinite}$  **shows**  $x * y \in \text{HInfinite}$

**proof** (*rule HInfiniteI, simp only: hnorm-mult*)

**have**  $x \neq 0$

**using** *Compl-HFinite HFinite-0 assms by blast*

**show**  $r < \text{hnorm } x * \text{hnorm } y$

**if**  $r \in \mathbf{R}$  **for**  $r :: \text{real star}$

**proof** –

**have**  $r = r * 1$

**by** *simp*

**also have**  $\dots < \text{hnorm } x * \text{hnorm } y$

**by** (*meson HInfiniteD Reals-1  $\langle x \neq 0 \rangle$  assms le-numeral-extra(1) mult-strict-mono that zero-less-hnorm-iff*)

**finally show** *?thesis* .

**qed**

**qed**

**lemma** *hypreal-add-zero-less-le-mono*:  $r < x \implies 0 \leq y \implies r < x + y$   
**for**  $r\ x\ y :: \text{hypreal}$   
**by** *simp*

**lemma** *HInfinite-add-ge-zero*:  $x \in \text{HInfinite} \implies 0 \leq y \implies 0 \leq x \implies x + y \in \text{HInfinite}$   
**for**  $x\ y :: \text{hypreal}$   
**by** (*auto simp: abs-if add commute HInfinite-def*)

**lemma** *HInfinite-add-ge-zero2*:  $x \in \text{HInfinite} \implies 0 \leq y \implies 0 \leq x \implies y + x \in \text{HInfinite}$   
**for**  $x\ y :: \text{hypreal}$   
**by** (*auto intro!: HInfinite-add-ge-zero simp add: add commute*)

**lemma** *HInfinite-add-gt-zero*:  $x \in \text{HInfinite} \implies 0 < y \implies 0 < x \implies x + y \in \text{HInfinite}$   
**for**  $x\ y :: \text{hypreal}$   
**by** (*blast intro: HInfinite-add-ge-zero order-less-imp-le*)

**lemma** *HInfinite-minus-iff*:  $-x \in \text{HInfinite} \iff x \in \text{HInfinite}$   
**by** (*simp add: HInfinite-def*)

**lemma** *HInfinite-add-le-zero*:  $x \in \text{HInfinite} \implies y \leq 0 \implies x \leq 0 \implies x + y \in \text{HInfinite}$   
**for**  $x\ y :: \text{hypreal}$

**by** (*metis (no-types, lifting) HInfinite-add-ge-zero2 HInfinite-minus-iff add.inverse-distrib-swap neg-0-le-iff-le*)

**lemma** *HInfinite-add-lt-zero*:  $x \in HInfinite \implies y < 0 \implies x < 0 \implies x + y \in HInfinite$

**for**  $x\ y :: \text{hypreal}$

**by** (*blast intro: HInfinite-add-le-zero order-less-imp-le*)

**lemma** *not-Infinitesimal-not-zero*:  $x \notin \text{Infinitesimal} \implies x \neq 0$

**by** *auto*

**lemma** *HFinite-diff-Infinitesimal-hrabs*:

$x \in HFinite - \text{Infinitesimal} \implies |x| \in HFinite - \text{Infinitesimal}$

**for**  $x :: \text{hypreal}$

**by** *blast*

**lemma** *hnorm-le-Infinitesimal*:  $e \in \text{Infinitesimal} \implies \text{hnorm } x \leq e \implies x \in \text{Infinitesimal}$

**by** (*auto simp: Infinitesimal-def abs-less-iff*)

**lemma** *hnorm-less-Infinitesimal*:  $e \in \text{Infinitesimal} \implies \text{hnorm } x < e \implies x \in \text{Infinitesimal}$

**by** (*erule hnorm-le-Infinitesimal, erule order-less-imp-le*)

**lemma** *hrabs-le-Infinitesimal*:  $e \in \text{Infinitesimal} \implies |x| \leq e \implies x \in \text{Infinitesimal}$

**for**  $x :: \text{hypreal}$

**by** (*erule hnorm-le-Infinitesimal*) *simp*

**lemma** *hrabs-less-Infinitesimal*:  $e \in \text{Infinitesimal} \implies |x| < e \implies x \in \text{Infinitesimal}$

**for**  $x :: \text{hypreal}$

**by** (*erule hnorm-less-Infinitesimal*) *simp*

**lemma** *Infinitesimal-interval*:

$e \in \text{Infinitesimal} \implies e' \in \text{Infinitesimal} \implies e' < x \implies x < e \implies x \in \text{Infinitesimal}$

**for**  $x :: \text{hypreal}$

**by** (*auto simp add: Infinitesimal-def abs-less-iff*)

**lemma** *Infinitesimal-interval2*:

$e \in \text{Infinitesimal} \implies e' \in \text{Infinitesimal} \implies e' \leq x \implies x \leq e \implies x \in \text{Infinitesimal}$

**for**  $x :: \text{hypreal}$

**by** (*auto intro: Infinitesimal-interval simp add: order-le-less*)

**lemma** *lemma-Infinitesimal-hyperpow*:  $x \in \text{Infinitesimal} \implies 0 < N \implies |x \text{ pow } N| \leq |x|$

**for**  $x :: \text{hypreal}$

**apply** (*clarsimp simp: Infinitesimal-def*)

**by** (*metis Reals-1 abs-ge-zero hyperpow-Suc-le-self2 hyperpow-hrabs hypnat-gt-zero-iff2 zero-less-one*)

**lemma** *Infinitesimal-hyperpow*:  $x \in \text{Infinitesimal} \implies 0 < N \implies x \text{ pow } N \in \text{Infinitesimal}$

**for**  $x :: \text{hypreal}$

**using** *hrabs-le-Infinitesimal lemma-Infinitesimal-hyperpow* **by** *blast*

**lemma** *hrealpow-hyperpow-Infinitesimal-iff*:

$(x \hat{\ } n \in \text{Infinitesimal}) \longleftrightarrow x \text{ pow } (\text{hypnat-of-nat } n) \in \text{Infinitesimal}$

**by** (*simp only: hyperpow-hypnat-of-nat*)

**lemma** *Infinitesimal-hrealpow*:  $x \in \text{Infinitesimal} \implies 0 < n \implies x \hat{\ } n \in \text{Infinitesimal}$

**for**  $x :: \text{hypreal}$

**by** (*simp add: hrealpow-hyperpow-Infinitesimal-iff Infinitesimal-hyperpow*)

**lemma** *not-Infinitesimal-mult*:

$x \notin \text{Infinitesimal} \implies y \notin \text{Infinitesimal} \implies x * y \notin \text{Infinitesimal}$

**for**  $x y :: 'a::\text{real-normed-div-algebra star}$

**by** (*metis (no-types, lifting) inverse-Infinitesimal-iff-HInfinite ComplI Compl-HFinite Infinitesimal-HFinite-mult divide-inverse eq-divide-imp inverse-inverse-eq mult-zero-right*)

**lemma** *Infinitesimal-mult-disj*:  $x * y \in \text{Infinitesimal} \implies x \in \text{Infinitesimal} \vee y \in \text{Infinitesimal}$

**for**  $x y :: 'a::\text{real-normed-div-algebra star}$

**using** *not-Infinitesimal-mult* **by** *blast*

**lemma** *HFinite-Infinitesimal-not-zero*:  $x \in \text{HFinite} - \text{Infinitesimal} \implies x \neq 0$

**by** *blast*

**lemma** *HFinite-Infinitesimal-diff-mult*:

$x \in \text{HFinite} - \text{Infinitesimal} \implies y \in \text{HFinite} - \text{Infinitesimal} \implies x * y \in \text{HFinite} - \text{Infinitesimal}$

**for**  $x y :: 'a::\text{real-normed-div-algebra star}$

**by** (*simp add: HFinite-mult not-Infinitesimal-mult*)

**lemma** *Infinitesimal-subset-HFinite*:  $\text{Infinitesimal} \subseteq \text{HFinite}$

**using** *HFinite-def InfinitesimalD Reals-1 zero-less-one* **by** *blast*

**lemma** *Infinitesimal-star-of-mult*:  $x \in \text{Infinitesimal} \implies x * \text{star-of } r \in \text{Infinitesimal}$

**for**  $x :: 'a::\text{real-normed-algebra star}$

**by** (*erule HFinite-star-of [THEN [2] Infinitesimal-HFinite-mult]*)

**lemma** *Infinitesimal-star-of-mult2*:  $x \in \text{Infinitesimal} \implies \text{star-of } r * x \in \text{Infinitesimal}$

**for**  $x :: 'a::\text{real-normed-algebra star}$

**by** (*erule HFinite-star-of [THEN [2] Infinitesimal-HFinite-mult2]*)



## 5.5 The Infinitely Close Relation

**lemma** *mem-infmal-iff*:  $x \in \text{Infinitesimal} \longleftrightarrow x \approx 0$   
**by** (*simp add: Infinitesimal-def approx-def*)

**lemma** *approx-minus-iff*:  $x \approx y \longleftrightarrow x - y \approx 0$   
**by** (*simp add: approx-def*)

**lemma** *approx-minus-iff2*:  $x \approx y \longleftrightarrow -y + x \approx 0$   
**by** (*simp add: approx-def add.commute*)

**lemma** *approx-refl [iff]*:  $x \approx x$   
**by** (*simp add: approx-def Infinitesimal-def*)

**lemma** *approx-sym*:  $x \approx y \Longrightarrow y \approx x$   
**by** (*metis Infinitesimal-minus-iff approx-def minus-diff-eq*)

**lemma** *approx-trans*:  
**assumes**  $x \approx y$   $y \approx z$  **shows**  $x \approx z$

**proof** –  
**have**  $x - y \in \text{Infinitesimal}$   $z - y \in \text{Infinitesimal}$   
**using** *assms approx-def approx-sym* **by** *auto*  
**then have**  $x - z \in \text{Infinitesimal}$   
**using** *Infinitesimal-diff* **by** *force*  
**then show** *?thesis*  
**by** (*simp add: approx-def*)

**qed**

**lemma** *approx-trans2*:  $r \approx x \Longrightarrow s \approx x \Longrightarrow r \approx s$   
**by** (*blast intro: approx-sym approx-trans*)

**lemma** *approx-trans3*:  $x \approx r \Longrightarrow x \approx s \Longrightarrow r \approx s$   
**by** (*blast intro: approx-sym approx-trans*)

**lemma** *approx-reorient*:  $x \approx y \longleftrightarrow y \approx x$   
**by** (*blast intro: approx-sym*)

Reorientation simplification procedure: reorients (polymorphic)  $0 = x$ ,  $1 = x$ ,  $nnn = x$  provided  $x$  isn't  $0$ ,  $1$  or a numeral.

**simproc-setup** *approx-reorient-simproc*  
 $(0 \approx x \mid 1 \approx y \mid \text{numeral } w \approx z \mid -1 \approx y \mid - \text{numeral } w \approx r) =$   
 $\langle$   
*let val rule = @{thm approx-reorient} RS eq-reflection*  
*fun proc phi ss ct =*  
*case Thm.term-of ct of*  
*- \$ t \$ u => if can HOLogic.dest-number u then NONE*  
*else if can HOLogic.dest-number t then SOME rule else NONE*  
*| - => NONE*  
*in proc end*  
 $\rangle$

**lemma** *Infinitesimal-approx-minus*:  $x - y \in \text{Infinitesimal} \longleftrightarrow x \approx y$   
**by** (*simp add: approx-minus-iff [symmetric] mem-infmal-iff*)

**lemma** *approx-monad-iff*:  $x \approx y \longleftrightarrow \text{monad } x = \text{monad } y$   
**apply** (*simp add: monad-def set-eq-iff*)  
**using** *approx-reorient approx-trans* **by** *blast*

**lemma** *Infinitesimal-approx*:  $x \in \text{Infinitesimal} \implies y \in \text{Infinitesimal} \implies x \approx y$   
**by** (*simp add: Infinitesimal-diff approx-def*)

**lemma** *approx-add*:  $a \approx b \implies c \approx d \implies a + c \approx b + d$

**proof** (*unfold approx-def*)  
**assume** *inf*:  $a - b \in \text{Infinitesimal}$   $c - d \in \text{Infinitesimal}$   
**have**  $a + c - (b + d) = (a - b) + (c - d)$  **by** *simp*  
**also have**  $\dots \in \text{Infinitesimal}$   
**using** *inf* **by** (*rule Infinitesimal-add*)  
**finally show**  $a + c - (b + d) \in \text{Infinitesimal}$  .  
**qed**

**lemma** *approx-minus*:  $a \approx b \implies -a \approx -b$   
**by** (*metis approx-def approx-sym minus-diff-eq minus-diff-minus*)

**lemma** *approx-minus2*:  $-a \approx -b \implies a \approx b$   
**by** (*auto dest: approx-minus*)

**lemma** *approx-minus-cancel [simp]*:  $-a \approx -b \longleftrightarrow a \approx b$   
**by** (*blast intro: approx-minus approx-minus2*)

**lemma** *approx-add-minus*:  $a \approx b \implies c \approx d \implies a + -c \approx b + -d$   
**by** (*blast intro!: approx-add approx-minus*)

**lemma** *approx-diff*:  $a \approx b \implies c \approx d \implies a - c \approx b - d$   
**using** *approx-add [of a b - c - d]* **by** *simp*

**lemma** *approx-mult1*:  $a \approx b \implies c \in \text{HFinite} \implies a * c \approx b * c$   
**for**  $a b c :: 'a::\text{real-normed-algebra star}$   
**by** (*simp add: approx-def Infinitesimal-HFinite-mult left-diff-distrib [symmetric]*)

**lemma** *approx-mult2*:  $a \approx b \implies c \in \text{HFinite} \implies c * a \approx c * b$   
**for**  $a b c :: 'a::\text{real-normed-algebra star}$   
**by** (*simp add: approx-def Infinitesimal-HFinite-mult2 right-diff-distrib [symmetric]*)

**lemma** *approx-mult-subst*:  $u \approx v * x \implies x \approx y \implies v \in \text{HFinite} \implies u \approx v * y$   
**for**  $u v x y :: 'a::\text{real-normed-algebra star}$   
**by** (*blast intro: approx-mult2 approx-trans*)

**lemma** *approx-mult-subst2*:  $u \approx x * v \implies x \approx y \implies v \in \text{HFinite} \implies u \approx y * v$   
**for**  $u v x y :: 'a::\text{real-normed-algebra star}$

by (blast intro: approx-mult1 approx-trans)

**lemma** *approx-mult-subst-star-of*:  $u \approx x * \text{star-of } v \implies x \approx y \implies u \approx y * \text{star-of } v$   
 for  $u x y :: 'a::\text{real-normed-algebra star}$   
 by (auto intro: approx-mult-subst2)

**lemma** *approx-eq-imp*:  $a = b \implies a \approx b$   
 by (simp add: approx-def)

**lemma** *Infinitesimal-minus-approx*:  $x \in \text{Infinitesimal} \implies -x \approx x$   
 by (blast intro: *Infinitesimal-minus-iff* [THEN *iffD2*] *mem-infmal-iff* [THEN *iffD1*] *approx-trans2*)

**lemma** *bex-Infinitesimal-iff*:  $(\exists y \in \text{Infinitesimal}. x - z = y) \longleftrightarrow x \approx z$   
 by (simp add: approx-def)

**lemma** *bex-Infinitesimal-iff2*:  $(\exists y \in \text{Infinitesimal}. x = z + y) \longleftrightarrow x \approx z$   
 by (force simp add: *bex-Infinitesimal-iff* [symmetric])

**lemma** *Infinitesimal-add-approx*:  $y \in \text{Infinitesimal} \implies x + y = z \implies x \approx z$   
 using *approx-sym bex-Infinitesimal-iff2* by blast

**lemma** *Infinitesimal-add-approx-self*:  $y \in \text{Infinitesimal} \implies x \approx x + y$   
 by (simp add: *Infinitesimal-add-approx*)

**lemma** *Infinitesimal-add-approx-self2*:  $y \in \text{Infinitesimal} \implies x \approx y + x$   
 by (auto dest: *Infinitesimal-add-approx-self* simp add: *add commute*)

**lemma** *Infinitesimal-add-minus-approx-self*:  $y \in \text{Infinitesimal} \implies x \approx x + -y$   
 by (blast intro!: *Infinitesimal-add-approx-self* *Infinitesimal-minus-iff* [THEN *iffD2*])

**lemma** *Infinitesimal-add-cancel*:  $y \in \text{Infinitesimal} \implies x + y \approx z \implies x \approx z$   
 using *Infinitesimal-add-approx approx-trans* by blast

**lemma** *Infinitesimal-add-right-cancel*:  $y \in \text{Infinitesimal} \implies x \approx z + y \implies x \approx z$   
 by (*metis* *Infinitesimal-add-approx-self approx-monad-iff*)

**lemma** *approx-add-left-cancel*:  $d + b \approx d + c \implies b \approx c$   
 by (*metis* *add-diff-cancel-left bex-Infinitesimal-iff*)

**lemma** *approx-add-right-cancel*:  $b + d \approx c + d \implies b \approx c$   
 by (simp add: approx-def)

**lemma** *approx-add-mono1*:  $b \approx c \implies d + b \approx d + c$   
 by (simp add: approx-add)

**lemma** *approx-add-mono2*:  $b \approx c \implies b + a \approx c + a$   
 by (simp add: *add commute approx-add-mono1*)

**lemma** *approx-add-left-iff* [*simp*]:  $a + b \approx a + c \longleftrightarrow b \approx c$   
**by** (*fast elim: approx-add-left-cancel approx-add-mono1*)

**lemma** *approx-add-right-iff* [*simp*]:  $b + a \approx c + a \longleftrightarrow b \approx c$   
**by** (*simp add: add.commute*)

**lemma** *approx-HFinite*:  $x \in \text{HFinite} \implies x \approx y \implies y \in \text{HFinite}$   
**by** (*metis HFinite-add Infinitesimal-subset-HFinite approx-sym subsetD bez-Infinitesimal-iff2*)

**lemma** *approx-star-of-HFinite*:  $x \approx \text{star-of } D \implies x \in \text{HFinite}$   
**by** (*rule approx-sym [THEN [2] approx-HFinite], auto*)

**lemma** *approx-mult-HFinite*:  $a \approx b \implies c \approx d \implies b \in \text{HFinite} \implies d \in \text{HFinite} \implies a * c \approx b * d$   
**for**  $a \ b \ c \ d :: 'a::\text{real-normed-algebra star}$   
**by** (*meson approx-HFinite approx-mult2 approx-mult-subst2 approx-sym*)

**lemma** *scaleHR-left-diff-distrib*:  $\bigwedge a \ b \ x. \text{scaleHR } (a - b) \ x = \text{scaleHR } a \ x - \text{scaleHR } b \ x$   
**by** *transfer (rule scaleR-left-diff-distrib)*

**lemma** *approx-scaleR1*:  $a \approx \text{star-of } b \implies c \in \text{HFinite} \implies \text{scaleHR } a \ c \approx b *_R c$   
**unfolding** *approx-def*  
**by** (*metis Infinitesimal-HFinite-scaleHR scaleHR-def scaleHR-left-diff-distrib star-scaleR-def starfun2-star-of*)

**lemma** *approx-scaleR2*:  $a \approx b \implies c *_R a \approx c *_R b$   
**by** (*simp add: approx-def Infinitesimal-scaleR2 scaleR-right-diff-distrib [symmetric]*)

**lemma** *approx-scaleR-HFinite*:  $a \approx \text{star-of } b \implies c \approx d \implies d \in \text{HFinite} \implies \text{scaleHR } a \ c \approx b *_R d$   
**by** (*meson approx-HFinite approx-scaleR1 approx-scaleR2 approx-sym approx-trans*)

**lemma** *approx-mult-star-of*:  $a \approx \text{star-of } b \implies c \approx \text{star-of } d \implies a * c \approx \text{star-of } b * \text{star-of } d$   
**for**  $a \ c :: 'a::\text{real-normed-algebra star}$   
**by** (*blast intro!: approx-mult-HFinite approx-star-of-HFinite HFinite-star-of*)

**lemma** *approx-SReal-mult-cancel-zero*:  
**fixes**  $a \ x :: \text{hypreal}$   
**assumes**  $a \in \mathbb{R} \ a \neq 0 \ a * x \approx 0$  **shows**  $x \approx 0$   
**proof** –  
**have**  $\text{inverse } a \in \text{HFinite}$   
**using** *Reals-inverse SReal-subset-HFinite assms(1)* **by** *blast*  
**then show** *?thesis*  
**using** *assms* **by** (*auto dest: approx-mult2 simp add: mult.assoc [symmetric]*)  
**qed**

**lemma** *approx-mult-SReal1*:  $a \in \mathbb{R} \implies x \approx 0 \implies x * a \approx 0$   
**for**  $a x :: \text{hypreal}$   
**by** (*auto dest: SReal-subset-HFinite [THEN subsetD] approx-mult1*)

**lemma** *approx-mult-SReal2*:  $a \in \mathbb{R} \implies x \approx 0 \implies a * x \approx 0$   
**for**  $a x :: \text{hypreal}$   
**by** (*auto dest: SReal-subset-HFinite [THEN subsetD] approx-mult2*)

**lemma** *approx-mult-SReal-zero-cancel-iff* [*simp*]:  $a \in \mathbb{R} \implies a \neq 0 \implies a * x \approx 0 \iff x \approx 0$   
**for**  $a x :: \text{hypreal}$   
**by** (*blast intro: approx-SReal-mult-cancel-zero approx-mult-SReal2*)

**lemma** *approx-SReal-mult-cancel*:  
**fixes**  $a w z :: \text{hypreal}$   
**assumes**  $a \in \mathbb{R} a \neq 0 a * w \approx a * z$  **shows**  $w \approx z$   
**proof** –  
**have** *inverse*  $a \in \text{HFinite}$   
**using** *Reals-inverse SReal-subset-HFinite assms(1)* **by** *blast*  
**then show** *?thesis*  
**using** *assms* **by** (*auto dest: approx-mult2 simp add: mult.assoc [symmetric]*)  
**qed**

**lemma** *approx-SReal-mult-cancel-iff1* [*simp*]:  $a \in \mathbb{R} \implies a \neq 0 \implies a * w \approx a * z \iff w \approx z$   
**for**  $a w z :: \text{hypreal}$   
**by** (*meson SReal-subset-HFinite approx-SReal-mult-cancel approx-mult2 subsetD*)

**lemma** *approx-le-bound*:  
**fixes**  $z :: \text{hypreal}$   
**assumes**  $z \leq f f \approx g g \leq z$  **shows**  $f \approx z$   
**proof** –  
**obtain**  $y$  **where**  $z \leq g + y$  **and**  $y \in \text{Infinitesimal}$   $f = g + y$   
**using** *assms* *bex-Infinitesimal-iff2* **by** *auto*  
**then have**  $z - g \in \text{Infinitesimal}$   
**using** *assms(3)* *hrabs-le-Infinitesimal* **by** *auto*  
**then show** *?thesis*  
**by** (*metis approx-def approx-trans2 assms(2)*)  
**qed**

**lemma** *approx-hnorm*:  $x \approx y \implies \text{hnorm } x \approx \text{hnorm } y$   
**for**  $x y :: \text{'a::real-normed-vector star}$   
**proof** (*unfold approx-def*)  
**assume**  $x - y \in \text{Infinitesimal}$   
**then have**  $\text{hnorm } (x - y) \in \text{Infinitesimal}$   
**by** (*simp only: Infinitesimal-hnorm-iff*)  
**moreover have**  $(0::\text{real star}) \in \text{Infinitesimal}$   
**by** (*rule Infinitesimal-zero*)  
**moreover have**  $0 \leq |\text{hnorm } x - \text{hnorm } y|$

by (rule abs-ge-zero)  
 moreover have  $|hnorm\ x - hnorm\ y| \leq hnorm\ (x - y)$   
 by (rule hnorm-triangle-ineq3)  
 ultimately have  $|hnorm\ x - hnorm\ y| \in Infinitesimal$   
 by (rule Infinitesimal-interval2)  
 then show  $hnorm\ x - hnorm\ y \in Infinitesimal$   
 by (simp only: Infinitesimal-hrabs-iff)  
 qed

## 5.6 Zero is the Only Infinitesimal that is also a Real

**lemma** *Infinitesimal-less-SReal*:  $x \in \mathbb{R} \implies y \in Infinitesimal \implies 0 < x \implies y < x$   
 for  $x\ y :: hypreal$   
 using *InfinitesimalD* by fastforce

**lemma** *Infinitesimal-less-SReal2*:  $y \in Infinitesimal \implies \forall r \in Reals. 0 < r \implies y < r$   
 for  $y :: hypreal$   
 by (blast intro: *Infinitesimal-less-SReal*)

**lemma** *SReal-not-Infinitesimal*:  $0 < y \implies y \in \mathbb{R} \implies y \notin Infinitesimal$   
 for  $y :: hypreal$   
 by (auto simp add: *Infinitesimal-def abs-iff*)

**lemma** *SReal-minus-not-Infinitesimal*:  $y < 0 \implies y \in \mathbb{R} \implies y \notin Infinitesimal$   
 for  $y :: hypreal$   
 using *Infinitesimal-minus-iff Reals-minus SReal-not-Infinitesimal neg-0-less-iff-less*  
 by blast

**lemma** *SReal-Int-Infinitesimal-zero*:  $\mathbb{R} \cap Int\ Infinitesimal = \{0 :: hypreal\}$   
 proof –  
 have  $x = 0$  if  $x \in \mathbb{R} \ x \in Infinitesimal$  for  $x :: real\ star$   
 using that *SReal-minus-not-Infinitesimal SReal-not-Infinitesimal not-less-iff-gr-or-eq*  
 by blast  
 then show ?thesis  
 by auto  
 qed

**lemma** *SReal-Infinitesimal-zero*:  $x \in \mathbb{R} \implies x \in Infinitesimal \implies x = 0$   
 for  $x :: hypreal$   
 using *SReal-Int-Infinitesimal-zero* by blast

**lemma** *SReal-HFinite-diff-Infinitesimal*:  $x \in \mathbb{R} \implies x \neq 0 \implies x \in HFinite - Infinitesimal$   
 for  $x :: hypreal$   
 by (auto dest: *SReal-Infinitesimal-zero SReal-subset-HFinite [THEN subsetD]*)

**lemma** *hypreal-of-real-HFinite-diff-Infinitesimal*:

*hypreal-of-real*  $x \neq 0 \implies \text{hypreal-of-real } x \in \text{HFinite} - \text{Infinitesimal}$   
**by** (rule *SReal-HFinite-diff-Infinitesimal*) *auto*

**lemma** *star-of-Infinitesimal-iff-0* [*iff*]: *star-of*  $x \in \text{Infinitesimal} \iff x = 0$

**proof**

**show**  $x = 0$  **if** *star-of*  $x \in \text{Infinitesimal}$

**proof** –

**have** *hnorm* (*star-n* ( $\lambda n. x$ ))  $\in \text{Standard}$

**by** (*metis* *Reals-eq-Standard SReal-iff star-of-def star-of-norm*)

**then show** *?thesis*

**by** (*metis* *InfinitesimalD2 less-irrefl star-of-norm that zero-less-norm-iff*)

**qed**

**qed** *auto*

**lemma** *star-of-HFinite-diff-Infinitesimal*:  $x \neq 0 \implies \text{star-of } x \in \text{HFinite} - \text{Infinitesimal}$

**by** *simp*

**lemma** *numeral-not-Infinitesimal* [*simp*]:

*numeral*  $w \neq (0 :: \text{hypreal}) \implies (\text{numeral } w :: \text{hypreal}) \notin \text{Infinitesimal}$

**by** (*fast dest*: *Reals-numeral [THEN SReal-Infinitesimal-zero]*)

Again: 1 is a special case, but not 0 this time.

**lemma** *one-not-Infinitesimal* [*simp*]:

( $1 :: 'a :: \{\text{real-normed-vector}, \text{zero-neq-one}\}$  *star*)  $\notin \text{Infinitesimal}$

**by** (*metis* *star-of-Infinitesimal-iff-0 star-one-def zero-neq-one*)

**lemma** *approx-SReal-not-zero*:  $y \in \mathbb{R} \implies x \approx y \implies y \neq 0 \implies x \neq 0$

**for**  $x y :: \text{hypreal}$

**using** *SReal-Infinitesimal-zero approx-sym mem-infmal-iff* **by** *auto*

**lemma** *HFinite-diff-Infinitesimal-approx*:

$x \approx y \implies y \in \text{HFinite} - \text{Infinitesimal} \implies x \in \text{HFinite} - \text{Infinitesimal}$

**by** (*meson* *Diff-iff approx-HFinite approx-sym approx-trans3 mem-infmal-iff*)

The premise  $y \neq 0$  is essential; otherwise  $x / y = 0$  and we lose the *HFinite* premise.

**lemma** *Infinitesimal-ratio*:

$y \neq 0 \implies y \in \text{Infinitesimal} \implies x / y \in \text{HFinite} \implies x \in \text{Infinitesimal}$

**for**  $x y :: 'a :: \{\text{real-normed-div-algebra}, \text{field}\}$  *star*

**using** *Infinitesimal-HFinite-mult* **by** *fastforce*

**lemma** *Infinitesimal-SReal-divide*:  $x \in \text{Infinitesimal} \implies y \in \mathbb{R} \implies x / y \in \text{Infinitesimal}$

**for**  $x y :: \text{hypreal}$

**by** (*metis* *HFinite-star-of Infinitesimal-HFinite-mult Reals-inverse SReal-iff divide-inverse*)

## 6 Standard Part Theorem

Every finite  $x \in R^*$  is infinitely close to a unique real number (i.e. a member of *Reals*).

### 6.1 Uniqueness: Two Infinitely Close Reals are Equal

**lemma** *star-of-approx-iff* [simp]:  $\text{star-of } x \approx \text{star-of } y \longleftrightarrow x = y$   
 by (*metis approx-def right-minus-eq star-of-Infinitesimal-iff-0 star-of-simps(2)*)

**lemma** *SReal-approx-iff*:  $x \in \mathbb{R} \implies y \in \mathbb{R} \implies x \approx y \longleftrightarrow x = y$   
 for  $x y :: \text{hypreal}$   
 by (*meson Reals-diff SReal-Infinitesimal-zero approx-def approx-refl right-minus-eq*)

**lemma** *numeral-approx-iff* [simp]:  
 $(\text{numeral } v \approx (\text{numeral } w :: 'a::\{\text{numeral,real-normed-vector}\} \text{star})) = (\text{numeral } v = (\text{numeral } w :: 'a))$   
 by (*metis star-of-approx-iff star-of-numeral*)

And also for  $0 \approx \#nn$  and  $1 \approx \#nn$ ,  $\#nn \approx 0$  and  $\#nn \approx 1$ .

**lemma** [simp]:  
 $(\text{numeral } w \approx (0::'a::\{\text{numeral,real-normed-vector}\} \text{star})) = (\text{numeral } w = (0::'a))$   
 $((0::'a::\{\text{numeral,real-normed-vector}\} \text{star}) \approx \text{numeral } w) = (\text{numeral } w = (0::'a))$   
 $(\text{numeral } w \approx (1::'b::\{\text{numeral,one,real-normed-vector}\} \text{star})) = (\text{numeral } w = (1::'b))$   
 $((1::'b::\{\text{numeral,one,real-normed-vector}\} \text{star}) \approx \text{numeral } w) = (\text{numeral } w = (1::'b))$   
 $\neg (0 \approx (1::'c::\{\text{zero-neq-one,real-normed-vector}\} \text{star}))$   
 $\neg (1 \approx (0::'c::\{\text{zero-neq-one,real-normed-vector}\} \text{star}))$   
**unfolding** *star-numeral-def star-zero-def star-one-def star-of-approx-iff*  
 by (*auto intro: sym*)

**lemma** *star-of-approx-numeral-iff* [simp]:  $\text{star-of } k \approx \text{numeral } w \longleftrightarrow k = \text{numeral } w$   
 by (*subst star-of-approx-iff [symmetric] auto*)

**lemma** *star-of-approx-zero-iff* [simp]:  $\text{star-of } k \approx 0 \longleftrightarrow k = 0$   
 by (*simp-all add: star-of-approx-iff [symmetric]*)

**lemma** *star-of-approx-one-iff* [simp]:  $\text{star-of } k \approx 1 \longleftrightarrow k = 1$   
 by (*simp-all add: star-of-approx-iff [symmetric]*)

**lemma** *approx-unique-real*:  $r \in \mathbb{R} \implies s \in \mathbb{R} \implies r \approx x \implies s \approx x \implies r = s$   
 for  $r s :: \text{hypreal}$   
 by (*blast intro: SReal-approx-iff [THEN iffD1] approx-trans2*)



## 6.2 Existence of Unique Real Infinitely Close

### 6.2.1 Lifting of the Ub and Lub Properties

**lemma** *hypreal-of-real-isUb-iff*:  $isUb \mathbb{R} (hypreal-of-real \text{ ‘ } Q) (hypreal-of-real Y) = isUb UNIV Q Y$   
**for**  $Q :: real\ set$  **and**  $Y :: real$   
**by** (*simp add: isUb-def settle-def*)

**lemma** *hypreal-of-real-isLub-iff*:  
 $isLub \mathbb{R} (hypreal-of-real \text{ ‘ } Q) (hypreal-of-real Y) = isLub (UNIV :: real\ set) Q Y$   
**(is ?lhs = ?rhs)**  
**for**  $Q :: real\ set$  **and**  $Y :: real$   
**proof**  
**assume**  $?lhs$   
**then show**  $?rhs$   
**by** (*simp add: isLub-def leastP-def*) (*metis hypreal-of-real-isUb-iff mem-Collect-eq setge-def star-of-le*)  
**next**  
**assume**  $?rhs$   
**then show**  $?lhs$   
**apply** (*simp add: isLub-def leastP-def hypreal-of-real-isUb-iff setge-def*)  
**by** (*metis SReal-iff hypreal-of-real-isUb-iff isUb-def star-of-le*)  
**qed**

**lemma** *lemma-isUb-hypreal-of-real*:  $isUb \mathbb{R} P Y \implies \exists Yo. isUb \mathbb{R} P (hypreal-of-real Yo)$   
**by** (*auto simp add: SReal-iff isUb-def*)

**lemma** *lemma-isLub-hypreal-of-real*:  $isLub \mathbb{R} P Y \implies \exists Yo. isLub \mathbb{R} P (hypreal-of-real Yo)$   
**by** (*auto simp add: isLub-def leastP-def isUb-def SReal-iff*)

**lemma** *SReal-complete*:  
**fixes**  $P :: hypreal\ set$   
**assumes**  $isUb \mathbb{R} P Y P \subseteq \mathbb{R} P \neq \{\}$   
**shows**  $\exists t. isLub \mathbb{R} P t$   
**proof** –  
**obtain**  $Q$  **where**  $P = hypreal-of-real \text{ ‘ } Q$   
**by** (*metis  $\langle P \subseteq \mathbb{R} \rangle hypreal-of-real-image subset-imageE$* )  
**then show**  $?thesis$   
**by** (*metis assms(1)  $\langle P \neq \{\} \rangle equals0I hypreal-of-real-isLub-iff hypreal-of-real-isUb-iff image-empty lemma-isUb-hypreal-of-real reals-complete$* )  
**qed**

Lemmas about lubs.

**lemma** *lemma-st-part-lub*:  
**fixes**  $x :: hypreal$   
**assumes**  $x \in HFinite$   
**shows**  $\exists t. isLub \mathbb{R} \{s. s \in \mathbb{R} \wedge s < x\} t$

**proof** –

**obtain**  $t$  **where**  $t: t \in \mathbb{R} \text{ hnorm } x < t$   
**using**  $HFiniteD$  *assms* **by** *blast*  
**then have**  $isUb \mathbb{R} \{s. s \in \mathbb{R} \wedge s < x\} t$   
**by** (*simp add: abs-less-iff isUbI le-less-linear less-imp-not-less settleI*)  
**moreover have**  $\exists y. y \in \mathbb{R} \wedge y < x$   
**using**  $t$  **by** (*rule-tac x = -t in exI*) (*auto simp add: abs-less-iff*)  
**ultimately show** *?thesis*  
**using**  $SReal-complete$  **by** *fastforce*

**qed**

**lemma** *hypreal-settle-less-trans*:  $S * <= x \implies x < y \implies S * <= y$   
**for**  $x y :: \text{hypreal}$   
**by** (*meson le-less-trans less-imp-le settle-def*)

**lemma** *hypreal-gt-isUb*:  $isUb R S x \implies x < y \implies y \in R \implies isUb R S y$   
**for**  $x y :: \text{hypreal}$   
**using** *hypreal-settle-less-trans isUb-def* **by** *blast*

**lemma** *lemma-SReal-ub*:  $x \in \mathbb{R} \implies isUb \mathbb{R} \{s. s \in \mathbb{R} \wedge s < x\} x$   
**for**  $x :: \text{hypreal}$   
**by** (*auto intro: isUbI settleI order-less-imp-le*)

**lemma** *lemma-SReal-lub*:

**fixes**  $x :: \text{hypreal}$   
**assumes**  $x \in \mathbb{R}$  **shows**  $isLub \mathbb{R} \{s. s \in \mathbb{R} \wedge s < x\} x$

**proof** –

**have**  $x \leq y$  **if**  $isUb \mathbb{R} \{s \in \mathbb{R}. s < x\} y$  **for**  $y$

**proof** –

**have**  $y \in \mathbb{R}$   
**using** *isUbD2a* **that** **by** *blast*  
**show** *?thesis*  
**proof** (*cases x y rule: linorder-cases*)  
**case** *greater*  
**then obtain**  $r$  **where**  $y < r r < x$   
**using** *dense* **by** *blast*  
**then show** *?thesis*  
**using** *isUbD* [*OF that*]  
**by** *simp* (*meson SReal-dense <y ∈ ℝ> assms greater not-le*)

**qed** *auto*

**qed**

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

**by** (*simp add: isLubI2 isUbI setgeI settleI*)

**qed**

**lemma** *lemma-st-part-major*:

**fixes**  $x r t :: \text{hypreal}$

**assumes**  $x: x \in HFinite$  **and**  $r: r \in \mathbb{R} 0 < r$  **and**  $t: isLub \mathbb{R} \{s. s \in \mathbb{R} \wedge s < x\} t$

**shows**  $|x - t| < r$   
**proof** –  
**have**  $t \in \mathbb{R}$   
**using** *isLubD1a t by blast*  
**have** *lemma-st-part-gt-ub:  $x < r \implies r \in \mathbb{R} \implies \text{isUb } \mathbb{R} \{s. s \in \mathbb{R} \wedge s < x\} r$*   
**for**  $r :: \text{hypreal}$   
**by** (*auto dest: order-less-trans intro: order-less-imp-le intro!: isUbI setleI*)  
  
**have** *isUb  $\mathbb{R} \{s \in \mathbb{R}. s < x\} t$*   
**by** (*simp add: t isLub-isUb*)  
**then have**  $\neg r + t < x$   
**by** (*metis (mono-tags, lifting) Reals-add  $\langle t \in \mathbb{R} \rangle$  add-le-same-cancel2 isUbD leD mem-Collect-eq r*)  
**then have**  $x - t \leq r$   
**by** *simp*  
**moreover have**  $\neg x < t - r$   
**using** *lemma-st-part-gt-ub isLub-le-isUb  $\langle t \in \mathbb{R} \rangle$  r t x by fastforce*  
**then have**  $-(x - t) \leq r$   
**by** *linarith*  
**moreover have** *False if  $x - t = r \vee -(x - t) = r$*   
**proof** –  
**have**  $x \in \mathbb{R}$   
**by** (*metis  $\langle t \in \mathbb{R} \rangle \langle r \in \mathbb{R} \rangle$  that Reals-add-cancel Reals-minus-iff add-uminus-conv-diff*)  
**then have** *isLub  $\mathbb{R} \{s \in \mathbb{R}. s < x\} x$*   
**by** (*rule lemma-SReal-lub*)  
**then show** *False*  
**using** *r t that x isLub-unique by force*  
**qed**  
**ultimately show** *?thesis*  
**using** *abs-less-iff dual-order.order-iff-strict by blast*  
**qed**

**lemma** *lemma-st-part-major2:*

$x \in \text{HFinite} \implies \text{isLub } \mathbb{R} \{s. s \in \mathbb{R} \wedge s < x\} t \implies \forall r \in \text{Reals}. 0 < r \longrightarrow |x - t| < r$   
**for**  $x t :: \text{hypreal}$   
**by** (*blast dest!: lemma-st-part-major*)

Existence of real and Standard Part Theorem.

**lemma** *lemma-st-part-Ex:  $x \in \text{HFinite} \implies \exists t \in \text{Reals}. \forall r \in \text{Reals}. 0 < r \longrightarrow |x - t| < r$*   
**for**  $x :: \text{hypreal}$   
**by** (*meson isLubD1a lemma-st-part-lub lemma-st-part-major2*)

**lemma** *st-part-Ex:  $x \in \text{HFinite} \implies \exists t \in \text{Reals}. x \approx t$*

**for**  $x :: \text{hypreal}$   
**by** (*metis InfinitesimalI approx-def hypreal-hnorm-def lemma-st-part-Ex*)

There is a unique real infinitely close.

**lemma** *st-part-Ex1*:  $x \in \text{HFinite} \implies \exists ! t :: \text{hypreal}. t \in \mathbf{R} \wedge x \approx t$   
**by** (*meson SReal-approx-iff approx-trans2 st-part-Ex*)

### 6.3 Finite, Infinite and Infinitesimal

**lemma** *HFinite-Int-HInfinite-empty* [*simp*]:  $\text{HFinite Int HInfinite} = \{\}$   
**using** *Compl-HFinite* **by** *blast*

**lemma** *HFinite-not-HInfinite*:  
**assumes**  $x: x \in \text{HFinite}$  **shows**  $x \notin \text{HInfinite}$   
**using** *Compl-HFinite*  $x$  **by** *blast*

**lemma** *not-HFinite-HInfinite*:  $x \notin \text{HFinite} \implies x \in \text{HInfinite}$   
**using** *Compl-HFinite* **by** *blast*

**lemma** *HInfinite-HFinite-disj*:  $x \in \text{HInfinite} \vee x \in \text{HFinite}$   
**by** (*blast intro: not-HFinite-HInfinite*)

**lemma** *HInfinite-HFinite-iff*:  $x \in \text{HInfinite} \longleftrightarrow x \notin \text{HFinite}$   
**by** (*blast dest: HFinite-not-HInfinite not-HFinite-HInfinite*)

**lemma** *HFinite-HInfinite-iff*:  $x \in \text{HFinite} \longleftrightarrow x \notin \text{HInfinite}$   
**by** (*simp add: HInfinite-HFinite-iff*)

**lemma** *HInfinite-diff-HFinite-Infinitesimal-disj*:  
 $x \notin \text{Infinitesimal} \implies x \in \text{HInfinite} \vee x \in \text{HFinite} - \text{Infinitesimal}$   
**by** (*fast intro: not-HFinite-HInfinite*)

**lemma** *HFinite-inverse*:  $x \in \text{HFinite} \implies x \notin \text{Infinitesimal} \implies \text{inverse } x \in \text{HFinite}$   
**for**  $x :: 'a :: \text{real-normed-div-algebra star}$   
**using** *HInfinite-inverse-Infinitesimal not-HFinite-HInfinite* **by** *force*

**lemma** *HFinite-inverse2*:  $x \in \text{HFinite} - \text{Infinitesimal} \implies \text{inverse } x \in \text{HFinite}$   
**for**  $x :: 'a :: \text{real-normed-div-algebra star}$   
**by** (*blast intro: HFinite-inverse*)

Stronger statement possible in fact.

**lemma** *Infinitesimal-inverse-HFinite*:  $x \notin \text{Infinitesimal} \implies \text{inverse } x \in \text{HFinite}$   
**for**  $x :: 'a :: \text{real-normed-div-algebra star}$   
**using** *HFinite-HInfinite-iff HInfinite-inverse-Infinitesimal* **by** *fastforce*

**lemma** *HFinite-not-Infinitesimal-inverse*:  
 $x \in \text{HFinite} - \text{Infinitesimal} \implies \text{inverse } x \in \text{HFinite} - \text{Infinitesimal}$   
**for**  $x :: 'a :: \text{real-normed-div-algebra star}$   
**using** *HFinite-Infinitesimal-not-zero HFinite-inverse2 Infinitesimal-HFinite-mult2*  
**by** *fastforce*

**lemma** *approx-inverse*:

**fixes**  $x\ y :: 'a::\text{real-normed-div-algebra star}$   
**assumes**  $x \approx y$  **and**  $y: y \in \text{HFinite} - \text{Infinitesimal}$  **shows**  $\text{inverse } x \approx \text{inverse } y$   
**proof** –  
**have**  $x: x \in \text{HFinite} - \text{Infinitesimal}$   
**using**  $\text{HFinite-diff-Infinitesimal-approx assms}(1)$   $y$  **by**  $\text{blast}$   
**with**  $y \text{HFinite-inverse2}$  **have**  $\text{inverse } x \in \text{HFinite}$   $\text{inverse } y \in \text{HFinite}$   
**by**  $\text{blast+}$   
**then have**  $\text{inverse } y * x \approx 1$   
**by** ( $\text{metis Diff-iff approx-mult2 assms}(1)$   $\text{left-inverse not-Infinitesimal-not-zero } y$ )  
**then show**  $?thesis$   
**by** ( $\text{metis (no-types, lifting) DiffD2 HFinite-Infinitesimal-not-zero Infinitesimal-mult-disj } x \text{ approx-def approx-sym left-diff-distrib left-inverse}$ )  
**qed**

**lemmas**  $\text{star-of-approx-inverse} = \text{star-of-HFinite-diff-Infinitesimal}$  [ $\text{THEN [2] approx-inverse}$ ]

**lemmas**  $\text{hypreal-of-real-approx-inverse} = \text{hypreal-of-real-HFinite-diff-Infinitesimal}$  [ $\text{THEN [2] approx-inverse}$ ]

**lemma**  $\text{inverse-add-Infinitesimal-approx}$ :

$x \in \text{HFinite} - \text{Infinitesimal} \implies h \in \text{Infinitesimal} \implies \text{inverse } (x + h) \approx \text{inverse } x$

**for**  $x\ h :: 'a::\text{real-normed-div-algebra star}$

**by** ( $\text{auto intro: approx-inverse approx-sym Infinitesimal-add-approx-self}$ )

**lemma**  $\text{inverse-add-Infinitesimal-approx2}$ :

$x \in \text{HFinite} - \text{Infinitesimal} \implies h \in \text{Infinitesimal} \implies \text{inverse } (h + x) \approx \text{inverse } x$

**for**  $x\ h :: 'a::\text{real-normed-div-algebra star}$

**by** ( $\text{metis add.commute inverse-add-Infinitesimal-approx}$ )

**lemma**  $\text{inverse-add-Infinitesimal-approx-Infinitesimal}$ :

$x \in \text{HFinite} - \text{Infinitesimal} \implies h \in \text{Infinitesimal} \implies \text{inverse } (x + h) - \text{inverse } x \approx h$

**for**  $x\ h :: 'a::\text{real-normed-div-algebra star}$

**by** ( $\text{meson Infinitesimal-approx bex-Infinitesimal-iff inverse-add-Infinitesimal-approx}$ )

**lemma**  $\text{Infinitesimal-square-iff}$ :  $x \in \text{Infinitesimal} \iff x * x \in \text{Infinitesimal}$

**for**  $x :: 'a::\text{real-normed-div-algebra star}$

**using**  $\text{Infinitesimal-mult Infinitesimal-mult-disj}$  **by**  $\text{auto}$

**declare**  $\text{Infinitesimal-square-iff}$  [ $\text{symmetric, simp}$ ]

**lemma**  $\text{HFinite-square-iff}$  [ $\text{simp}$ ]:  $x * x \in \text{HFinite} \iff x \in \text{HFinite}$

**for**  $x :: 'a::\text{real-normed-div-algebra star}$

**using**  $\text{HFinite-HInfinite-iff HFinite-mult HInfinite-mult}$  **by**  $\text{blast}$

**lemma** *HInfinite-square-iff* [*simp*]:  $x * x \in HInfinite \longleftrightarrow x \in HInfinite$   
**for**  $x :: 'a::real-normed-div-algebra\ star$   
**by** (*auto simp add: HInfinite-HFinite-iff*)

**lemma** *approx-HFinite-mult-cancel*:  $a \in HFinite - Infinitesimal \implies a * w \approx a * z \implies w \approx z$   
**for**  $a\ w\ z :: 'a::real-normed-div-algebra\ star$   
**by** (*metis DiffD2 Infinitesimal-mult-disj beX-Infinitesimal-iff right-diff-distrib*)

**lemma** *approx-HFinite-mult-cancel-iff1*:  $a \in HFinite - Infinitesimal \implies a * w \approx a * z \longleftrightarrow w \approx z$   
**for**  $a\ w\ z :: 'a::real-normed-div-algebra\ star$   
**by** (*auto intro: approx-mult2 approx-HFinite-mult-cancel*)

**lemma** *HInfinite-HFinite-add-cancel*:  $x + y \in HInfinite \implies y \in HFinite \implies x \in HInfinite$   
**using** *HFinite-add HInfinite-HFinite-iff* **by** *blast*

**lemma** *HInfinite-HFinite-add*:  $x \in HInfinite \implies y \in HFinite \implies x + y \in HInfinite$   
**by** (*metis (no-types, opaque-lifting) HFinite-HInfinite-iff HFinite-add HFinite-minus-iff add commute add-minus-cancel*)

**lemma** *HInfinite-ge-HInfinite*:  $x \in HInfinite \implies x \leq y \implies 0 \leq x \implies y \in HInfinite$   
**for**  $x\ y :: hypreal$   
**by** (*auto intro: HFinite-bounded simp add: HInfinite-HFinite-iff*)

**lemma** *Infinitesimal-inverse-HInfinite*:  $x \in Infinitesimal \implies x \neq 0 \implies inverse\ x \in HInfinite$   
**for**  $x :: 'a::real-normed-div-algebra\ star$   
**by** (*metis Infinitesimal-HFinite-mult not-HFinite-HInfinite one-not-Infinitesimal right-inverse*)

**lemma** *HInfinite-HFinite-not-Infinitesimal-mult*:  
 $x \in HInfinite \implies y \in HFinite - Infinitesimal \implies x * y \in HInfinite$   
**for**  $x\ y :: 'a::real-normed-div-algebra\ star$   
**by** (*metis (no-types, opaque-lifting) HFinite-HInfinite-iff HFinite-Infinitesimal-not-zero HFinite-inverse2 HFinite-mult mult.assoc mult.right-neutral right-inverse*)

**lemma** *HInfinite-HFinite-not-Infinitesimal-mult2*:  
 $x \in HInfinite \implies y \in HFinite - Infinitesimal \implies y * x \in HInfinite$   
**for**  $x\ y :: 'a::real-normed-div-algebra\ star$   
**by** (*metis Diff-iff HInfinite-HFinite-iff HInfinite-inverse-Infinitesimal Infinitesimal-HFinite-mult2 divide-inverse mult-zero-right nonzero-eq-divide-eq*)

**lemma** *HInfinite-gt-SReal*:  $x \in HInfinite \implies 0 < x \implies y \in \mathbb{R} \implies y < x$   
**for**  $x\ y :: hypreal$   
**by** (*auto dest!: bspec simp add: HInfinite-def abs-if order-less-imp-le*)

**lemma** *HInfinite-gt-zero-gt-one*:  $x \in \text{HInfinite} \implies 0 < x \implies 1 < x$   
**for**  $x :: \text{hypreal}$   
**by** (*auto intro: HInfinite-gt-SReal*)

**lemma** *not-HInfinite-one* [*simp*]:  $1 \notin \text{HInfinite}$   
**by** (*simp add: HInfinite-HFinite-iff*)

**lemma** *approx-hrabs-disj*:  $|x| \approx x \vee |x| \approx -x$   
**for**  $x :: \text{hypreal}$   
**by** (*simp add: abs-iff*)

## 6.4 Theorems about Monads

**lemma** *monad-hrabs-Un-subset*:  $\text{monad } |x| \leq \text{monad } x \cup \text{monad } (-x)$   
**for**  $x :: \text{hypreal}$   
**by** (*simp add: abs-iff*)

**lemma** *Infinesimal-monad-eq*:  $e \in \text{Infinesimal} \implies \text{monad } (x + e) = \text{monad } x$   
**by** (*fast intro!: Infinesimal-add-approx-self [THEN approx-sym] approx-monad-iff [THEN iffD1]*)

**lemma** *mem-monad-iff*:  $u \in \text{monad } x \longleftrightarrow -u \in \text{monad } (-x)$   
**by** (*simp add: monad-def*)

**lemma** *Infinesimal-monad-zero-iff*:  $x \in \text{Infinesimal} \longleftrightarrow x \in \text{monad } 0$   
**by** (*auto intro: approx-sym simp add: monad-def mem-infmal-iff*)

**lemma** *monad-zero-minus-iff*:  $x \in \text{monad } 0 \longleftrightarrow -x \in \text{monad } 0$   
**by** (*simp add: Infinesimal-monad-zero-iff [symmetric]*)

**lemma** *monad-zero-hrabs-iff*:  $x \in \text{monad } 0 \longleftrightarrow |x| \in \text{monad } 0$   
**for**  $x :: \text{hypreal}$   
**using** *Infinesimal-monad-zero-iff* **by** *blast*

**lemma** *mem-monad-self* [*simp*]:  $x \in \text{monad } x$   
**by** (*simp add: monad-def*)

## 6.5 Proof that $x \approx y$ implies $|x| \approx |y|$

**lemma** *approx-subset-monad*:  $x \approx y \implies \{x, y\} \leq \text{monad } x$   
**by** (*simp (no-asm)*) (*simp add: approx-monad-iff*)

**lemma** *approx-subset-monad2*:  $x \approx y \implies \{x, y\} \leq \text{monad } y$   
**using** *approx-subset-monad approx-sym* **by** *auto*

**lemma** *mem-monad-approx*:  $u \in \text{monad } x \implies x \approx u$   
**by** (*simp add: monad-def*)

**lemma** *approx-mem-monad*:  $x \approx u \implies u \in \text{monad } x$

by (*simp add: monad-def*)

**lemma** *approx-mem-monad2*:  $x \approx u \implies x \in \text{monad } u$   
 using *approx-mem-monad approx-sym* by *blast*

**lemma** *approx-mem-monad-zero*:  $x \approx y \implies x \in \text{monad } 0 \implies y \in \text{monad } 0$   
 using *approx-trans monad-def* by *blast*

**lemma** *Infinitesimal-approx-hrabs*:  $x \approx y \implies x \in \text{Infinitesimal} \implies |x| \approx |y|$   
 for  $x y :: \text{hypreal}$   
 using *approx-hnorm* by *fastforce*

**lemma** *less-Infinitesimal-less*:  $0 < x \implies x \notin \text{Infinitesimal} \implies e \in \text{Infinitesimal} \implies e < x$   
 for  $x :: \text{hypreal}$   
 using *Infinitesimal-interval less-linear* by *blast*

**lemma** *Ball-mem-monad-gt-zero*:  $0 < x \implies x \notin \text{Infinitesimal} \implies u \in \text{monad } x \implies 0 < u$   
 for  $u x :: \text{hypreal}$   
 by (*metis* *bex-Infinitesimal-iff2 less-Infinitesimal-less less-add-same-cancel2 mem-monad-approx*)

**lemma** *Ball-mem-monad-less-zero*:  $x < 0 \implies x \notin \text{Infinitesimal} \implies u \in \text{monad } x \implies u < 0$   
 for  $u x :: \text{hypreal}$   
 by (*metis* *Ball-mem-monad-gt-zero approx-monad-iff less-asm linorder-neqE-linordered-idom mem-infmal-iff mem-monad-approx mem-monad-self*)

**lemma** *lemma-approx-gt-zero*:  $0 < x \implies x \notin \text{Infinitesimal} \implies x \approx y \implies 0 < y$   
 for  $x y :: \text{hypreal}$   
 by (*blast* *dest: Ball-mem-monad-gt-zero approx-subset-monad*)

**lemma** *lemma-approx-less-zero*:  $x < 0 \implies x \notin \text{Infinitesimal} \implies x \approx y \implies y < 0$   
 for  $x y :: \text{hypreal}$   
 by (*blast* *dest: Ball-mem-monad-less-zero approx-subset-monad*)

**lemma** *approx-hrabs*:  $x \approx y \implies |x| \approx |y|$   
 for  $x y :: \text{hypreal}$   
 by (*drule approx-hnorm*) *simp*

**lemma** *approx-hrabs-zero-cancel*:  $|x| \approx 0 \implies x \approx 0$   
 for  $x :: \text{hypreal}$   
 using *mem-infmal-iff* by *blast*

**lemma** *approx-hrabs-add-Infinitesimal*:  $e \in \text{Infinitesimal} \implies |x| \approx |x + e|$   
 for  $e x :: \text{hypreal}$   
 by (*fast intro: approx-hrabs Infinitesimal-add-approx-self*)



**lemma** *approx-hrabs-add-minus-Infinitesimal*:  $e \in \text{Infinitesimal} \implies |x| \approx |x + -e|$   
**for**  $e x :: \text{hypreal}$   
**by** (*fast intro: approx-hrabs Infinitesimal-add-minus-approx-self*)

**lemma** *hrabs-add-Infinitesimal-cancel*:  
 $e \in \text{Infinitesimal} \implies e' \in \text{Infinitesimal} \implies |x + e| = |y + e'| \implies |x| \approx |y|$   
**for**  $e e' x y :: \text{hypreal}$   
**by** (*metis approx-hrabs-add-Infinitesimal approx-trans2*)

**lemma** *hrabs-add-minus-Infinitesimal-cancel*:  
 $e \in \text{Infinitesimal} \implies e' \in \text{Infinitesimal} \implies |x + -e| = |y + -e'| \implies |x| \approx |y|$   
**for**  $e e' x y :: \text{hypreal}$   
**by** (*meson Infinitesimal-minus-iff hrabs-add-Infinitesimal-cancel*)

## 6.6 More HFinite and Infinitesimal Theorems

Interesting slightly counterintuitive theorem: necessary for proving that an open interval is an NS open set.

**lemma** *Infinitesimal-add-hypreal-of-real-less*:  
**assumes**  $x < y$  **and**  $u: u \in \text{Infinitesimal}$   
**shows** *hypreal-of-real*  $x + u < \text{hypreal-of-real } y$

**proof** –  
**have**  $|u| < \text{hypreal-of-real } y - \text{hypreal-of-real } x$   
**using** *InfinitesimalD*  $\langle x < y \rangle u$  **by** *fastforce*  
**then show** *?thesis*  
**by** (*simp add: abs-less-iff*)

**qed**

**lemma** *Infinitesimal-add-hrabs-hypreal-of-real-less*:  
 $x \in \text{Infinitesimal} \implies |\text{hypreal-of-real } r| < \text{hypreal-of-real } y \implies$   
 $|\text{hypreal-of-real } r + x| < \text{hypreal-of-real } y$   
**by** (*metis Infinitesimal-add-hypreal-of-real-less approx-hrabs-add-Infinitesimal approx-sym beX-Infinitesimal-iff2 star-of-abs star-of-less*)

**lemma** *Infinitesimal-add-hrabs-hypreal-of-real-less2*:  
 $x \in \text{Infinitesimal} \implies |\text{hypreal-of-real } r| < \text{hypreal-of-real } y \implies$   
 $|x + \text{hypreal-of-real } r| < \text{hypreal-of-real } y$   
**using** *Infinitesimal-add-hrabs-hypreal-of-real-less* **by** *fastforce*

**lemma** *hypreal-of-real-le-add-Infinitesimal-cancel*:  
**assumes**  $le: \text{hypreal-of-real } x + u \leq \text{hypreal-of-real } y + v$   
**and**  $u: u \in \text{Infinitesimal}$  **and**  $v: v \in \text{Infinitesimal}$   
**shows** *hypreal-of-real*  $x \leq \text{hypreal-of-real } y$   
**proof** (*rule ccontr*)  
**assume**  $\neg \text{hypreal-of-real } x \leq \text{hypreal-of-real } y$   
**then have** *hypreal-of-real*  $y + (v - u) < \text{hypreal-of-real } x$   
**by** (*simp add: Infinitesimal-add-hypreal-of-real-less Infinitesimal-diff u v*)  
**then show** *False*

**by** (*simp add: add-diff-eq add-le-imp-le-diff le leD*)  
**qed**

**lemma** *hypreal-of-real-le-add-Infininitesimal-cancel2*:  
 $u \in \text{Infininitesimal} \implies v \in \text{Infininitesimal} \implies$   
 $\text{hypreal-of-real } x + u \leq \text{hypreal-of-real } y + v \implies x \leq y$   
**by** (*blast intro: star-of-le [THEN iffD1] intro!: hypreal-of-real-le-add-Infininitesimal-cancel*)

**lemma** *hypreal-of-real-less-Infininitesimal-le-zero*:  
 $\text{hypreal-of-real } x < e \implies e \in \text{Infininitesimal} \implies \text{hypreal-of-real } x \leq 0$   
**by** (*metis Infininitesimal-interval eq-iff le-less-linear star-of-Infininitesimal-iff-0 star-of-eq-0*)

**lemma** *Infininitesimal-add-not-zero*:  $h \in \text{Infininitesimal} \implies x \neq 0 \implies \text{star-of } x + h \neq 0$   
**by** (*metis Infininitesimal-add-approx-self star-of-approx-zero-iff*)

**lemma** *monad-hrabs-less*:  $y \in \text{monad } x \implies 0 < \text{hypreal-of-real } e \implies |y - x| < \text{hypreal-of-real } e$   
**by** (*simp add: Infininitesimal-approx-minus approx-sym less-Infininitesimal-less mem-monad-approx*)

**lemma** *mem-monad-SReal-HFfinite*:  $x \in \text{monad } (\text{hypreal-of-real } a) \implies x \in \text{HFfinite}$   
**using** *HFfinite-star-of approx-HFfinite mem-monad-approx by blast*

## 6.7 Theorems about Standard Part

**lemma** *st-approx-self*:  $x \in \text{HFfinite} \implies \text{st } x \approx x$   
**by** (*metis (no-types, lifting) approx-refl approx-trans3 someI-ex st-def st-part-Ex st-part-Ex1*)

**lemma** *st-SReal*:  $x \in \text{HFfinite} \implies \text{st } x \in \mathbb{R}$   
**by** (*metis (mono-tags, lifting) approx-sym someI-ex st-def st-part-Ex*)

**lemma** *st-HFfinite*:  $x \in \text{HFfinite} \implies \text{st } x \in \text{HFfinite}$   
**by** (*erule st-SReal [THEN SReal-subset-HFfinite [THEN subsetD]]*)

**lemma** *st-unique*:  $r \in \mathbb{R} \implies r \approx x \implies \text{st } x = r$   
**by** (*meson SReal-subset-HFfinite approx-HFfinite approx-unique-real st-SReal st-approx-self subsetD*)

**lemma** *st-SReal-eq*:  $x \in \mathbb{R} \implies \text{st } x = x$   
**by** (*metis approx-refl st-unique*)

**lemma** *st-hypreal-of-real [simp]*:  $\text{st } (\text{hypreal-of-real } x) = \text{hypreal-of-real } x$   
**by** (*rule SReal-hypreal-of-real [THEN st-SReal-eq]*)

**lemma** *st-eq-approx*:  $x \in \text{HFfinite} \implies y \in \text{HFfinite} \implies \text{st } x = \text{st } y \implies x \approx y$   
**by** (*auto dest!: st-approx-self elim!: approx-trans3*)

**lemma** *approx-st-eq*:

**assumes**  $x: x \in \mathit{HFinite}$  **and**  $y: y \in \mathit{HFinite}$  **and**  $xy: x \approx y$

**shows**  $st\ x = st\ y$

**proof** –

**have**  $st\ x \approx x$   $st\ y \approx y$   $st\ x \in \mathbb{R}$   $st\ y \in \mathbb{R}$

**by** (*simp-all add: st-approx-self st-SReal x y*)

**with**  $xy$  **show** *?thesis*

**by** (*fast elim: approx-trans approx-trans2 SReal-approx-iff [THEN iffD1]*)

**qed**

**lemma** *st-eq-approx-iff*:  $x \in \mathit{HFinite} \implies y \in \mathit{HFinite} \implies x \approx y \longleftrightarrow st\ x = st\ y$

**by** (*blast intro: approx-st-eq st-eq-approx*)

**lemma** *st-Infinitesimal-add-SReal*:  $x \in \mathbb{R} \implies e \in \mathit{Infinitesimal} \implies st\ (x + e) = x$

**by** (*simp add: Infinitesimal-add-approx-self st-unique*)

**lemma** *st-Infinitesimal-add-SReal2*:  $x \in \mathbb{R} \implies e \in \mathit{Infinitesimal} \implies st\ (e + x) = x$

**by** (*metis add.commute st-Infinitesimal-add-SReal*)

**lemma** *HFinite-st-Infinitesimal-add*:  $x \in \mathit{HFinite} \implies \exists e \in \mathit{Infinitesimal}. x = st(x) + e$

**by** (*blast dest!: st-approx-self [THEN approx-sym] beX-Infinitesimal-iff2 [THEN iffD2]*)

**lemma** *st-add*:  $x \in \mathit{HFinite} \implies y \in \mathit{HFinite} \implies st\ (x + y) = st\ x + st\ y$

**by** (*simp add: st-unique st-SReal st-approx-self approx-add*)

**lemma** *st-numeral [simp]*:  $st\ (\mathit{numeral}\ w) = \mathit{numeral}\ w$

**by** (*rule Reals-numeral [THEN st-SReal-eq]*)

**lemma** *st-neg-numeral [simp]*:  $st\ (-\ \mathit{numeral}\ w) = -\ \mathit{numeral}\ w$

**using** *st-unique by auto*

**lemma** *st-0 [simp]*:  $st\ 0 = 0$

**by** (*simp add: st-SReal-eq*)

**lemma** *st-1 [simp]*:  $st\ 1 = 1$

**by** (*simp add: st-SReal-eq*)

**lemma** *st-neg-1 [simp]*:  $st\ (-\ 1) = -\ 1$

**by** (*simp add: st-SReal-eq*)

**lemma** *st-minus*:  $x \in \mathit{HFinite} \implies st\ (-\ x) = -\ st\ x$

**by** (*simp add: st-unique st-SReal st-approx-self approx-minus*)

**lemma** *st-diff*:  $\llbracket x \in \mathit{HFinite}; y \in \mathit{HFinite} \rrbracket \implies st\ (x - y) = st\ x - st\ y$

**by** (*simp add: st-unique st-SReal st-approx-self approx-diff*)

**lemma** *st-mult*:  $\llbracket x \in \mathit{HFinite}; y \in \mathit{HFinite} \rrbracket \implies \mathit{st} (x * y) = \mathit{st} x * \mathit{st} y$   
**by** (*simp add: st-unique st-SReal st-approx-self approx-mult-HFinite*)

**lemma** *st-Infinitesimal*:  $x \in \mathit{Infinitesimal} \implies \mathit{st} x = 0$   
**by** (*simp add: st-unique mem-infmal-iff*)

**lemma** *st-not-Infinitesimal*:  $\mathit{st}(x) \neq 0 \implies x \notin \mathit{Infinitesimal}$   
**by** (*fast intro: st-Infinitesimal*)

**lemma** *st-inverse*:  $x \in \mathit{HFinite} \implies \mathit{st} x \neq 0 \implies \mathit{st} (\mathit{inverse} x) = \mathit{inverse} (\mathit{st} x)$   
**by** (*simp add: approx-inverse st-SReal st-approx-self st-not-Infinitesimal st-unique*)

**lemma** *st-divide* [*simp*]:  $x \in \mathit{HFinite} \implies y \in \mathit{HFinite} \implies \mathit{st} y \neq 0 \implies \mathit{st} (x / y) = \mathit{st} x / \mathit{st} y$   
**by** (*simp add: divide-inverse st-mult st-not-Infinitesimal HFinite-inverse st-inverse*)

**lemma** *st-idempotent* [*simp*]:  $x \in \mathit{HFinite} \implies \mathit{st} (\mathit{st} x) = \mathit{st} x$   
**by** (*blast intro: st-HFinite st-approx-self approx-st-eq*)

**lemma** *Infinitesimal-add-st-less*:  
 $x \in \mathit{HFinite} \implies y \in \mathit{HFinite} \implies u \in \mathit{Infinitesimal} \implies \mathit{st} x < \mathit{st} y \implies \mathit{st} x + u < \mathit{st} y$   
**by** (*metis Infinitesimal-add-hypreal-of-real-less SReal-iff st-SReal star-of-less*)

**lemma** *Infinitesimal-add-st-le-cancel*:  
 $x \in \mathit{HFinite} \implies y \in \mathit{HFinite} \implies u \in \mathit{Infinitesimal} \implies \mathit{st} x \leq \mathit{st} y + u \implies \mathit{st} x \leq \mathit{st} y$   
**by** (*meson Infinitesimal-add-st-less leD le-less-linear*)

**lemma** *st-le*:  $x \in \mathit{HFinite} \implies y \in \mathit{HFinite} \implies x \leq y \implies \mathit{st} x \leq \mathit{st} y$   
**by** (*metis approx-le-bound approx-sym linear st-SReal st-approx-self st-part-Ex1*)

**lemma** *st-zero-le*:  $0 \leq x \implies x \in \mathit{HFinite} \implies 0 \leq \mathit{st} x$   
**by** (*metis HFinite-0 st-0 st-le*)

**lemma** *st-zero-ge*:  $x \leq 0 \implies x \in \mathit{HFinite} \implies \mathit{st} x \leq 0$   
**by** (*metis HFinite-0 st-0 st-le*)

**lemma** *st-hrabs*:  $x \in \mathit{HFinite} \implies |\mathit{st} x| = \mathit{st} |x|$   
**by** (*simp add: order-class.order.antisym st-zero-ge linorder-not-le st-zero-le abs-if st-minus linorder-not-less*)

## 6.8 Alternative Definitions using Free Ultrafilter

### 6.8.1 *HFinite*

**lemma** *HFinite-FreeUltrafilterNat*:  
**assumes** *star-n*  $X \in \mathit{HFinite}$   
**shows**  $\exists u. \text{eventually } (\lambda n. \text{norm } (X n) < u) \mathcal{U}$

**proof** –

**obtain**  $r$  **where**  $hnorm (star-n X) < hypreal-of-real r$   
**using**  $HFiniteD SReal-iff$  **assms** **by**  $fastforce$   
**then have**  $\forall_F n \text{ in } \mathcal{U}. norm (X n) < r$   
**by** ( $simp$   $add$ :  $hnorm-def star-n-less star-of-def starfun-star-n$ )  
**then show**  $?thesis ..$

**qed**

**lemma**  $FreeUltrafilterNat-HFinite$ :

**assumes**  $eventually (\lambda n. norm (X n) < u) \mathcal{U}$   
**shows**  $star-n X \in HFinite$

**proof** –

**have**  $hnorm (star-n X) < hypreal-of-real u$   
**by** ( $simp$   $add$ :  $assms hnorm-def star-n-less star-of-def starfun-star-n$ )  
**then show**  $?thesis$   
**by** ( $meson HInfiniteD SReal-hypreal-of-real less-asm not-HFinite-HInfinite$ )

**qed**

**lemma**  $HFinite-FreeUltrafilterNat-iff$ :

$star-n X \in HFinite \longleftrightarrow (\exists u. eventually (\lambda n. norm (X n) < u) \mathcal{U})$   
**using**  $FreeUltrafilterNat-HFinite HFinite-FreeUltrafilterNat$  **by**  $blast$

### 6.8.2 $HInfinite$

Exclude this type of sets from free ultrafilter for Infinite numbers!

**lemma**  $FreeUltrafilterNat-const-Finite$ :

$eventually (\lambda n. norm (X n) = u) \mathcal{U} \implies star-n X \in HFinite$   
**by** ( $simp$   $add$ :  $FreeUltrafilterNat-HFinite$  [**where**  $u = u+1$ ]  $eventually-mono$ )

**lemma**  $HInfinite-FreeUltrafilterNat$ :

**assumes**  $star-n X \in HInfinite$  **shows**  $\forall_F n \text{ in } \mathcal{U}. u < norm (X n)$

**proof** –

**have**  $\neg (\forall_F n \text{ in } \mathcal{U}. norm (X n) < u + 1)$   
**using**  $FreeUltrafilterNat-HFinite HFinite-HInfinite-iff$  **assms** **by**  $auto$   
**then show**  $?thesis$   
**by** ( $auto$   $simp$   $flip$ :  $FreeUltrafilterNat.eventually-not-iff elim$ :  $eventually-mono$ )

**qed**

**lemma**  $FreeUltrafilterNat-HInfinite$ :

**assumes**  $\bigwedge u. eventually (\lambda n. u < norm (X n)) \mathcal{U}$   
**shows**  $star-n X \in HInfinite$

**proof** –

{ **fix**  $u$   
**assume**  $\forall_F n \text{ in } \mathcal{U}. norm (X n) < u \forall_F n \text{ in } \mathcal{U}. u < norm (X n)$   
**then have**  $\forall_F x \text{ in } \mathcal{U}. False$   
**by**  $eventually-elim auto$   
**then have**  $False$   
**by** ( $simp$   $add$ :  $eventually-False FreeUltrafilterNat.proper$ ) }

**then show**  $?thesis$

**using** *HFinite-FreeUltrafilterNat HInfinite-HFinite-iff* **assms** **by** *blast*  
**qed**

**lemma** *HInfinite-FreeUltrafilterNat-iff*:  
 $star-n X \in HInfinite \longleftrightarrow (\forall u. eventually (\lambda n. u < norm (X n)) \mathcal{U})$   
**using** *HInfinite-FreeUltrafilterNat FreeUltrafilterNat-HInfinite* **by** *blast*

### 6.8.3 Infinitesimal

**lemma** *ball-SReal-eq*:  $(\forall x::hypreal \in Reals. P x) \longleftrightarrow (\forall x::real. P (star-of x))$   
**by** *(auto simp: SReal-def)*

**lemma** *Infinitesimal-FreeUltrafilterNat-iff*:  
 $(star-n X \in Infinitesimal) = (\forall u>0. eventually (\lambda n. norm (X n) < u) \mathcal{U})$  **(is**  
 $?lhs = ?rhs)$   
**proof** –  
**have**  $?lhs \longleftrightarrow (\forall r>0. hnorm (star-n X) < hypreal-of-real r)$   
**by** *(simp add: Infinitesimal-def ball-SReal-eq)*  
**also have**  $\dots \longleftrightarrow ?rhs$   
**by** *(simp add: hnorm-def starfun-star-n star-of-def star-less-def starP2-star-n)*  
**finally show**  $?thesis$  .  
**qed**

Infinitesimals as smaller than  $1/n$  for all  $n::nat (> 0)$ .

**lemma** *lemma-Infinitesimal*:  $(\forall r. 0 < r \longrightarrow x < r) \longleftrightarrow (\forall n. x < inverse (real (Suc n)))$   
**by** *(meson inverse-positive-iff-positive less-trans of-nat-0-less-iff reals-Archimedean zero-less-Suc)*

**lemma** *lemma-Infinitesimal2*:  
 $(\forall r \in Reals. 0 < r \longrightarrow x < r) \longleftrightarrow (\forall n. x < inverse(hypreal-of-nat (Suc n)))$   
**(is - = ?rhs)**  
**proof** *(intro iffI strip)*  
**assume**  $R: ?rhs$   
**fix**  $r::hypreal$   
**assume**  $r \in \mathbf{R} \ 0 < r$   
**then obtain**  $n \ y$  **where**  $inverse (real (Suc n)) < y$  **and**  $r: r = hypreal-of-real y$   
**by** *(metis SReal-iff reals-Archimedean star-of-0-less)*  
**then have**  $inverse (1 + hypreal-of-nat n) < hypreal-of-real y$   
**by** *(metis of-nat-Suc star-of-inverse star-of-less star-of-nat-def)*  
**then show**  $x < r$   
**by** *(metis R r le-less-trans less-imp-le of-nat-Suc)*  
**qed** *(meson Reals-inverse Reals-of-nat of-nat-0-less-iff positive-imp-inverse-positive zero-less-Suc)*

**lemma** *Infinitesimal-hypreal-of-nat-iff*:  
 $Infinitesimal = \{x. \forall n. hnorm x < inverse (hypreal-of-nat (Suc n))\}$

using *Infinitesimal-def lemma-Infinitesimal2* by *auto*

## 6.9 Proof that $\omega$ is an infinite number

It will follow that  $\varepsilon$  is an infinitesimal number.

**lemma** *Suc-Un-eq*:  $\{n. n < \text{Suc } m\} = \{n. n < m\} \cup \{n. n = m\}$   
by (*auto simp add: less-Suc-eq*)

Prove that any segment is finite and hence cannot belong to  $\mathcal{U}$ .

**lemma** *finite-real-of-nat-segment*: *finite*  $\{n::\text{nat}. \text{real } n < \text{real } (m::\text{nat})\}$   
by *auto*

**lemma** *finite-real-of-nat-less-real*: *finite*  $\{n::\text{nat}. \text{real } n < u\}$

**proof** –

obtain  $m$  where  $u < \text{real } m$

using *reals-Archimedean2* by *blast*

then have  $\{n. \text{real } n < u\} \subseteq \{.. < m\}$

by *force*

then show *?thesis*

using *finite-nat-iff-bounded* by *force*

qed

**lemma** *finite-real-of-nat-le-real*: *finite*  $\{n::\text{nat}. \text{real } n \leq u\}$

by (*metis infinite-nat-iff-unbounded leD le-nat-floor mem-Collect-eq*)

**lemma** *finite-rabs-real-of-nat-le-real*: *finite*  $\{n::\text{nat}. |\text{real } n| \leq u\}$

by (*simp add: finite-real-of-nat-le-real*)

**lemma** *rabs-real-of-nat-le-real-FreeUltrafilterNat*:

$\neg$  *eventually*  $(\lambda n. |\text{real } n| \leq u) \mathcal{U}$

by (*blast intro!: FreeUltrafilterNat.finite finite-rabs-real-of-nat-le-real*)

**lemma** *FreeUltrafilterNat-nat-gt-real*: *eventually*  $(\lambda n. u < \text{real } n) \mathcal{U}$

**proof** –

have  $\{n::\text{nat}. \neg u < \text{real } n\} = \{n. \text{real } n \leq u\}$

by *auto*

then show *?thesis*

by (*auto simp add: FreeUltrafilterNat.finite' finite-real-of-nat-le-real*)

qed

The complement of  $\{n. |\text{real } n| \leq u\} = \{n. u < |\text{real } n|\}$  is in  $\mathcal{U}$  by property of (free) ultrafilters.

$\omega$  is a member of *HInfinite*.

**theorem** *HInfinite-omega* [*simp*]:  $\omega \in \text{HInfinite}$

**proof** –

have  $\forall_F n$  in  $\mathcal{U}. u < \text{norm } (1 + \text{real } n)$  for  $u$

using *FreeUltrafilterNat-nat-gt-real* [*of u-1*] *eventually-mono* by *fastforce*

**then show** *?thesis*  
**by** (*simp add: omega-def FreeUltrafilterNat-HInfinite*)  
**qed**

Epsilon is a member of Infinitesimal.

**lemma** *Infinitesimal-epsilon* [*simp*]:  $\varepsilon \in \text{Infinitesimal}$   
**by** (*auto intro!: HInfinite-inverse-Infinitesimal HInfinite-omega simp add: epsilon-inverse-omega*)

**lemma** *HFinite-epsilon* [*simp*]:  $\varepsilon \in \text{HFinite}$   
**by** (*auto intro: Infinitesimal-subset-HFinite [THEN subsetD]*)

**lemma** *epsilon-approx-zero* [*simp*]:  $\varepsilon \approx 0$   
**by** (*simp add: mem-infmal-iff [symmetric]*)

Needed for proof that we define a hyperreal  $[\langle X(n) \rangle] \approx \text{hypreal-of-real } a$  given that  $\forall n. |X\ n - a| < 1/n$ . Used in proof of *NSLIM*  $\Rightarrow$  *LIM*.

**lemma** *real-of-nat-less-inverse-iff*:  $0 < u \implies u < \text{inverse}(\text{real}(\text{Suc } n)) \longleftrightarrow \text{real}(\text{Suc } n) < \text{inverse } u$   
**using** *less-imp-inverse-less* **by** *force*

**lemma** *finite-inverse-real-of-posnat-gt-real*:  $0 < u \implies \text{finite } \{n. u < \text{inverse}(\text{real}(\text{Suc } n))\}$

**proof** (*simp only: real-of-nat-less-inverse-iff*)  
**have**  $\{n. 1 + \text{real } n < \text{inverse } u\} = \{n. \text{real } n < \text{inverse } u - 1\}$   
**by** *fastforce*  
**then show**  $\text{finite } \{n. \text{real}(\text{Suc } n) < \text{inverse } u\}$   
**using** *finite-real-of-nat-less-real [of inverse u - 1]*  
**by** *auto*

**qed**

**lemma** *finite-inverse-real-of-posnat-ge-real*:

**assumes**  $0 < u$   
**shows**  $\text{finite } \{n. u \leq \text{inverse}(\text{real}(\text{Suc } n))\}$

**proof** –

**have**  $\forall na. u \leq \text{inverse}(1 + \text{real } na) \longrightarrow na \leq \text{ceiling}(\text{inverse } u)$   
**by** (*smt (verit, best) assms ceiling-less-cancel ceiling-of-nat inverse-inverse-eq inverse-le-iff-le*)

**then show** *?thesis*

**apply** (*auto simp add: finite-nat-set-iff-bounded-le*)  
**by** (*meson assms inverse-positive-iff-positive le-nat-iff less-imp-le zero-less-ceiling*)

**qed**

**lemma** *inverse-real-of-posnat-ge-real-FreeUltrafilterNat*:

$0 < u \implies \neg \text{eventually } (\lambda n. u \leq \text{inverse}(\text{real}(\text{Suc } n))) \mathcal{U}$   
**by** (*blast intro!: FreeUltrafilterNat.finite finite-inverse-real-of-posnat-ge-real*)

**lemma** *FreeUltrafilterNat-inverse-real-of-posnat*:

$0 < u \implies \text{eventually } (\lambda n. \text{inverse}(\text{real}(\text{Suc } n)) < u) \mathcal{U}$



**by** (*drule inverse-real-of-posnat-ge-real-FreeUltrafilterNat*)  
*(simp add: FreeUltrafilterNat.eventually-not-iff not-le[symmetric])*)

Example of an hypersequence (i.e. an extended standard sequence) whose term with an hypernatural suffix is an infinitesimal i.e. the  $n$ 'th term of the hypersequence is a member of *Infinitesimal*

**lemma** *SEQ-Infinitesimal*: ( $*f*$  ( $\lambda n::nat. inverse(real(Suc n))$ ))  $whn \in Infinitesimal$

**by** (*simp add: hypnat-omega-def starfun-star-n star-n-inverse Infinitesimal-FreeUltrafilterNat-iff FreeUltrafilterNat-inverse-real-of-posnat del: of-nat-Suc*)

Example where we get a hyperreal from a real sequence for which a particular property holds. The theorem is used in proofs about equivalence of nonstandard and standard neighbourhoods. Also used for equivalence of nonstandard and standard definitions of pointwise limit.

$|X(n) - x| < 1/n \implies [X n] - hypreal-of-real x \in Infinitesimal$

**lemma** *real-seq-to-hypreal-Infinitesimal*:

$\forall n. norm (X n - x) < inverse (real (Suc n)) \implies star-n X - star-of x \in Infinitesimal$

**unfolding** *star-n-diff star-of-def Infinitesimal-FreeUltrafilterNat-iff star-n-inverse*

**by** (*auto dest!: FreeUltrafilterNat-inverse-real-of-posnat intro: order-less-trans elim!: eventually-mono*)

**lemma** *real-seq-to-hypreal-approx*:

$\forall n. norm (X n - x) < inverse (real (Suc n)) \implies star-n X \approx star-of x$

**by** (*metis bex-Infinitesimal-iff real-seq-to-hypreal-Infinitesimal*)

**lemma** *real-seq-to-hypreal-approx2*:

$\forall n. norm (x - X n) < inverse(real(Suc n)) \implies star-n X \approx star-of x$

**by** (*metis norm-minus-commute real-seq-to-hypreal-approx*)

**lemma** *real-seq-to-hypreal-Infinitesimal2*:

$\forall n. norm(X n - Y n) < inverse(real(Suc n)) \implies star-n X - star-n Y \in Infinitesimal$

**unfolding** *Infinitesimal-FreeUltrafilterNat-iff star-n-diff*

**by** (*auto dest!: FreeUltrafilterNat-inverse-real-of-posnat intro: order-less-trans elim!: eventually-mono*)

**end**

## 7 Nonstandard Complex Numbers

**theory** *NSComplex*

**imports** *NSA*

**begin**

**type-synonym** *hcomplex = complex star*

**abbreviation**  $hcomplex\text{-of-complex} :: complex \Rightarrow complex\ star$   
**where**  $hcomplex\text{-of-complex} \equiv star\text{-of}$

**abbreviation**  $hmod :: complex\ star \Rightarrow real\ star$   
**where**  $hmod \equiv hnorm$

### 7.0.1 Real and Imaginary parts

**definition**  $hRe :: hcomplex \Rightarrow hypreal$   
**where**  $hRe = *f* Re$

**definition**  $hIm :: hcomplex \Rightarrow hypreal$   
**where**  $hIm = *f* Im$

### 7.0.2 Imaginary unit

**definition**  $iii :: hcomplex$   
**where**  $iii = star\text{-of} i$

### 7.0.3 Complex conjugate

**definition**  $hcnj :: hcomplex \Rightarrow hcomplex$   
**where**  $hcnj = *f* cnj$

### 7.0.4 Argand

**definition**  $hsgn :: hcomplex \Rightarrow hcomplex$   
**where**  $hsgn = *f* sgn$

**definition**  $harg :: hcomplex \Rightarrow hypreal$   
**where**  $harg = *f* Arg$

**definition** — abbreviation for  $\cos a + i \sin a$   
 $hcis :: hypreal \Rightarrow hcomplex$   
**where**  $hcis = *f* cis$

### 7.0.5 Injection from hyperreals

**abbreviation**  $hcomplex\text{-of-hypreal} :: hypreal \Rightarrow hcomplex$   
**where**  $hcomplex\text{-of-hypreal} \equiv of\text{-hypreal}$

**definition** — abbreviation for  $r * (\cos a + i \sin a)$   
 $hrcis :: hypreal \Rightarrow hypreal \Rightarrow hcomplex$   
**where**  $hrcis = *f2* rcis$

### 7.0.6 $e^{\wedge}(x + iy)$

**definition**  $hExp :: hcomplex \Rightarrow hcomplex$   
**where**  $hExp = *f* exp$

**definition**  $HComplex :: hypreal \Rightarrow hypreal \Rightarrow hcomplex$   
**where**  $HComplex = *f2* Complex$

**lemmas**  $hcomplex-defs [transfer-unfold] =$   
 $hRe-def hIm-def iii-def hcnj-def hsgn-def harg-def hcis-def$   
 $hrcis-def hExp-def HComplex-def$

**lemma**  $Standard-hRe [simp]: x \in Standard \Longrightarrow hRe x \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-hIm [simp]: x \in Standard \Longrightarrow hIm x \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-iii [simp]: iii \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-hcnj [simp]: x \in Standard \Longrightarrow hcnj x \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-hsgn [simp]: x \in Standard \Longrightarrow hsgn x \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-harg [simp]: x \in Standard \Longrightarrow harg x \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-hcis [simp]: r \in Standard \Longrightarrow hcis r \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-hExp [simp]: x \in Standard \Longrightarrow hExp x \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-hrcis [simp]: r \in Standard \Longrightarrow s \in Standard \Longrightarrow hrcis r s \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $Standard-HComplex [simp]: r \in Standard \Longrightarrow s \in Standard \Longrightarrow HComplex r s \in Standard$   
**by** ( $simp$  add:  $hcomplex-defs$ )

**lemma**  $hcmmod-def: hcmmod = *f* cmod$   
**by** ( $rule hnorm-def$ )

## 7.1 Properties of Nonstandard Real and Imaginary Parts

**lemma**  $hcomplex-hRe-hIm-cancel-iff: \bigwedge w z. w = z \longleftrightarrow hRe w = hRe z \wedge hIm w = hIm z$   
**by**  $transfer (rule complex-eq-iff)$

**lemma** *hcomplex-equality* [*intro?*]:  $\bigwedge z w. hRe\ z = hRe\ w \implies hIm\ z = hIm\ w \implies z = w$

**by** *transfer* (rule *complex-eqI*)

**lemma** *hcomplex-hRe-zero* [*simp*]:  $hRe\ 0 = 0$

**by** *transfer simp*

**lemma** *hcomplex-hIm-zero* [*simp*]:  $hIm\ 0 = 0$

**by** *transfer simp*

**lemma** *hcomplex-hRe-one* [*simp*]:  $hRe\ 1 = 1$

**by** *transfer simp*

**lemma** *hcomplex-hIm-one* [*simp*]:  $hIm\ 1 = 0$

**by** *transfer simp*

## 7.2 Addition for Nonstandard Complex Numbers

**lemma** *hRe-add*:  $\bigwedge x y. hRe\ (x + y) = hRe\ x + hRe\ y$

**by** *transfer simp*

**lemma** *hIm-add*:  $\bigwedge x y. hIm\ (x + y) = hIm\ x + hIm\ y$

**by** *transfer simp*

## 7.3 More Minus Laws

**lemma** *hRe-minus*:  $\bigwedge z. hRe\ (-z) = -hRe\ z$

**by** *transfer* (rule *uminus-complex.sel*)

**lemma** *hIm-minus*:  $\bigwedge z. hIm\ (-z) = -hIm\ z$

**by** *transfer* (rule *uminus-complex.sel*)

**lemma** *hcomplex-add-minus-eq-minus*:  $x + y = 0 \implies x = -y$

**for**  $x\ y :: hcomplex$

**apply** (drule *minus-unique*)

**apply** (*simp add: minus-equation-iff* [of  $x\ y$ ])

**done**

**lemma** *hcomplex-i-mult-eq* [*simp*]:  $iii * iii = -1$

**by** *transfer* (rule *i-squared*)

**lemma** *hcomplex-i-mult-left* [*simp*]:  $\bigwedge z. iii * (iii * z) = -z$

**by** *transfer* (rule *complex-i-mult-minus*)

**lemma** *hcomplex-i-not-zero* [*simp*]:  $iii \neq 0$

**by** *transfer* (rule *complex-i-not-zero*)

## 7.4 More Multiplication Laws

**lemma** *hcomplex-mult-minus-one*:  $-1 * z = -z$

**for**  $z :: hcomplex$   
**by** *simp*

**lemma** *hcomplex-mult-minus-one-right*:  $z * - 1 = - z$   
**for**  $z :: hcomplex$   
**by** *simp*

**lemma** *hcomplex-mult-left-cancel*:  $c \neq 0 \implies c * a = c * b \longleftrightarrow a = b$   
**for**  $a b c :: hcomplex$   
**by** *simp*

**lemma** *hcomplex-mult-right-cancel*:  $c \neq 0 \implies a * c = b * c \longleftrightarrow a = b$   
**for**  $a b c :: hcomplex$   
**by** *simp*

## 7.5 Subtraction and Division

**lemma** *hcomplex-diff-eq-eq* [*simp*]:  $x - y = z \longleftrightarrow x = z + y$   
**for**  $x y z :: hcomplex$   
**by** (*rule diff-eq-eq*)

## 7.6 Embedding Properties for *hcomplex-of-hypreal* Map

**lemma** *hRe-hcomplex-of-hypreal* [*simp*]:  $\bigwedge z. hRe (hcomplex-of-hypreal z) = z$   
**by** *transfer (rule Re-complex-of-real)*

**lemma** *hIm-hcomplex-of-hypreal* [*simp*]:  $\bigwedge z. hIm (hcomplex-of-hypreal z) = 0$   
**by** *transfer (rule Im-complex-of-real)*

**lemma** *hcomplex-of-epsilon-not-zero* [*simp*]: *hcomplex-of-hypreal*  $\varepsilon \neq 0$   
**by** (*simp add: epsilon-not-zero*)

## 7.7 *HComplex* theorems

**lemma** *hRe-HComplex* [*simp*]:  $\bigwedge x y. hRe (HComplex x y) = x$   
**by** *transfer simp*

**lemma** *hIm-HComplex* [*simp*]:  $\bigwedge x y. hIm (HComplex x y) = y$   
**by** *transfer simp*

**lemma** *hcomplex-surj* [*simp*]:  $\bigwedge z. HComplex (hRe z) (hIm z) = z$   
**by** *transfer (rule complex-surj)*

**lemma** *hcomplex-induct* [*case-names rect*]:  
 $(\bigwedge x y. P (HComplex x y)) \implies P z$   
**by** (*rule hcomplex-surj [THEN subst]*) *blast*

## 7.8 Modulus (Absolute Value) of Nonstandard Complex Number

**lemma** *hcomplex-of-hypreal-abs*:

*hcomplex-of-hypreal*  $|x| = \text{hcomplex-of-hypreal } (\text{hcmmod } (\text{hcomplex-of-hypreal } x))$   
by *simp*

**lemma** *HComplex-inject* [*simp*]:  $\bigwedge x y x' y'. \text{HComplex } x y = \text{HComplex } x' y' \longleftrightarrow x = x' \wedge y = y'$

by *transfer* (*rule complex.inject*)

**lemma** *HComplex-add* [*simp*]:

$\bigwedge x1 y1 x2 y2. \text{HComplex } x1 y1 + \text{HComplex } x2 y2 = \text{HComplex } (x1 + x2) (y1 + y2)$

by *transfer* (*rule complex-add*)

**lemma** *HComplex-minus* [*simp*]:  $\bigwedge x y. - \text{HComplex } x y = \text{HComplex } (- x) (- y)$

by *transfer* (*rule complex-minus*)

**lemma** *HComplex-diff* [*simp*]:

$\bigwedge x1 y1 x2 y2. \text{HComplex } x1 y1 - \text{HComplex } x2 y2 = \text{HComplex } (x1 - x2) (y1 - y2)$

by *transfer* (*rule complex-diff*)

**lemma** *HComplex-mult* [*simp*]:

$\bigwedge x1 y1 x2 y2. \text{HComplex } x1 y1 * \text{HComplex } x2 y2 = \text{HComplex } (x1 * x2 - y1 * y2) (x1 * y2 + y1 * x2)$

by *transfer* (*rule complex-mult*)

*HComplex-inverse* is proved below.

**lemma** *hcomplex-of-hypreal-eq*:  $\bigwedge r. \text{hcomplex-of-hypreal } r = \text{HComplex } r 0$

by *transfer* (*rule complex-of-real-def*)

**lemma** *HComplex-add-hcomplex-of-hypreal* [*simp*]:

$\bigwedge x y r. \text{HComplex } x y + \text{hcomplex-of-hypreal } r = \text{HComplex } (x + r) y$

by *transfer* (*rule Complex-add-complex-of-real*)

**lemma** *hcomplex-of-hypreal-add-HComplex* [*simp*]:

$\bigwedge r x y. \text{hcomplex-of-hypreal } r + \text{HComplex } x y = \text{HComplex } (r + x) y$

by *transfer* (*rule complex-of-real-add-Complex*)

**lemma** *HComplex-mult-hcomplex-of-hypreal*:

$\bigwedge x y r. \text{HComplex } x y * \text{hcomplex-of-hypreal } r = \text{HComplex } (x * r) (y * r)$

by *transfer* (*rule Complex-mult-complex-of-real*)

**lemma** *hcomplex-of-hypreal-mult-HComplex*:

$\bigwedge r x y. \text{hcomplex-of-hypreal } r * \text{HComplex } x y = \text{HComplex } (r * x) (r * y)$

by *transfer* (*rule complex-of-real-mult-Complex*)

**lemma** *i-hcomplex-of-hypreal* [simp]:  $\bigwedge r. \text{iii} * \text{hcomplex-of-hypreal } r = \text{HComplex } 0 \ r$

**by** transfer (rule *i-complex-of-real*)

**lemma** *hcomplex-of-hypreal-i* [simp]:  $\bigwedge r. \text{hcomplex-of-hypreal } r * \text{iii} = \text{HComplex } 0 \ r$

**by** transfer (rule *complex-of-real-i*)

## 7.9 Conjugation

**lemma** *hcomplex-hcnj-cancel-iff* [iff]:  $\bigwedge x \ y. \text{hcnj } x = \text{hcnj } y \longleftrightarrow x = y$

**by** transfer (rule *complex-cnj-cancel-iff*)

**lemma** *hcomplex-hcnj-hcnj* [simp]:  $\bigwedge z. \text{hcnj } (\text{hcnj } z) = z$

**by** transfer (rule *complex-cnj-cnj*)

**lemma** *hcomplex-hcnj-hcomplex-of-hypreal* [simp]:

$\bigwedge x. \text{hcnj } (\text{hcomplex-of-hypreal } x) = \text{hcomplex-of-hypreal } x$

**by** transfer (rule *complex-cnj-complex-of-real*)

**lemma** *hcomplex-hmod-hcnj* [simp]:  $\bigwedge z. \text{hcm}od (\text{hcnj } z) = \text{hcm}od \ z$

**by** transfer (rule *complex-mod-cnj*)

**lemma** *hcomplex-hcnj-minus*:  $\bigwedge z. \text{hcnj } (- \ z) = - \ \text{hcnj } z$

**by** transfer (rule *complex-cnj-minus*)

**lemma** *hcomplex-hcnj-inverse*:  $\bigwedge z. \text{hcnj } (\text{inverse } z) = \text{inverse } (\text{hcnj } z)$

**by** transfer (rule *complex-cnj-inverse*)

**lemma** *hcomplex-hcnj-add*:  $\bigwedge w \ z. \text{hcnj } (w + z) = \text{hcnj } w + \text{hcnj } z$

**by** transfer (rule *complex-cnj-add*)

**lemma** *hcomplex-hcnj-diff*:  $\bigwedge w \ z. \text{hcnj } (w - z) = \text{hcnj } w - \text{hcnj } z$

**by** transfer (rule *complex-cnj-diff*)

**lemma** *hcomplex-hcnj-mult*:  $\bigwedge w \ z. \text{hcnj } (w * z) = \text{hcnj } w * \text{hcnj } z$

**by** transfer (rule *complex-cnj-mult*)

**lemma** *hcomplex-hcnj-divide*:  $\bigwedge w \ z. \text{hcnj } (w / z) = \text{hcnj } w / \text{hcnj } z$

**by** transfer (rule *complex-cnj-divide*)

**lemma** *hcnj-one* [simp]:  $\text{hcnj } 1 = 1$

**by** transfer (rule *complex-cnj-one*)

**lemma** *hcomplex-hcnj-zero* [simp]:  $\text{hcnj } 0 = 0$

**by** transfer (rule *complex-cnj-zero*)

**lemma** *hcomplex-hcnj-zero-iff* [iff]:  $\bigwedge z. \text{hcnj } z = 0 \longleftrightarrow z = 0$

**by** transfer (rule *complex-cnj-zero-iff*)

**lemma** *hcomplex-mult-hcnj*:  $\bigwedge z. z * \text{hcnj } z = \text{hcomplex-of-hypreal } ((\text{hRe } z)^2 + (\text{hIm } z)^2)$   
**by** *transfer (rule complex-mult-cnj)*

## 7.10 More Theorems about the Function *hcmmod*

**lemma** *hcmmod-hcomplex-of-hypreal-of-nat [simp]*:  
 $\text{hcmmod } (\text{hcomplex-of-hypreal } (\text{hypreal-of-nat } n)) = \text{hypreal-of-nat } n$   
**by** *simp*

**lemma** *hcmmod-hcomplex-of-hypreal-of-hypnat [simp]*:  
 $\text{hcmmod } (\text{hcomplex-of-hypreal}(\text{hypreal-of-hypnat } n)) = \text{hypreal-of-hypnat } n$   
**by** *simp*

**lemma** *hcmmod-mult-hcnj*:  $\bigwedge z. \text{hcmmod } (z * \text{hcnj } z) = (\text{hcmmod } z)^2$   
**by** *transfer (rule complex-mod-mult-cnj)*

**lemma** *hcmmod-triangle-ineq2 [simp]*:  $\bigwedge a b. \text{hcmmod } (b + a) - \text{hcmmod } b \leq \text{hcmmod } a$   
**by** *transfer (rule complex-mod-triangle-ineq2)*

**lemma** *hcmmod-diff-ineq [simp]*:  $\bigwedge a b. \text{hcmmod } a - \text{hcmmod } b \leq \text{hcmmod } (a + b)$   
**by** *transfer (rule norm-diff-ineq)*

## 7.11 Exponentiation

**lemma** *hcomplexpow-0 [simp]*:  $z \wedge 0 = 1$   
**for**  $z :: \text{hcomplex}$   
**by** *(rule power-0)*

**lemma** *hcomplexpow-Suc [simp]*:  $z \wedge (\text{Suc } n) = z * (z \wedge n)$   
**for**  $z :: \text{hcomplex}$   
**by** *(rule power-Suc)*

**lemma** *hcomplexpow-i-squared [simp]*:  $i \wedge 2 = -1$   
**by** *transfer (rule power2-i)*

**lemma** *hcomplex-of-hypreal-pow*:  $\bigwedge x. \text{hcomplex-of-hypreal } (x \wedge n) = \text{hcomplex-of-hypreal } x \wedge n$   
**by** *transfer (rule of-real-power)*

**lemma** *hcomplex-hcnj-pow*:  $\bigwedge z. \text{hcnj } (z \wedge n) = \text{hcnj } z \wedge n$   
**by** *transfer (rule complex-cnj-power)*

**lemma** *hcmmod-hcomplexpow*:  $\bigwedge x. \text{hcmmod } (x \wedge n) = \text{hcmmod } x \wedge n$   
**by** *transfer (rule norm-power)*

**lemma** *hcpow-minus*:  
 $\bigwedge x n. (-x :: \text{hcomplex}) \text{ pow } n = (\text{if } (*p* \text{ even}) \text{ then } (x \text{ pow } n) \text{ else } -(x \text{ pow } n))$



by *transfer simp*

**lemma** *hcpow-mult*:  $(r * s) \text{ pow } n = (r \text{ pow } n) * (s \text{ pow } n)$   
 for  $r s :: \text{hcomplex}$   
 by (*fact hyperpow-mult*)

**lemma** *hcpow-zero2* [*simp*]:  $\bigwedge n. 0 \text{ pow } (\text{hSuc } n) = (0::'a::\text{semiring-1 star})$   
 by *transfer (rule power-0-Suc)*

**lemma** *hcpow-not-zero* [*simp,intro*]:  $\bigwedge r n. r \neq 0 \implies r \text{ pow } n \neq (0::\text{hcomplex})$   
 by (*fact hyperpow-not-zero*)

**lemma** *hcpow-zero-zero*:  $r \text{ pow } n = 0 \implies r = 0$   
 for  $r :: \text{hcomplex}$   
 by (*blast intro: ccontr dest: hcpow-not-zero*)

## 7.12 The Function *hsgn*

**lemma** *hsgn-zero* [*simp*]:  $\text{hsgn } 0 = 0$   
 by *transfer (rule sgn-zero)*

**lemma** *hsgn-one* [*simp*]:  $\text{hsgn } 1 = 1$   
 by *transfer (rule sgn-one)*

**lemma** *hsgn-minus*:  $\bigwedge z. \text{hsgn } (-z) = - \text{hsgn } z$   
 by *transfer (rule sgn-minus)*

**lemma** *hsgn-eq*:  $\bigwedge z. \text{hsgn } z = z / \text{hcomplex-of-hypreal } (\text{hmod } z)$   
 by *transfer (rule sgn-eq)*

**lemma** *hmod-i*:  $\bigwedge x y. \text{hmod } (\text{HComplex } x y) = (*\text{ sqrt}) (x^2 + y^2)$   
 by *transfer (rule complex-norm)*

**lemma** *hcomplex-eq-cancel-iff1* [*simp*]:  
 $\text{hcomplex-of-hypreal } xa = \text{HComplex } x y \longleftrightarrow xa = x \wedge y = 0$   
 by (*simp add: hcomplex-of-hypreal-eq*)

**lemma** *hcomplex-eq-cancel-iff2* [*simp*]:  
 $\text{HComplex } x y = \text{hcomplex-of-hypreal } xa \longleftrightarrow x = xa \wedge y = 0$   
 by (*simp add: hcomplex-of-hypreal-eq*)

**lemma** *HComplex-eq-0* [*simp*]:  $\bigwedge x y. \text{HComplex } x y = 0 \longleftrightarrow x = 0 \wedge y = 0$   
 by *transfer (rule Complex-eq-0)*

**lemma** *HComplex-eq-1* [*simp*]:  $\bigwedge x y. \text{HComplex } x y = 1 \longleftrightarrow x = 1 \wedge y = 0$   
 by *transfer (rule Complex-eq-1)*

**lemma** *i-eq-HComplex-0-1*:  $iii = \text{HComplex } 0 1$   
 by *transfer (simp add: complex-eq-iff)*

**lemma** *HComplex-eq-i* [simp]:  $\bigwedge x y. HComplex\ x\ y = iii \longleftrightarrow x = 0 \wedge y = 1$   
 by transfer (rule *Complex-eq-i*)

**lemma** *hRe-hsgn* [simp]:  $\bigwedge z. hRe\ (hsgn\ z) = hRe\ z / hmod\ z$   
 by transfer (rule *Re-sgn*)

**lemma** *hIm-hsgn* [simp]:  $\bigwedge z. hIm\ (hsgn\ z) = hIm\ z / hmod\ z$   
 by transfer (rule *Im-sgn*)

**lemma** *HComplex-inverse*:  $\bigwedge x y. inverse\ (HComplex\ x\ y) = HComplex\ (x / (x^2 + y^2))\ (-y / (x^2 + y^2))$   
 by transfer (rule *complex-inverse*)

**lemma** *hRe-mult-i-eq*[simp]:  $\bigwedge y. hRe\ (iii * hcomplex-of-hypreal\ y) = 0$   
 by transfer simp

**lemma** *hIm-mult-i-eq* [simp]:  $\bigwedge y. hIm\ (iii * hcomplex-of-hypreal\ y) = y$   
 by transfer simp

**lemma** *hmod-mult-i* [simp]:  $\bigwedge y. hmod\ (iii * hcomplex-of-hypreal\ y) = |y|$   
 by transfer (simp add: *norm-complex-def*)

**lemma** *hmod-mult-i2* [simp]:  $\bigwedge y. hmod\ (hcomplex-of-hypreal\ y * iii) = |y|$   
 by transfer (simp add: *norm-complex-def*)

### 7.12.1 harg

**lemma** *cos-harg-i-mult-zero* [simp]:  $\bigwedge y. y \neq 0 \implies (*f* cos)\ (harg\ (HComplex\ 0\ y)) = 0$   
 by transfer (simp add: *Complex-eq*)

## 7.13 Polar Form for Nonstandard Complex Numbers

**lemma** *complex-split-polar2*:  $\forall n. \exists r a. (z\ n) = complex-of-real\ r * Complex\ (cos\ a)\ (sin\ a)$   
 unfolding *Complex-eq* by (auto intro: *complex-split-polar*)

**lemma** *hcomplex-split-polar*:  
 $\bigwedge z. \exists r a. z = hcomplex-of-hypreal\ r * (HComplex\ ((*f* cos)\ a)\ ((*f* sin)\ a))$   
 by transfer (simp add: *Complex-eq complex-split-polar*)

**lemma** *hcis-eq*:  
 $\bigwedge a. hcis\ a = hcomplex-of-hypreal\ ((*f* cos)\ a) + iii * hcomplex-of-hypreal\ ((*f* sin)\ a)$   
 by transfer (simp add: *complex-eq-iff*)

**lemma** *hrcis-Ex*:  $\bigwedge z. \exists r a. z = hrcis\ r\ a$   
 by transfer (rule *rcis-Ex*)

**lemma** *hRe-hcomplex-polar* [simp]:

$\bigwedge r a. hRe (hcomplex-of-hypreal r * HComplex (( *f* cos) a) (( *f* sin) a)) = r$   
 $* (*f* cos) a$   
 by transfer simp

**lemma** *hRe-hrcis* [simp]:  $\bigwedge r a. hRe (hrcis r a) = r * (*f* cos) a$   
 by transfer (rule Re-rcis)

**lemma** *hIm-hcomplex-polar* [simp]:

$\bigwedge r a. hIm (hcomplex-of-hypreal r * HComplex (( *f* cos) a) (( *f* sin) a)) = r$   
 $* (*f* sin) a$   
 by transfer simp

**lemma** *hIm-hrcis* [simp]:  $\bigwedge r a. hIm (hrcis r a) = r * (*f* sin) a$   
 by transfer (rule Im-rcis)

**lemma** *hcmmod-unit-one* [simp]:  $\bigwedge a. hcmmod (HComplex (( *f* cos) a) (( *f* sin) a)) = 1$   
 by transfer (simp add: cmod-unit-one)

**lemma** *hcmmod-complex-polar* [simp]:

$\bigwedge r a. hcmmod (hcomplex-of-hypreal r * HComplex (( *f* cos) a) (( *f* sin) a))$   
 $= |r|$   
 by transfer (simp add: Complex-eq cmod-complex-polar)

**lemma** *hcmmod-hrcis* [simp]:  $\bigwedge r a. hcmmod(hrcis r a) = |r|$   
 by transfer (rule complex-mod-rcis)

$(r1 * hrcis a) * (r2 * hrcis b) = r1 * r2 * hrcis (a + b)$

**lemma** *hcis-hrcis-eq*:  $\bigwedge a. hcis a = hrcis 1 a$

by transfer (rule cis-rcis-eq)

**declare** *hcis-hrcis-eq* [symmetric, simp]

**lemma** *hrcis-mult*:  $\bigwedge a b r1 r2. hrcis r1 a * hrcis r2 b = hrcis (r1 * r2) (a + b)$   
 by transfer (rule rcis-mult)

**lemma** *hcis-mult*:  $\bigwedge a b. hcis a * hcis b = hcis (a + b)$   
 by transfer (rule cis-mult)

**lemma** *hcis-zero* [simp]:  $hcis 0 = 1$   
 by transfer (rule cis-zero)

**lemma** *hrcis-zero-mod* [simp]:  $\bigwedge a. hrcis 0 a = 0$   
 by transfer (rule rcis-zero-mod)

**lemma** *hrcis-zero-arg* [simp]:  $\bigwedge r. hrcis r 0 = hcomplex-of-hypreal r$   
 by transfer (rule rcis-zero-arg)

**lemma** *hcomplex-i-mult-minus* [simp]:  $\bigwedge x. iii * (iii * x) = - x$

by *transfer (rule complex-i-mult-minus)*

**lemma** *hcomplex-i-mult-minus2 [simp]*:  $iii * iii * x = - x$   
by *simp*

**lemma** *hcis-hypreal-of-nat-Suc-mult*:

$\bigwedge a. hcis (hypreal-of-nat (Suc n) * a) = hcis a * hcis (hypreal-of-nat n * a)$   
by *transfer (simp add: distrib-right cis-mult)*

**lemma** *NSDeMoivre*:  $\bigwedge a. (hcis a) ^ n = hcis (hypreal-of-nat n * a)$   
by *transfer (rule DeMoivre)*

**lemma** *hcis-hypreal-of-hypnat-Suc-mult*:

$\bigwedge a n. hcis (hypreal-of-hypnat (n + 1) * a) = hcis a * hcis (hypreal-of-hypnat n * a)$   
by *transfer (simp add: distrib-right cis-mult)*

**lemma** *NSDeMoivre-ext*:  $\bigwedge a n. (hcis a) pow n = hcis (hypreal-of-hypnat n * a)$   
by *transfer (rule DeMoivre)*

**lemma** *NSDeMoivre2*:  $\bigwedge a r. (hrcis r a) ^ n = hrcis (r ^ n) (hypreal-of-nat n * a)$   
by *transfer (rule DeMoivre2)*

**lemma** *DeMoivre2-ext*:  $\bigwedge a r n. (hrcis r a) pow n = hrcis (r pow n) (hypreal-of-hypnat n * a)$   
by *transfer (rule DeMoivre2)*

**lemma** *hcis-inverse [simp]*:  $\bigwedge a. inverse (hcis a) = hcis (- a)$   
by *transfer (rule cis-inverse)*

**lemma** *hrcis-inverse*:  $\bigwedge a r. inverse (hrcis r a) = hrcis (inverse r) (- a)$   
by *transfer (simp add: rcis-inverse inverse-eq-divide [symmetric])*

**lemma** *hRe-hcis [simp]*:  $\bigwedge a. hRe (hcis a) = (*f* cos) a$   
by *transfer simp*

**lemma** *hIm-hcis [simp]*:  $\bigwedge a. hIm (hcis a) = (*f* sin) a$   
by *transfer simp*

**lemma** *cos-n-hRe-hcis-pow-n*:  $(*f* cos) (hypreal-of-nat n * a) = hRe (hcis a ^ n)$   
by *(simp add: NSDeMoivre)*

**lemma** *sin-n-hIm-hcis-pow-n*:  $(*f* sin) (hypreal-of-nat n * a) = hIm (hcis a ^ n)$   
by *(simp add: NSDeMoivre)*

**lemma** *cos-n-hRe-hcis-hcpow-n*:  $(*f* cos) (hypreal-of-hypnat n * a) = hRe (hcis a pow n)$   
by *(simp add: NSDeMoivre-ext)*

**lemma** *sin-n-hIm-hcis-hcpow-n*: ( $*f*$  *sin*) (*hypreal-of-hypnat*  $n * a$ ) = *hIm* (*hcis*  $a$  *pow*  $n$ )

**by** (*simp add: NSDeMoivre-ext*)

**lemma** *hExp-add*:  $\bigwedge a b. hExp (a + b) = hExp a * hExp b$

**by** *transfer (rule exp-add)*

### 7.14 *hcomplex-of-complex*: the Injection from type *complex* to *hcomplex*

**lemma** *hcomplex-of-complex-i*: *iii* = *hcomplex-of-complex* *i*

**by** (*rule iii-def*)

**lemma** *hRe-hcomplex-of-complex*: *hRe* (*hcomplex-of-complex*  $z$ ) = *hypreal-of-real* (*Re*  $z$ )

**by** *transfer (rule refl)*

**lemma** *hIm-hcomplex-of-complex*: *hIm* (*hcomplex-of-complex*  $z$ ) = *hypreal-of-real* (*Im*  $z$ )

**by** *transfer (rule refl)*

**lemma** *hmod-hcomplex-of-complex*: *hmod* (*hcomplex-of-complex*  $x$ ) = *hypreal-of-real* (*cmod*  $x$ )

**by** *transfer (rule refl)*

### 7.15 Numerals and Arithmetic

**lemma** *hcomplex-of-hypreal-eq-hcomplex-of-complex*:

*hcomplex-of-hypreal* (*hypreal-of-real*  $x$ ) = *hcomplex-of-complex* (*complex-of-real*  $x$ )

**by** *transfer (rule refl)*

**lemma** *hcomplex-hypreal-numeral*:

*hcomplex-of-complex* (*numeral*  $w$ ) = *hcomplex-of-hypreal*(*numeral*  $w$ )

**by** *transfer (rule of-real-numeral [symmetric])*

**lemma** *hcomplex-hypreal-neg-numeral*:

*hcomplex-of-complex* ( $-$  *numeral*  $w$ ) = *hcomplex-of-hypreal*( $-$  *numeral*  $w$ )

**by** *transfer (rule of-real-neg-numeral [symmetric])*

**lemma** *hcomplex-numeral-hcnj* [*simp*]: *hcnj* (*numeral*  $v :: hcomplex$ ) = *numeral*  $v$

**by** *transfer (rule complex-cnj-numeral)*

**lemma** *hcomplex-numeral-hmod* [*simp*]: *hmod* (*numeral*  $v :: hcomplex$ ) = (*numeral*  $v :: hypreal$ )

**by** *transfer (rule norm-numeral)*

**lemma** *hcomplex-neg-numeral-hmod* [*simp*]: *hmod* ( $-$  *numeral*  $v :: hcomplex$ ) = (*numeral*  $v :: hypreal$ )

**by** *transfer (rule norm-neg-numeral)*

**lemma** *hcomplex-numeral-hRe* [*simp*]:  $hRe (numeral\ v :: hcomplex) = numeral\ v$   
**by** *transfer* (*rule complex-Re-numeral*)

**lemma** *hcomplex-numeral-hIm* [*simp*]:  $hIm (numeral\ v :: hcomplex) = 0$   
**by** *transfer* (*rule complex-Im-numeral*)

**end**

## 8 Star-Transforms in Non-Standard Analysis

**theory** *Star*  
**imports** *NSA*  
**begin**

**definition** — internal sets  
*starset-n* ::  $(nat \Rightarrow 'a\ set) \Rightarrow 'a\ star\ set$  (*\*sn\** - [80] 80)  
**where** *\*sn\** *As* = *Iset* (*star-n* *As*)

**definition** *InternalSets* ::  $'a\ star\ set\ set$   
**where** *InternalSets* =  $\{X. \exists As. X = *sn* As\}$

**definition** — nonstandard extension of function  
*is-starext* ::  $('a\ star \Rightarrow 'a\ star) \Rightarrow ('a \Rightarrow 'a) \Rightarrow bool$   
**where** *is-starext* *F*  $f \longleftrightarrow$   
 $(\forall x\ y. \exists X \in Rep\text{-}star\ x. \exists Y \in Rep\text{-}star\ y. y = F\ x \longleftrightarrow eventually\ (\lambda n. Y\ n = f(X\ n))\ \mathcal{U})$

**definition** — internal functions  
*starfun-n* ::  $(nat \Rightarrow 'a \Rightarrow 'b) \Rightarrow 'a\ star \Rightarrow 'b\ star$  (*\*fn\** - [80] 80)  
**where** *\*fn\** *F* = *Ifun* (*star-n* *F*)

**definition** *InternalFuns* ::  $('a\ star \Rightarrow 'b\ star)\ set$   
**where** *InternalFuns* =  $\{X. \exists F. X = *fn* F\}$

### 8.1 Preamble - Pulling $\exists$ over $\forall$

This proof does not need AC and was suggested by the referee for the JCM Paper: let  $f\ x$  be least  $y$  such that  $Q\ x\ y$ .

**lemma** *no-choice*:  $\forall x. \exists y. Q\ x\ y \implies \exists f :: 'a \Rightarrow nat. \forall x. Q\ x\ (f\ x)$   
**by** (*rule exI* [**where**  $x = \lambda x. LEAST\ y. Q\ x\ y$ ]) (*blast intro: LeastI*)

### 8.2 Properties of the Star-transform Applied to Sets of Reals

**lemma** *STAR-star-of-image-subset*:  $star\text{-of}\ 'A \subseteq *s* A$   
**by** *auto*

**lemma** *STAR-hypreal-of-real-Int*:  $*s* X \cap \mathbf{R} = hypreal\text{-of}\text{-real}\ 'X$

by (auto simp add: SReal-def)

**lemma** STAR-star-of-Int:  $*s* X \cap \text{Standard} = \text{star-of } X$   
by (auto simp add: Standard-def)

**lemma** lemma-not-hyprealA:  $x \notin \text{hypreal-of-real } A \implies \forall y \in A. x \neq \text{hypreal-of-real } y$   
by auto

**lemma** lemma-not-starA:  $x \notin \text{star-of } A \implies \forall y \in A. x \neq \text{star-of } y$   
by auto

**lemma** STAR-real-seq-to-hypreal:  $\forall n. (X n) \notin M \implies \text{star-n } X \notin *s* M$   
by (simp add: starset-def star-of-def Iset-star-n FreeUltrafilterNat.proper)

**lemma** STAR-singleton:  $*s* \{x\} = \{\text{star-of } x\}$   
by simp

**lemma** STAR-not-mem:  $x \notin F \implies \text{star-of } x \notin *s* F$   
by transfer

**lemma** STAR-subset-closed:  $x \in *s* A \implies A \subseteq B \implies x \in *s* B$   
by (erule rev-subsetD) simp

Nonstandard extension of a set (defined using a constant sequence) as a special case of an internal set.

**lemma** starset-n-starset:  $\forall n. A s n = A \implies *s n* A s = *s* A$   
by (drule fun-eq-iff [THEN iffD2]) (simp add: starset-n-def starset-def star-of-def)

### 8.3 Theorems about nonstandard extensions of functions

Nonstandard extension of a function (defined using a constant sequence) as a special case of an internal function.

**lemma** starfun-n-starfun:  $F = (\lambda n. f) \implies *f n* F = *f* f$   
by (simp add: starfun-n-def starfun-def star-of-def)

Prove that *abs* for hypreal is a nonstandard extension of *abs* for real w/o use of congruence property (proved after this for general nonstandard extensions of real valued functions).

Proof now Uses the ultrafilter tactic!

**lemma** hrabs-is-starext-rabs: *is-starext abs abs*

**proof** –

**have**  $\exists f \in \text{Rep-star } (\text{star-n } h). \exists g \in \text{Rep-star } (\text{star-n } k). (\text{star-n } k = |\text{star-n } h|) =$   
 $(\forall_F n \text{ in } \mathcal{U}. (g n :: 'a) = |f n|)$   
**for**  $x y :: 'a \text{ star}$  **and**  $h k$   
**by** (metis (full-types) Rep-star-star-n star-n-abs star-n-eq-iff)  
**then show** ?thesis

**unfolding** *is-starext-def* **by** (*metis star-cases*)  
**qed**

Nonstandard extension of functions.

**lemma** *starfun*:  $(** f) (star-n X) = star-n (\lambda n. f (X n))$   
**by** (*rule starfun-star-n*)

**lemma** *starfun-if-eq*:  $\bigwedge w. w \neq star-of\ x \implies (** (\lambda z. if\ z = x\ then\ a\ else\ g\ z))$   
 $w = (** g) w$   
**by** *transfer simp*

Multiplication:  $(** f) x (** g) = *(f\ x\ g)$

**lemma** *starfun-mult*:  $\bigwedge x. (** f) x (** g) x = (** (\lambda x. f\ x * g\ x)) x$   
**by** *transfer (rule refl)*

**declare** *starfun-mult* [*symmetric, simp*]

Addition:  $(** f) + (** g) = *(f + g)$

**lemma** *starfun-add*:  $\bigwedge x. (** f) x + (** g) x = (** (\lambda x. f\ x + g\ x)) x$   
**by** *transfer (rule refl)*

**declare** *starfun-add* [*symmetric, simp*]

Subtraction:  $(** f) + -(** g) = *(f + -g)$

**lemma** *starfun-minus*:  $\bigwedge x. -(** f) x = (** (\lambda x. - f\ x)) x$   
**by** *transfer (rule refl)*

**declare** *starfun-minus* [*symmetric, simp*]

**lemma** *starfun-add-minus*:  $\bigwedge x. (** f) x + -(** g) x = (** (\lambda x. f\ x + -g\ x)) x$

**by** *transfer (rule refl)*

**declare** *starfun-add-minus* [*symmetric, simp*]

**lemma** *starfun-diff*:  $\bigwedge x. (** f) x - (** g) x = (** (\lambda x. f\ x - g\ x)) x$   
**by** *transfer (rule refl)*

**declare** *starfun-diff* [*symmetric, simp*]

Composition:  $(** f) \circ (** g) = *(f \circ g)$

**lemma** *starfun-o2*:  $(\lambda x. (** f) ((** g) x)) = (** (\lambda x. f (g\ x)))$   
**by** *transfer (rule refl)*

**lemma** *starfun-o*:  $(** f) \circ (** g) = (** (f \circ g))$   
**by** (*transfer o-def*) (*rule refl*)

NS extension of constant function.

**lemma** *starfun-const-fun* [*simp*]:  $\bigwedge x. (** (\lambda x. k)) x = star-of\ k$   
**by** *transfer (rule refl)*

The NS extension of the identity function.



**lemma** *starfun-Id* [*simp*]:  $\bigwedge x. (*f* (\lambda x. x)) x = x$   
**by** *transfer (rule refl)*

The Star-function is a (nonstandard) extension of the function.

**lemma** *is-starext-starfun*: *is-starext* ( $*f*$   $f$ )  $f$   
**proof** –  
**have**  $\exists X \in \text{Rep-star } x. \exists Y \in \text{Rep-star } y. (y = (*f* f) x) = (\forall_F n \text{ in } \mathcal{U}. Y n = f (X n))$   
**for**  $x y$   
**by** (*metis (mono-tags) Rep-star-star-n star-cases star-n-eq-iff starfun-star-n*)  
**then show** *?thesis*  
**by** (*auto simp: is-starext-def*)  
**qed**

Any nonstandard extension is in fact the Star-function.

**lemma** *is-starfun-starext*:  
**assumes** *is-starext*  $F f$   
**shows**  $F = *f* f$   
**proof** –  
**have**  $F x = (*f* f) x$   
**if**  $\forall x y. \exists X \in \text{Rep-star } x. \exists Y \in \text{Rep-star } y. (y = F x) = (\forall_F n \text{ in } \mathcal{U}. Y n = f (X n))$  **for**  $x$   
**by** (*metis that mem-Rep-star-iff star-n-eq-iff starfun-star-n*)  
**with** *assms* **show** *?thesis*  
**by** (*force simp add: is-starext-def*)  
**qed**

**lemma** *is-starext-starfun-iff*: *is-starext*  $F f \longleftrightarrow F = *f* f$   
**by** (*blast intro: is-starfun-starext is-starext-starfun*)

Extended function has same solution as its standard version for real arguments. i.e they are the same for all real arguments.

**lemma** *starfun-eq*:  $(*f* f) (\text{star-of } a) = \text{star-of } (f a)$   
**by** (*rule starfun-star-of*)

**lemma** *starfun-approx*:  $(*f* f) (\text{star-of } a) \approx \text{star-of } (f a)$   
**by** *simp*

Useful for NS definition of derivatives.

**lemma** *starfun-lambda-cancel*:  $\bigwedge x'. (*f* (\lambda h. f (x + h))) x' = (*f* f) (\text{star-of } x + x')$   
**by** *transfer (rule refl)*

**lemma** *starfun-lambda-cancel2*:  $(*f* (\lambda h. f (g (x + h)))) x' = (*f* (f \circ g)) (\text{star-of } x + x')$   
**unfolding** *o-def* **by** (*rule starfun-lambda-cancel*)

**lemma** *starfun-mult-HFinite-approx*:

$( *f* f) x \approx l \implies ( *f* g) x \approx m \implies l \in HFinite \implies m \in HFinite \implies$   
 $( *f* (\lambda x. f x * g x)) x \approx l * m$   
**for**  $l m :: 'a::real-normed-algebra star$   
**using** *approx-mult-HFinite* **by** *auto*

**lemma** *starfun-add-approx*:  $( *f* f) x \approx l \implies ( *f* g) x \approx m \implies ( *f* (\%x. f x + g x)) x \approx l + m$   
**by** (*auto intro: approx-add*)

Examples: *hrabs* is nonstandard extension of *rabs*, *inverse* is nonstandard extension of *inverse*.

Can be proved easily using theorem *starfun* and properties of ultrafilter as for *inverse* below we use the theorem we proved above instead.

**lemma** *starfun-rabs-hrabs*:  $*f* abs = abs$   
**by** (*simp only: star-abs-def*)

**lemma** *starfun-inverse-inverse* [*simp*]:  $( *f* inverse) x = inverse x$   
**by** (*simp only: star-inverse-def*)

**lemma** *starfun-inverse*:  $\bigwedge x. inverse (( *f* f) x) = ( *f* (\lambda x. inverse (f x))) x$   
**by** *transfer (rule refl)*  
**declare** *starfun-inverse* [*symmetric, simp*]

**lemma** *starfun-divide*:  $\bigwedge x. ( *f* f) x / ( *f* g) x = ( *f* (\lambda x. f x / g x)) x$   
**by** *transfer (rule refl)*  
**declare** *starfun-divide* [*symmetric, simp*]

**lemma** *starfun-inverse2*:  $\bigwedge x. inverse (( *f* f) x) = ( *f* (\lambda x. inverse (f x))) x$   
**by** *transfer (rule refl)*

General lemma/theorem needed for proofs in elementary topology of the reals.

**lemma** *starfun-mem-starset*:  $\bigwedge x. ( *f* f) x \in *s* A \implies x \in *s* \{x. f x \in A\}$   
**by** *transfer simp*

Alternative definition for *hrabs* with *rabs* function applied entrywise to equivalence class representative. This is easily proved using *starfun* and ns extension thm.

**lemma** *hypreal-hrabs*:  $|star-n X| = star-n (\lambda n. |X n|)$   
**by** (*simp only: starfun-rabs-hrabs [symmetric] starfun*)

Nonstandard extension of set through nonstandard extension of *rabs* function i.e. *hrabs*. A more general result should be where we replace *rabs* by some arbitrary function *f* and *hrabs* by its NS extension. See second NS set extension below.

**lemma** *STAR-rabs-add-minus*:  $*s* \{x. |x + - y| < r\} = \{x. |x + -star-of y| < star-of r\}$

by *transfer (rule refl)*

**lemma** *STAR-starfun-rabs-add-minus:*

$*s* \{x. |f x + - y| < r\} = \{x. |( *f* f) x + -star-of y| < star-of r\}$

by *transfer (rule refl)*

Another characterization of Infinitesimal and one of  $\approx$  relation. In this theory since *hypreal-hrabs* proved here. Maybe move both theorems??

**lemma** *Infinitesimal-FreeUltrafilterNat-iff2:*

$star-n X \in Infinitesimal \longleftrightarrow (\forall m. eventually (\lambda n. norm (X n) < inverse (real (Suc m))) \mathcal{U})$

by (*simp add: Infinitesimal-hypreal-of-nat-iff star-of-def hnorm-def star-of-nat-def starfun-star-n star-n-inverse star-n-less*)

**lemma** *HNatInfinite-inverse-Infinitesimal [simp]:*

assumes  $n \in HNatInfinite$

shows  $inverse (hypreal-of-hypnat n) \in Infinitesimal$

**proof** (*cases n*)

case (*star-n X*)

then have  $*$ :  $\bigwedge k. \forall_F n \text{ in } \mathcal{U}. k < X n$

using *HNatInfinite-FreeUltrafilterNat assms* by *blast*

have  $\forall_F n \text{ in } \mathcal{U}. inverse (real (X n)) < inverse (1 + real m)$  for  $m$

using  $*$  [*of Suc m*] by (*auto elim!: eventually-mono*)

then show *?thesis*

using *star-n* by (*auto simp: of-hypnat-def starfun-star-n star-n-inverse Infinitesimal-FreeUltrafilterNat-iff2*)

**qed**

**lemma** *approx-FreeUltrafilterNat-iff:*

$star-n X \approx star-n Y \longleftrightarrow (\forall r > 0. eventually (\lambda n. norm (X n - Y n) < r) \mathcal{U})$

(*is ?lhs = ?rhs*)

**proof** –

have *?lhs* = (*star-n X - star-n Y  $\approx 0$* )

using *approx-minus-iff* by *blast*

also have *... = ?rhs*

by (*metis (full-types) Infinitesimal-FreeUltrafilterNat-iff mem-infmal-iff star-n-diff*)

finally show *?thesis* .

**qed**

**lemma** *approx-FreeUltrafilterNat-iff2:*

$star-n X \approx star-n Y \longleftrightarrow (\forall m. eventually (\lambda n. norm (X n - Y n) < inverse (real (Suc m))) \mathcal{U})$

(*is ?lhs = ?rhs*)

**proof** –

have *?lhs* = (*star-n X - star-n Y  $\approx 0$* )

using *approx-minus-iff* by *blast*

also have *... = ?rhs*

by (*metis (full-types) Infinitesimal-FreeUltrafilterNat-iff2 mem-infmal-iff star-n-diff*)

finally show *?thesis* .

qed

**lemma** *inj-starfun: inj starfun*

**proof** (rule *inj-onI*)

show  $\varphi = \psi$  if eq:  $*f* \varphi = *f* \psi$  for  $\varphi \psi :: 'a \Rightarrow 'b$

**proof** (rule *ext*, rule *ccontr*)

show *False*

if  $\varphi x \neq \psi x$  for  $x$

by (metis eq that star-of-inject starfun-eq)

qed

qed

end

## 9 Star-transforms for the Hypernaturals

**theory** *NatStar*

imports *Star*

begin

**lemma** *star-n-eq-starfun-whn: star-n X = (\*f\* X) whn*

by (simp add: *hypnat-omega-def starfun-def star-of-def Ifun-star-n*)

**lemma** *starset-n-Un: \*sn\* ( $\lambda n. (A n) \cup (B n)$ ) = \*sn\* A  $\cup$  \*sn\* B*

**proof** –

have  $\bigwedge N. \text{Iset } ((*f* (\lambda n. \{x. x \in A n \vee x \in B n\})) N) =$   
 $\{x. x \in \text{Iset } ((*f* A) N) \vee x \in \text{Iset } ((*f* B) N)\}$

by *transfer simp*

then show *?thesis*

by (simp add: *starset-n-def star-n-eq-starfun-whn Un-def*)

qed

**lemma** *InternalSets-Un: X  $\in$  InternalSets  $\implies$  Y  $\in$  InternalSets  $\implies$  X  $\cup$  Y  $\in$  InternalSets*

by (auto simp add: *InternalSets-def starset-n-Un [symmetric]*)

**lemma** *starset-n-Int: \*sn\* ( $\lambda n. A n \cap B n$ ) = \*sn\* A  $\cap$  \*sn\* B*

**proof** –

have  $\bigwedge N. \text{Iset } ((*f* (\lambda n. \{x. x \in A n \wedge x \in B n\})) N) =$   
 $\{x. x \in \text{Iset } ((*f* A) N) \wedge x \in \text{Iset } ((*f* B) N)\}$

by *transfer simp*

then show *?thesis*

by (simp add: *starset-n-def star-n-eq-starfun-whn Int-def*)

qed

**lemma** *InternalSets-Int: X  $\in$  InternalSets  $\implies$  Y  $\in$  InternalSets  $\implies$  X  $\cap$  Y  $\in$  InternalSets*

by (auto simp add: *InternalSets-def starset-n-Int [symmetric]*)

**lemma** *starset-n-Compl*:  $*sn* ((\lambda n. - A n)) = - (*sn* A)$

**proof** –

**have**  $\bigwedge N. Iset ((*f* (\lambda n. \{x. x \notin A n\})) N) =$   
 $\{x. x \notin Iset ((*f* A) N)\}$

**by** *transfer simp*

**then show** *?thesis*

**by** (*simp add: starset-n-def star-n-eq-starfun-whn Compl-eq*)

**qed**

**lemma** *InternalSets-Compl*:  $X \in InternalSets \implies - X \in InternalSets$

**by** (*auto simp add: InternalSets-def starset-n-Compl [symmetric]*)

**lemma** *starset-n-diff*:  $*sn* (\lambda n. (A n) - (B n)) = *sn* A - *sn* B$

**proof** –

**have**  $\bigwedge N. Iset ((*f* (\lambda n. \{x. x \in A n \wedge x \notin B n\})) N) =$   
 $\{x. x \in Iset ((*f* A) N) \wedge x \notin Iset ((*f* B) N)\}$

**by** *transfer simp*

**then show** *?thesis*

**by** (*simp add: starset-n-def star-n-eq-starfun-whn set-diff-eq*)

**qed**

**lemma** *InternalSets-diff*:  $X \in InternalSets \implies Y \in InternalSets \implies X - Y \in InternalSets$

**by** (*auto simp add: InternalSets-def starset-n-diff [symmetric]*)

**lemma** *NatStar-SHNat-subset*:  $Nats \leq *s* (UNIV:: nat set)$

**by** *simp*

**lemma** *NatStar-hypreal-of-real-Int*:  $*s* X Int Nats = hypnat-of-nat ' X$

**by** (*auto simp add: SHNat-eq*)

**lemma** *starset-starset-n-eq*:  $*s* X = *sn* (\lambda n. X)$

**by** (*simp add: starset-n-starset*)

**lemma** *InternalSets-starset-n [simp]*:  $(*s* X) \in InternalSets$

**by** (*auto simp add: InternalSets-def starset-starset-n-eq*)

**lemma** *InternalSets-UNIV-diff*:  $X \in InternalSets \implies UNIV - X \in InternalSets$

**by** (*simp add: InternalSets-Compl diff-eq*)

## 9.1 Nonstandard Extensions of Functions

Example of transfer of a property from reals to hyperreals — used for limit comparison of sequences.

**lemma** *starfun-le-mono*:  $\forall n. N \leq n \longrightarrow f n \leq g n \implies$

$\forall n. hypnat-of-nat N \leq n \longrightarrow (*f* f) n \leq (*f* g) n$

**by** *transfer*

And another:

**lemma** *starfun-less-mono*:

$\forall n. N \leq n \longrightarrow f\ n < g\ n \implies \forall n. \text{hypnat-of-nat } N \leq n \longrightarrow (*f* f)\ n < (*f* g)\ n$   
**by** *transfer*

Nonstandard extension when we increment the argument by one.

**lemma** *starfun-shift-one*:  $\bigwedge N. (*f* (\lambda n. f\ (Suc\ n)))\ N = (*f* f)\ (N + (1::\text{hypnat}))$   
**by** *transfer simp*

Nonstandard extension with absolute value.

**lemma** *starfun-abs*:  $\bigwedge N. (*f* (\lambda n. |f\ n|))\ N = |(*f* f)\ N|$   
**by** *transfer (rule refl)*

The *hyperpow* function as a nonstandard extension of *realpow*.

**lemma** *starfun-pow*:  $\bigwedge N. (*f* (\lambda n. r \hat{\ } n))\ N = \text{hypreal-of-real } r\ \text{pow } N$   
**by** *transfer (rule refl)*

**lemma** *starfun-pow2*:  $\bigwedge N. (*f* (\lambda n. X\ n \hat{\ } m))\ N = (*f* X)\ N\ \text{pow } \text{hypnat-of-nat } m$   
**by** *transfer (rule refl)*

**lemma** *starfun-pow3*:  $\bigwedge R. (*f* (\lambda r. r \hat{\ } n))\ R = R\ \text{pow } \text{hypnat-of-nat } n$   
**by** *transfer (rule refl)*

The *hypreal-of-hypnat* function as a nonstandard extension of *real*.

**lemma** *starfunNat-real-of-nat*:  $(*f* \text{real}) = \text{hypreal-of-hypnat}$   
**by** *transfer (simp add: fun-eq-iff)*

**lemma** *starfun-inverse-real-of-nat-eq*:

$N \in \text{HNatInfinite} \implies (*f* (\lambda x::\text{nat}. \text{inverse } (\text{real } x)))\ N = \text{inverse } (\text{hypreal-of-hypnat } N)$   
**by** *(metis of-hypnat-def starfun-inverse2)*

Internal functions – some redundancy with *\*f\** now.

**lemma** *starfun-n*:  $(*fn* f)\ (\text{star-n } X) = \text{star-n } (\lambda n. f\ n\ (X\ n))$   
**by** *(simp add: starfun-n-def Ifun-star-n)*

Multiplication:  $(*fn)\ x\ (*gn) = *(fn\ x\ gn)$

**lemma** *starfun-n-mult*:  $(*fn* f)\ z\ (*fn* g)\ z = (*fn* (\lambda i\ x. f\ i\ x\ *g\ i\ x))\ z$   
**by** *(cases z) (simp add: starfun-n star-n-mult)*

Addition:  $(*fn) + (*gn) = *(fn + gn)$

**lemma** *starfun-n-add*:  $(*fn* f)\ z + (*fn* g)\ z = (*fn* (\lambda i\ x. f\ i\ x + g\ i\ x))\ z$   
**by** *(cases z) (simp add: starfun-n star-n-add)*

Subtraction:  $(*fn) - (*gn) = *(fn + -gn)$

**lemma** *starfun-n-add-minus*:  $(*fn* f)\ z + -( *fn* g)\ z = (*fn* (\lambda i\ x. f\ i\ x + -g\ i\ x))\ z$

by (cases z) (simp add: starfun-n star-n-minus star-n-add)

Composition: ( $*fn$ )  $\circ$  ( $*gn$ ) =  $*(fn \circ gn)$

**lemma** starfun-n-const-fun [simp]: ( $*fn*$  ( $\lambda i x. k$ )) z = star-of k  
by (cases z) (simp add: starfun-n star-of-def)

**lemma** starfun-n-minus:  $-( *fn* f ) x = ( *fn* (\lambda i x. - (f i) x) ) x$   
by (cases x) (simp add: starfun-n star-n-minus)

**lemma** starfun-n-eq [simp]: ( $*fn* f$ ) (star-of n) = star-n ( $\lambda i. f i$  n)  
by (simp add: starfun-n star-of-def)

**lemma** starfun-eq-iff: (( $*f*$  f) = ( $*f*$  g))  $\longleftrightarrow$  f = g  
by transfer (rule refl)

**lemma** starfunNat-inverse-real-of-nat-Infinitesimal [simp]:  
N  $\in$  HNatInfinite  $\implies$  ( $*f*$  ( $\lambda x. \text{inverse (real x)}$ )) N  $\in$  Infinitesimal  
using starfun-inverse-real-of-nat-eq by auto

## 9.2 Nonstandard Characterization of Induction

**lemma** hypnat-induct-obj:  
 $\bigwedge n. (( *p* P ) (0::hypnat) \wedge (\forall n. ( *p* P ) n \longrightarrow ( *p* P ) (n + 1))) \longrightarrow ( *p* P ) n$   
by transfer (induct-tac n, auto)

**lemma** hypnat-induct:  
 $\bigwedge n. ( *p* P ) (0::hypnat) \implies (\bigwedge n. ( *p* P ) n \implies ( *p* P ) (n + 1)) \implies ( *p* P ) n$   
by transfer (induct-tac n, auto)

**lemma** starP2-eq-iff: ( $*p2*$  (=)) = (=)  
by transfer (rule refl)

**lemma** starP2-eq-iff2: ( $*p2*$  ( $\lambda x y. x = y$ )) X Y  $\longleftrightarrow$  X = Y  
by (simp add: starP2-eq-iff)

**lemma** nonempty-set-star-has-least-lemma:  
 $\exists n \in S. \forall m \in S. n \leq m$  if  $S \neq \{\}$  for  $S :: \text{nat set}$   
**proof**  
show  $\forall m \in S. (\text{LEAST } n. n \in S) \leq m$   
by (simp add: Least-le)  
show  $(\text{LEAST } n. n \in S) \in S$   
by (meson that LeastI-ex equals0I)  
**qed**

**lemma** nonempty-set-star-has-least:  
 $\bigwedge S::\text{nat set star. Iset } S \neq \{\} \implies \exists n \in \text{Iset } S. \forall m \in \text{Iset } S. n \leq m$   
using nonempty-set-star-has-least-lemma by (transfer empty-def)

**lemma** *nonempty-InternalNatSet-has-least*:  $S \in \text{InternalSets} \implies S \neq \{\} \implies \exists n \in S. \forall m \in S. n \leq m$   
**for**  $S :: \text{hypnat set}$   
**by** (*force simp add: InternalSets-def starset-n-def dest!: nonempty-set-star-has-least*)

Goldblatt, page 129 Thm 11.3.2.

**lemma** *internal-induct-lemma*:  
 $\bigwedge X :: \text{nat set star.}$   
 $(0 :: \text{hypnat}) \in \text{Iset } X \implies \forall n. n \in \text{Iset } X \longrightarrow n + 1 \in \text{Iset } X \implies \text{Iset } X =$   
 $(\text{UNIV} :: \text{hypnat set})$   
**apply** (*transfer UNIV-def*)  
**apply** (*rule equalityI [OF subset-UNIV subsetI]*)  
**apply** (*induct-tac x, auto*)  
**done**

**lemma** *internal-induct*:  
 $X \in \text{InternalSets} \implies (0 :: \text{hypnat}) \in X \implies \forall n. n \in X \longrightarrow n + 1 \in X \implies X =$   
 $(\text{UNIV} :: \text{hypnat set})$   
**apply** (*clarsimp simp add: InternalSets-def starset-n-def*)  
**apply** (*erule (1) internal-induct-lemma*)  
**done**

**end**

## 10 Sequences and Convergence (Nonstandard)

**theory** *HSEQ*  
**imports** *Complex-Main NatStar*  
**abbrevs**  $----> = \longrightarrow_{NS}$   
**begin**

**definition** *NSLIMSEQ* ::  $(\text{nat} \Rightarrow 'a :: \text{real-normed-vector}) \Rightarrow 'a \Rightarrow \text{bool}$   
 $(((-) / \longrightarrow_{NS} (-)) [60, 60] 60)$  **where**  
 — Nonstandard definition of convergence of sequence  
 $X \longrightarrow_{NS} L \longleftrightarrow (\forall N \in \text{HNatInfinite. } (*f* X) N \approx \text{star-of } L)$

**definition** *nslim* ::  $(\text{nat} \Rightarrow 'a :: \text{real-normed-vector}) \Rightarrow 'a$   
**where**  $nslim X = (\text{THE } L. X \longrightarrow_{NS} L)$   
 — Nonstandard definition of limit using choice operator

**definition** *NSconvergent* ::  $(\text{nat} \Rightarrow 'a :: \text{real-normed-vector}) \Rightarrow \text{bool}$   
**where**  $\text{NSconvergent } X \longleftrightarrow (\exists L. X \longrightarrow_{NS} L)$   
 — Nonstandard definition of convergence

**definition** *NSBseq* ::  $(\text{nat} \Rightarrow 'a :: \text{real-normed-vector}) \Rightarrow \text{bool}$   
**where**  $\text{NSBseq } X \longleftrightarrow (\forall N \in \text{HNatInfinite. } (*f* X) N \in \text{HFinite})$   
 — Nonstandard definition for bounded sequence



**definition** *NSCauchy* :: (nat  $\Rightarrow$  'a::real-normed-vector)  $\Rightarrow$  bool  
**where** *NSCauchy* X  $\leftrightarrow$  ( $\forall M \in \text{HNatInfinite}. \forall N \in \text{HNatInfinite}. (*f* X) M \approx (*f* X) N$ )  
 — Nonstandard definition

## 10.1 Limits of Sequences

**lemma** *NSLIMSEQ-I*: ( $\bigwedge N. N \in \text{HNatInfinite} \Rightarrow \text{starfun } X \ N \approx \text{star-of } L$ )  $\Rightarrow$   
 $X \longrightarrow_{NS} L$   
**by** (*simp add: NSLIMSEQ-def*)

**lemma** *NSLIMSEQ-D*:  $X \longrightarrow_{NS} L \Rightarrow N \in \text{HNatInfinite} \Rightarrow \text{starfun } X \ N \approx \text{star-of } L$   
**by** (*simp add: NSLIMSEQ-def*)

**lemma** *NSLIMSEQ-const*:  $(\lambda n. k) \longrightarrow_{NS} k$   
**by** (*simp add: NSLIMSEQ-def*)

**lemma** *NSLIMSEQ-add*:  $X \longrightarrow_{NS} a \Rightarrow Y \longrightarrow_{NS} b \Rightarrow (\lambda n. X \ n + Y \ n) \longrightarrow_{NS} a + b$   
**by** (*auto intro: approx-add simp add: NSLIMSEQ-def*)

**lemma** *NSLIMSEQ-add-const*:  $f \longrightarrow_{NS} a \Rightarrow (\lambda n. f \ n + b) \longrightarrow_{NS} a + b$   
**by** (*simp only: NSLIMSEQ-add NSLIMSEQ-const*)

**lemma** *NSLIMSEQ-mult*:  $X \longrightarrow_{NS} a \Rightarrow Y \longrightarrow_{NS} b \Rightarrow (\lambda n. X \ n * Y \ n) \longrightarrow_{NS} a * b$   
**for**  $a \ b :: 'a::\text{real-normed-algebra}$   
**by** (*auto intro!: approx-mult-HFinite simp add: NSLIMSEQ-def*)

**lemma** *NSLIMSEQ-minus*:  $X \longrightarrow_{NS} a \Rightarrow (\lambda n. - X \ n) \longrightarrow_{NS} - a$   
**by** (*auto simp add: NSLIMSEQ-def*)

**lemma** *NSLIMSEQ-minus-cancel*:  $(\lambda n. - X \ n) \longrightarrow_{NS} - a \Rightarrow X \longrightarrow_{NS} a$   
**by** (*drule NSLIMSEQ-minus simp*)

**lemma** *NSLIMSEQ-diff*:  $X \longrightarrow_{NS} a \Rightarrow Y \longrightarrow_{NS} b \Rightarrow (\lambda n. X \ n - Y \ n) \longrightarrow_{NS} a - b$   
**using** *NSLIMSEQ-add* [of  $X \ a - Y \ - b$ ] **by** (*simp add: NSLIMSEQ-minus fun-Compl-def*)

**lemma** *NSLIMSEQ-diff-const*:  $f \longrightarrow_{NS} a \Rightarrow (\lambda n. f \ n - b) \longrightarrow_{NS} a - b$   
**by** (*simp add: NSLIMSEQ-diff NSLIMSEQ-const*)

**lemma** *NSLIMSEQ-inverse*:  $X \longrightarrow_{NS} a \Rightarrow a \neq 0 \Rightarrow (\lambda n. \text{inverse } (X \ n)) \longrightarrow_{NS} \text{inverse } a$   
**for**  $a :: 'a::\text{real-normed-div-algebra}$

by (simp add: NSLIMSEQ-def star-of-approx-inverse)

**lemma** NSLIMSEQ-mult-inverse:  $X \longrightarrow_{NS} a \implies Y \longrightarrow_{NS} b \implies b \neq 0$   
 $\implies (\lambda n. X\ n / Y\ n) \longrightarrow_{NS} a / b$   
 for  $a\ b :: 'a::\text{real-normed-field}$   
 by (simp add: NSLIMSEQ-mult NSLIMSEQ-inverse divide-inverse)

**lemma** starfun-hnorm:  $\bigwedge x. \text{hnorm} (( *f* f) x) = ( *f* (\lambda x. \text{norm} (f x))) x$   
 by transfer simp

**lemma** NSLIMSEQ-norm:  $X \longrightarrow_{NS} a \implies (\lambda n. \text{norm} (X\ n)) \longrightarrow_{NS} \text{norm}\ a$   
 by (simp add: NSLIMSEQ-def starfun-hnorm [symmetric] approx-hnorm)

Uniqueness of limit.

**lemma** NSLIMSEQ-unique:  $X \longrightarrow_{NS} a \implies X \longrightarrow_{NS} b \implies a = b$   
 unfolding NSLIMSEQ-def  
 using HNatInfinite-whn approx-trans3 star-of-approx-iff by blast

**lemma** NSLIMSEQ-pow [rule-format]:  $(X \longrightarrow_{NS} a) \longrightarrow ((\lambda n. (X\ n) ^ m) \longrightarrow_{NS} a ^ m)$   
 for  $a :: 'a::\{\text{real-normed-algebra,power}\}$   
 by (induct m) (auto intro: NSLIMSEQ-mult NSLIMSEQ-const)

We can now try and derive a few properties of sequences, starting with the limit comparison property for sequences.

**lemma** NSLIMSEQ-le:  $f \longrightarrow_{NS} l \implies g \longrightarrow_{NS} m \implies \exists N. \forall n \geq N. f\ n \leq g\ n \implies l \leq m$   
 for  $l\ m :: \text{real}$   
 unfolding NSLIMSEQ-def  
 by (metis HNatInfinite-whn bex-Infinitesimal-iff2 hypnat-of-nat-le-whn hypreal-of-real-le-add-Infinitesimal-c starfun-le-mono)

**lemma** NSLIMSEQ-le-const:  $X \longrightarrow_{NS} r \implies \forall n. a \leq X\ n \implies a \leq r$   
 for  $a\ r :: \text{real}$   
 by (erule NSLIMSEQ-le [OF NSLIMSEQ-const]) auto

**lemma** NSLIMSEQ-le-const2:  $X \longrightarrow_{NS} r \implies \forall n. X\ n \leq a \implies r \leq a$   
 for  $a\ r :: \text{real}$   
 by (erule NSLIMSEQ-le [OF - NSLIMSEQ-const]) auto

Shift a convergent series by 1: By the equivalence between Cauchiness and convergence and because the successor of an infinite hypernatural is also infinite.

**lemma** NSLIMSEQ-Suc-iff:  $((\lambda n. f (Suc\ n)) \longrightarrow_{NS} l) \longleftrightarrow (f \longrightarrow_{NS} l)$   
**proof**  
 assume \*:  $f \longrightarrow_{NS} l$   
 show  $(\lambda n. f(Suc\ n)) \longrightarrow_{NS} l$

```

proof (rule NSLIMSEQ-I)
  fix  $N$ 
  assume  $N \in \text{HNatInfinite}$ 
  then have  $(*f* f) (N + 1) \approx \text{star-of } l$ 
    by (simp add: HNatInfinite-add NSLIMSEQ-D *)
  then show  $(*f* (\lambda n. f (\text{Suc } n))) N \approx \text{star-of } l$ 
    by (simp add: starfun-shift-one)
qed
next
assume  $*$ :  $(\lambda n. f(\text{Suc } n)) \longrightarrow_{NS} l$ 
show  $f \longrightarrow_{NS} l$ 
proof (rule NSLIMSEQ-I)
  fix  $N$ 
  assume  $N \in \text{HNatInfinite}$ 
  then have  $(*f* (\lambda n. f (\text{Suc } n))) (N - 1) \approx \text{star-of } l$ 
    using  $*$  by (simp add: HNatInfinite-diff NSLIMSEQ-D)
  then show  $(*f* f) N \approx \text{star-of } l$ 
    by (simp add:  $\langle N \in \text{HNatInfinite} \rangle$  one-le-HNatInfinite starfun-shift-one)
qed
qed

```

### 10.1.1 Equivalence of *LIMSEQ* and *NSLIMSEQ*

**lemma** *LIMSEQ-NSLIMSEQ*:

```

assumes  $X$ :  $X \longrightarrow L$ 
shows  $X \longrightarrow_{NS} L$ 
proof (rule NSLIMSEQ-I)
  fix  $N$ 
  assume  $N$ :  $N \in \text{HNatInfinite}$ 
  have starfun  $X N - \text{star-of } L \in \text{Infinitesimal}$ 
  proof (rule InfinitesimalI2)
    fix  $r :: \text{real}$ 
    assume  $r$ :  $0 < r$ 
    from LIMSEQ-D [OF  $X r$ ] obtain no where  $\forall n \geq \text{no. norm } (X n - L) < r ..$ 
    then have  $\forall n \geq \text{star-of no. hnorm } (\text{starfun } X n - \text{star-of } L) < \text{star-of } r$ 
      by transfer
    then show  $\text{hnorm } (\text{starfun } X N - \text{star-of } L) < \text{star-of } r$ 
      using  $N$  by (simp add: star-of-le-HNatInfinite)
  qed
  then show starfun  $X N \approx \text{star-of } L$ 
    by (simp only: approx-def)
qed

```

**lemma** *NSLIMSEQ-LIMSEQ*:

```

assumes  $X$ :  $X \longrightarrow_{NS} L$ 
shows  $X \longrightarrow L$ 
proof (rule LIMSEQ-I)
  fix  $r :: \text{real}$ 
  assume  $r$ :  $0 < r$ 

```

**have**  $\exists no. \forall n \geq no. hnorm (starfun X n - star-of L) < star-of r$   
**proof** (intro exI allI impI)  
**fix**  $n$   
**assume**  $whn \leq n$   
**with**  $HNatInfinite-whn$  **have**  $n \in HNatInfinite$   
**by** (rule  $HNatInfinite-upward-closed$ )  
**with**  $X$  **have**  $starfun X n \approx star-of L$   
**by** (rule  $NSLIMSEQ-D$ )  
**then have**  $starfun X n - star-of L \in Infinitesimal$   
**by** (simp only:  $approx-def$ )  
**then show**  $hnorm (starfun X n - star-of L) < star-of r$   
**using**  $r$  **by** (rule  $InfinitesimalD2$ )  
**qed**  
**then show**  $\exists no. \forall n \geq no. norm (X n - L) < r$   
**by** transfer  
**qed**

**theorem**  $LIMSEQ-NSLIMSEQ-iff: f \longrightarrow L \longleftrightarrow f \longrightarrow_{NS} L$   
**by** (blast intro:  $LIMSEQ-NSLIMSEQ NSLIMSEQ-LIMSEQ$ )

### 10.1.2 Derived theorems about $NSLIMSEQ$

We prove the NS version from the standard one, since the NS proof seems more complicated than the standard one above!

**lemma**  $NSLIMSEQ-norm-zero: (\lambda n. norm (X n)) \longrightarrow_{NS} 0 \longleftrightarrow X \longrightarrow_{NS} 0$   
**by** (simp add:  $LIMSEQ-NSLIMSEQ-iff$  [symmetric]  $tendsto-norm-zero-iff$ )

**lemma**  $NSLIMSEQ-rabs-zero: (\lambda n. |f n|) \longrightarrow_{NS} 0 \longleftrightarrow f \longrightarrow_{NS} (0::real)$   
**by** (simp add:  $LIMSEQ-NSLIMSEQ-iff$  [symmetric]  $tendsto-rabs-zero-iff$ )

Generalization to other limits.

**lemma**  $NSLIMSEQ-imp-rabs: f \longrightarrow_{NS} l \implies (\lambda n. |f n|) \longrightarrow_{NS} |l|$   
**for**  $l :: real$   
**by** (simp add:  $NSLIMSEQ-def$ ) (auto intro:  $approx-hrabs$  simp add:  $starfun-abs$ )

**lemma**  $NSLIMSEQ-inverse-zero: \forall y::real. \exists N. \forall n \geq N. y < f n \implies (\lambda n. inverse (f n)) \longrightarrow_{NS} 0$   
**by** (simp add:  $LIMSEQ-NSLIMSEQ-iff$  [symmetric]  $LIMSEQ-inverse-zero$ )

**lemma**  $NSLIMSEQ-inverse-real-of-nat: (\lambda n. inverse (real (Suc n))) \longrightarrow_{NS} 0$   
**by** (simp add:  $LIMSEQ-NSLIMSEQ-iff$  [symmetric]  $LIMSEQ-inverse-real-of-nat$   
del:  $of-nat-Suc$ )

**lemma**  $NSLIMSEQ-inverse-real-of-nat-add: (\lambda n. r + inverse (real (Suc n))) \longrightarrow_{NS} r$   
**by** (simp add:  $LIMSEQ-NSLIMSEQ-iff$  [symmetric]  $LIMSEQ-inverse-real-of-nat-add$   
del:  $of-nat-Suc$ )

**lemma** *NSLIMSEQ-inverse-real-of-nat-add-minus*:  $(\lambda n. r + - \text{inverse} (\text{real} (\text{Suc } n))) \longrightarrow_{NS} r$   
**using** *LIMSEQ-inverse-real-of-nat-add-minus* **by** (*simp add: LIMSEQ-NSLIMSEQ-iff* [*symmetric*])

**lemma** *NSLIMSEQ-inverse-real-of-nat-add-minus-mult*:  
 $(\lambda n. r * (1 + - \text{inverse} (\text{real} (\text{Suc } n)))) \longrightarrow_{NS} r$   
**using** *LIMSEQ-inverse-real-of-nat-add-minus-mult*  
**by** (*simp add: LIMSEQ-NSLIMSEQ-iff* [*symmetric*])

## 10.2 Convergence

**lemma** *nslimI*:  $X \longrightarrow_{NS} L \implies \text{nslim } X = L$   
**by** (*simp add: nslim-def*) (*blast intro: NSLIMSEQ-unique*)

**lemma** *lim-nslim-iff*:  $\text{lim } X = \text{nslim } X$   
**by** (*simp add: lim-def nslim-def LIMSEQ-NSLIMSEQ-iff*)

**lemma** *NSconvergentD*:  $\text{NSconvergent } X \implies \exists L. X \longrightarrow_{NS} L$   
**by** (*simp add: NSconvergent-def*)

**lemma** *NSconvergentI*:  $X \longrightarrow_{NS} L \implies \text{NSconvergent } X$   
**by** (*auto simp add: NSconvergent-def*)

**lemma** *convergent-NSconvergent-iff*:  $\text{convergent } X = \text{NSconvergent } X$   
**by** (*simp add: convergent-def NSconvergent-def LIMSEQ-NSLIMSEQ-iff*)

**lemma** *NSconvergent-NSLIMSEQ-iff*:  $\text{NSconvergent } X \longleftrightarrow X \longrightarrow_{NS} \text{nslim } X$   
**by** (*auto intro: theI NSLIMSEQ-unique simp add: NSconvergent-def nslim-def*)

## 10.3 Bounded Monotonic Sequences

**lemma** *NSBseqD*:  $\text{NSBseq } X \implies N \in \text{HNatInfinite} \implies (*f* X) N \in \text{HFinite}$   
**by** (*simp add: NSBseq-def*)

**lemma** *Standard-subset-HFfinite*:  $\text{Standard} \subseteq \text{HFfinite}$   
**by** (*auto simp: Standard-def*)

**lemma** *NSBseqD2*:  $\text{NSBseq } X \implies (*f* X) N \in \text{HFfinite}$   
**using** *HNatInfinite-def NSBseq-def Nats-eq-Standard Standard-starfun Standard-subset-HFfinite*  
**by** *blast*

**lemma** *NSBseqI*:  $\forall N \in \text{HNatInfinite}. (*f* X) N \in \text{HFfinite} \implies \text{NSBseq } X$   
**by** (*simp add: NSBseq-def*)

The standard definition implies the nonstandard definition.

**lemma** *Bseq-NSBseq*:  $\text{Bseq } X \implies \text{NSBseq } X$   
**unfolding** *NSBseq-def*

```

proof safe
  assume  $X: Bseq\ X$ 
  fix  $N$ 
  assume  $N: N \in HNatInfinite$ 
  from  $BseqD\ [OF\ X]$  obtain  $K$  where  $\forall n. norm\ (X\ n) \leq K$ 
  by fast
  then have  $\forall N. hnorm\ (starfun\ X\ N) \leq star-of\ K$ 
  by transfer
  then have  $hnorm\ (starfun\ X\ N) \leq star-of\ K$ 
  by simp
  also have  $star-of\ K < star-of\ (K + 1)$ 
  by simp
  finally have  $\exists x \in Reals. hnorm\ (starfun\ X\ N) < x$ 
  by (rule  $bexI$ ) simp
  then show  $starfun\ X\ N \in HFinite$ 
  by (simp add: HFinite-def)
qed

```

The nonstandard definition implies the standard definition.

```

lemma SReal-less-omega:  $r \in \mathbf{R} \implies r < \omega$ 
  using HInfinite-omega
  by (simp add: HInfinite-def) (simp add: order-less-imp-le)

```

```

lemma NSBseq-Bseq:  $NSBseq\ X \implies Bseq\ X$ 
proof (rule ccontr)
  let  $?n = \lambda K. LEAST\ n. K < norm\ (X\ n)$ 
  assume  $NSBseq\ X$ 
  then have  $finite: (*f* X) (( *f* ?n) \omega) \in HFinite$ 
  by (rule NSBseqD2)
  assume  $\neg Bseq\ X$ 
  then have  $\forall K > 0. \exists n. K < norm\ (X\ n)$ 
  by (simp add: Bseq-def linorder-not-le)
  then have  $\forall K > 0. K < norm\ (X\ (?n\ K))$ 
  by (auto intro: LeastI-ex)
  then have  $\forall K > 0. K < hnorm\ ((*f* X) (( *f* ?n) K))$ 
  by transfer
  then have  $\omega < hnorm\ ((*f* X) (( *f* ?n) \omega))$ 
  by simp
  then have  $\forall r \in \mathbf{R}. r < hnorm\ ((*f* X) (( *f* ?n) \omega))$ 
  by (simp add: order-less-trans [OF SReal-less-omega])
  then have  $(*f* X) (( *f* ?n) \omega) \in HInfinite$ 
  by (simp add: HInfinite-def)
  with  $finite$  show False
  by (simp add: HFinite-HInfinite-iff)
qed

```

Equivalence of nonstandard and standard definitions for a bounded sequence.

```

lemma Bseq-NSBseq-iff:  $Bseq\ X = NSBseq\ X$ 

```

by (*blast intro!*: *NSBseq-Bseq Bseq-NSBseq*)

A convergent sequence is bounded: Boundedness as a necessary condition for convergence. The nonstandard version has no existential, as usual.

**lemma** *NSconvergent-NSBseq*: *NSconvergent X  $\implies$  NSBseq X*  
 by (*simp add*: *NSconvergent-def NSBseq-def NSLIMSEQ-def*)  
 (*blast intro*: *HFinite-star-of approx-sym approx-HFinite*)

Standard Version: easily now proved using equivalence of NS and standard definitions.

**lemma** *convergent-Bseq*: *convergent X  $\implies$  Bseq X*  
 for *X :: nat  $\Rightarrow$  'b::real-normed-vector*  
 by (*simp add*: *NSconvergent-NSBseq convergent-NSconvergent-iff Bseq-NSBseq-iff*)

### 10.3.1 Upper Bounds and Lubs of Bounded Sequences

**lemma** *NSBseq-isUb*: *NSBseq X  $\implies$   $\exists U::real. isUb UNIV \{x. \exists n. X n = x\} U$*   
 by (*simp add*: *Bseq-NSBseq-iff [symmetric] Bseq-isUb*)

**lemma** *NSBseq-isLub*: *NSBseq X  $\implies$   $\exists U::real. isLub UNIV \{x. \exists n. X n = x\} U$*   
 by (*simp add*: *Bseq-NSBseq-iff [symmetric] Bseq-isLub*)

### 10.3.2 A Bounded and Monotonic Sequence Converges

The best of both worlds: Easier to prove this result as a standard theorem and then use equivalence to "transfer" it into the equivalent nonstandard form if needed!

**lemma** *Bmonoseq-NSLIMSEQ*:  *$\forall_F k$  in sequentially.  $X k = X m \implies X \longrightarrow_{NS} X m$*

**unfolding** *LIMSEQ-NSLIMSEQ-iff [symmetric]*  
 by (*simp add*: *eventually-mono eventually-nhds-x-imp-x filterlim-iff*)

**lemma** *NSBseq-mono-NSconvergent*: *NSBseq X  $\implies$   $\forall m. \forall n \geq m. X m \leq X n$*   
 $\implies$  *NSconvergent X*

for *X :: nat  $\Rightarrow$  real*  
 by (*auto intro*: *Bseq-mono-convergent*  
*simp*: *convergent-NSconvergent-iff [symmetric] Bseq-NSBseq-iff [symmetric]*)

## 10.4 Cauchy Sequences

**lemma** *NSCauchyI*:

( $\bigwedge M N. M \in \text{HNatInfinite} \implies N \in \text{HNatInfinite} \implies \text{starfun } X M \approx \text{starfun } X N$ )  $\implies$  *NSCauchy X*

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

**lemma** *NSCauchyD*:

*NSCauchy X  $\implies$   $M \in \text{HNatInfinite} \implies N \in \text{HNatInfinite} \implies \text{starfun } X M \approx \text{starfun } X N$*

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

## 10.4.1 Equivalence Between NS and Standard

**lemma** *Cauchy-NSCauchy*:

**assumes**  $X$ : *Cauchy*  $X$

**shows** *NSCauchy*  $X$

**proof** (*rule NSCauchyI*)

**fix**  $M$

**assume**  $M$ :  $M \in \text{HNatInfinite}$

**fix**  $N$

**assume**  $N$ :  $N \in \text{HNatInfinite}$

**have** *starfun*  $X$   $M$  – *starfun*  $X$   $N \in \text{Infinitesimal}$

**proof** (*rule InfinitesimalI2*)

**fix**  $r$  :: *real*

**assume**  $r$ :  $0 < r$

**from** *CauchyD* [*OF*  $X$   $r$ ] **obtain**  $k$  **where**  $\forall m \geq k. \forall n \geq k. \text{norm} (X\ m - X\ n) < r$  ..

**then have**  $\forall m \geq \text{star-of } k. \forall n \geq \text{star-of } k. \text{hnorm} (\text{starfun } X\ m - \text{starfun } X\ n) < \text{star-of } r$

**by** *transfer*

**then show**  $\text{hnorm} (\text{starfun } X\ M - \text{starfun } X\ N) < \text{star-of } r$

**using**  $M$   $N$  **by** (*simp add: star-of-le-HNatInfinite*)

**qed**

**then show** *starfun*  $X$   $M \approx \text{starfun } X$   $N$

**by** (*simp only: approx-def*)

**qed**

**lemma** *NSCauchy-Cauchy*:

**assumes**  $X$ : *NSCauchy*  $X$

**shows** *Cauchy*  $X$

**proof** (*rule CauchyI*)

**fix**  $r$  :: *real*

**assume**  $r$ :  $0 < r$

**have**  $\exists k. \forall m \geq k. \forall n \geq k. \text{hnorm} (\text{starfun } X\ m - \text{starfun } X\ n) < \text{star-of } r$

**proof** (*intro exI allI impI*)

**fix**  $M$

**assume**  $\text{whn} \leq M$

**with** *HNatInfinite-whn* **have**  $M$ :  $M \in \text{HNatInfinite}$

**by** (*rule HNatInfinite-upward-closed*)

**fix**  $N$

**assume**  $\text{whn} \leq N$

**with** *HNatInfinite-whn* **have**  $N$ :  $N \in \text{HNatInfinite}$

**by** (*rule HNatInfinite-upward-closed*)

**from**  $X$   $M$   $N$  **have** *starfun*  $X$   $M \approx \text{starfun } X$   $N$

**by** (*rule NSCauchyD*)

**then have** *starfun*  $X$   $M$  – *starfun*  $X$   $N \in \text{Infinitesimal}$

**by** (*simp only: approx-def*)

**then show**  $\text{hnorm} (\text{starfun } X\ M - \text{starfun } X\ N) < \text{star-of } r$

**using**  $r$  **by** (*rule InfinitesimalD2*)

**qed**

**then show**  $\exists k. \forall m \geq k. \forall n \geq k. \text{norm} (X\ m - X\ n) < r$



by transfer  
qed

**theorem** *NSCauchy-Cauchy-iff*:  $NSCauchy\ X = Cauchy\ X$   
by (*blast intro!*: *NSCauchy-Cauchy Cauchy-NSCauchy*)

#### 10.4.2 Cauchy Sequences are Bounded

A Cauchy sequence is bounded – nonstandard version.

**lemma** *NSCauchy-NSBseq*:  $NSCauchy\ X \implies NSBseq\ X$   
by (*simp add*: *Cauchy-Bseq Bseq-NSBseq-iff [symmetric] NSCauchy-Cauchy-iff*)

#### 10.4.3 Cauchy Sequences are Convergent

Equivalence of Cauchy criterion and convergence: We will prove this using our NS formulation which provides a much easier proof than using the standard definition. We do not need to use properties of subsequences such as boundedness, monotonicity etc... Compare with Harrison’s corresponding proof in HOL which is much longer and more complicated. Of course, we do not have problems which he encountered with guessing the right instantiations for his ‘epsilon-delta’ proof(s) in this case since the NS formulations do not involve existential quantifiers.

**lemma** *NSconvergent-NSCauchy*:  $NSconvergent\ X \implies NSCauchy\ X$   
by (*simp add*: *NSconvergent-def NSLIMSEQ-def NSCauchy-def*) (*auto intro*: *approx-trans2*)

**lemma** *real-NSCauchy-NSconvergent*:

fixes  $X :: nat \Rightarrow real$

assumes *NSCauchy X* shows *NSconvergent X*

unfolding *NSconvergent-def NSLIMSEQ-def*

**proof** –

have ( $*f* X$ ) *whn*  $\in HFinite$

by (*simp add*: *NSBseqD2 NSCauchy-NSBseq assms*)

moreover have  $\forall N \in HNatInfinite. (*f* X) whn \approx (*f* X) N$

using *HNatInfinite-whn NSCauchy-def assms* by *blast*

ultimately show  $\exists L. \forall N \in HNatInfinite. (*f* X) N \approx hypreal-of-real L$

by (*force dest!*: *st-part-Ex simp add*: *SReal-iff intro*: *approx-trans3*)

qed

**lemma** *NSCauchy-NSconvergent*:  $NSCauchy\ X \implies NSconvergent\ X$

for  $X :: nat \Rightarrow 'a::banach$

using *Cauchy-convergent NSCauchy-Cauchy convergent-NSconvergent-iff* by *auto*

**lemma** *NSCauchy-NSconvergent-iff*:  $NSCauchy\ X = NSconvergent\ X$

for  $X :: nat \Rightarrow 'a::banach$

by (*fast intro*: *NSCauchy-NSconvergent NSconvergent-NSCauchy*)

## 10.5 Power Sequences

The sequence  $x^n$  tends to 0 if  $(0::'a) \leq x$  and  $x < (1::'a)$ . Proof will use (NS) Cauchy equivalence for convergence and also fact that bounded and monotonic sequence converges.

We now use NS criterion to bring proof of theorem through.

**lemma** *NSLIMSEQ-realpow-zero*:

**fixes**  $x :: \text{real}$

**assumes**  $0 \leq x < 1$  **shows**  $(\lambda n. x \wedge n) \longrightarrow_{NS} 0$

**proof** –

**have**  $(** (\wedge) x) N \approx 0$

**if**  $N: N \in \text{HNatInfinite}$  **and**  $x: \text{NSconvergent} ((\wedge) x)$  **for**  $N$

**proof** –

**have** *hypreal-of-real*  $x \text{ pow } N \approx \text{hypreal-of-real } x \text{ pow } (N + 1)$

**by** *(metis HNatInfinite-add N NSCauchy-NSconvergent-iff NSCauchy-def starfun-pow x)*

**moreover obtain**  $L$  **where**  $L: \text{hypreal-of-real } x \text{ pow } N \approx \text{hypreal-of-real } L$

**using** *NSconvergentD [OF x] N* **by** *(auto simp add: NSLIMSEQ-def starfun-pow)*

**ultimately have** *hypreal-of-real*  $x \text{ pow } N \approx \text{hypreal-of-real } L * \text{hypreal-of-real } x$

**by** *(simp add: approx-mult-subst-star-of hyperpow-add)*

**then have** *hypreal-of-real*  $L \approx \text{hypreal-of-real } L * \text{hypreal-of-real } x$

**using**  $L$  *approx-trans3* **by** *blast*

**then show** *?thesis*

**by** *(metis L ⟨x < 1⟩ hyperpow-def less-irrefl mult.right-neutral mult-left-cancel star-of-approx-iff star-of-mult star-of-simps(9) starfun2-star-of)*

**qed**

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

**by** *(force dest!: convergent-realpow simp add: NSLIMSEQ-def convergent-NSconvergent-iff)*

**qed**

**lemma** *NSLIMSEQ-abs-realpow-zero*:  $|c| < 1 \implies (\lambda n. |c| \wedge n) \longrightarrow_{NS} 0$

**for**  $c :: \text{real}$

**by** *(simp add: LIMSEQ-abs-realpow-zero LIMSEQ-NSLIMSEQ-iff [symmetric])*

**lemma** *NSLIMSEQ-abs-realpow-zero2*:  $|c| < 1 \implies (\lambda n. c \wedge n) \longrightarrow_{NS} 0$

**for**  $c :: \text{real}$

**by** *(simp add: LIMSEQ-abs-realpow-zero2 LIMSEQ-NSLIMSEQ-iff [symmetric])*

**end**

## 11 Finite Summation and Infinite Series for Hyperreals

**theory** *HSeries*

**imports** *HSEQ*

begin

**definition**  $sumhr :: hypnat \times hypnat \times (nat \Rightarrow real) \Rightarrow hypreal$   
**where**  $sumhr = (\lambda(M,N,f). starfun2 (\lambda m n. sum f \{m..<n\})) M N$

**definition**  $NSsums :: (nat \Rightarrow real) \Rightarrow real \Rightarrow bool$  (**infixr**  $NSsums$  80)  
**where**  $f NSsums s = (\lambda n. sum f \{..<n\}) \longrightarrow_{NS} s$

**definition**  $NSsummable :: (nat \Rightarrow real) \Rightarrow bool$   
**where**  $NSsummable f \longleftrightarrow (\exists s. f NSsums s)$

**definition**  $NSsuminf :: (nat \Rightarrow real) \Rightarrow real$   
**where**  $NSsuminf f = (THE s. f NSsums s)$

**lemma**  $sumhr\text{-}app$ :  $sumhr (M, N, f) = (*f2* (\lambda m n. sum f \{m..<n\})) M N$   
**by** ( $simp$   $add$ :  $sumhr\text{-}def$ )

Base case in definition of  $sumr$ .

**lemma**  $sumhr\text{-}zero$  [ $simp$ ]:  $\bigwedge m. sumhr (m, 0, f) = 0$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$   $simp$

Recursive case in definition of  $sumr$ .

**lemma**  $sumhr\text{-}if$ :  
 $\bigwedge m n. sumhr (m, n + 1, f) = (if\ n + 1 \leq m\ then\ 0\ else\ sumhr (m, n, f) + (*f* f) n)$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$   $simp$

**lemma**  $sumhr\text{-}Suc\text{-}zero$  [ $simp$ ]:  $\bigwedge n. sumhr (n + 1, n, f) = 0$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$   $simp$

**lemma**  $sumhr\text{-}eq\text{-}bounds$  [ $simp$ ]:  $\bigwedge n. sumhr (n, n, f) = 0$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$   $simp$

**lemma**  $sumhr\text{-}Suc$  [ $simp$ ]:  $\bigwedge m. sumhr (m, m + 1, f) = (*f* f) m$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$   $simp$

**lemma**  $sumhr\text{-}add\text{-}lbound\text{-}zero$  [ $simp$ ]:  $\bigwedge k m. sumhr (m + k, k, f) = 0$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$   $simp$

**lemma**  $sumhr\text{-}add$ :  $\bigwedge m n. sumhr (m, n, f) + sumhr (m, n, g) = sumhr (m, n, \lambda i. f i + g i)$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$  ( $rule$   $sum.distrib$  [ $symmetric$ ])

**lemma**  $sumhr\text{-}mult$ :  $\bigwedge m n. hypreal\text{-}of\text{-}real\ r * sumhr (m, n, f) = sumhr (m, n, \lambda n. r * f n)$   
**unfolding**  $sumhr\text{-}app$  **by**  $transfer$  ( $rule$   $sum\text{-}distrib\text{-}left$ )

**lemma**  $sumhr\text{-}split\text{-}add$ :  $\bigwedge n p. n < p \implies sumhr (0, n, f) + sumhr (n, p, f) = sumhr (0, p, f)$

**unfolding** *sumhr-app* by *transfer* (*simp add: sum.atLeastLessThan-concat*)

**lemma** *sumhr-split-diff*:  $n < p \implies \text{sumhr } (0, p, f) - \text{sumhr } (0, n, f) = \text{sumhr } (n, p, f)$

**by** (*drule sumhr-split-add [symmetric, where f = f]*) *simp*

**lemma** *sumhr-hrabs*:  $\bigwedge m n. |\text{sumhr } (m, n, f)| \leq \text{sumhr } (m, n, \lambda i. |f i|)$

**unfolding** *sumhr-app* by *transfer* (*rule sum-abs*)

Other general version also needed.

**lemma** *sumhr-fun-hypnat-eq*:

$(\forall r. m \leq r \wedge r < n \implies f r = g r) \implies$   
 $\text{sumhr } (\text{hypnat-of-nat } m, \text{hypnat-of-nat } n, f) =$   
 $\text{sumhr } (\text{hypnat-of-nat } m, \text{hypnat-of-nat } n, g)$

**unfolding** *sumhr-app* by *transfer simp*

**lemma** *sumhr-const*:  $\bigwedge n. \text{sumhr } (0, n, \lambda i. r) = \text{hypreal-of-hypnat } n * \text{hypreal-of-real } r$

**unfolding** *sumhr-app* by *transfer simp*

**lemma** *sumhr-less-bounds-zero* [*simp*]:  $\bigwedge m n. n < m \implies \text{sumhr } (m, n, f) = 0$

**unfolding** *sumhr-app* by *transfer simp*

**lemma** *sumhr-minus*:  $\bigwedge m n. \text{sumhr } (m, n, \lambda i. -f i) = - \text{sumhr } (m, n, f)$

**unfolding** *sumhr-app* by *transfer* (*rule sum-negf*)

**lemma** *sumhr-shift-bounds*:

$\bigwedge m n. \text{sumhr } (m + \text{hypnat-of-nat } k, n + \text{hypnat-of-nat } k, f) =$   
 $\text{sumhr } (m, n, \lambda i. f (i + k))$

**unfolding** *sumhr-app* by *transfer* (*rule sum.shift-bounds-nat-ivl*)

## 11.1 Nonstandard Sums

Infinite sums are obtained by summing to some infinite hypernatural (such as *whn*).

**lemma** *sumhr-hypreal-of-hypnat-omega*:  $\text{sumhr } (0, \text{whn}, \lambda i. 1) = \text{hypreal-of-hypnat } \text{whn}$

**by** (*simp add: sumhr-const*)

**lemma** *whn-eq- $\omega$ m1*:  $\text{hypreal-of-hypnat } \text{whn} = \omega - 1$

**unfolding** *star-class-defs omega-def hypnat-omega-def of-hypnat-def star-of-def*

**by** (*simp add: starfun-star-n starfun2-star-n*)

**lemma** *sumhr-hypreal-omega-minus-one*:  $\text{sumhr}(0, \text{whn}, \lambda i. 1) = \omega - 1$

**by** (*simp add: sumhr-const whn-eq- $\omega$ m1*)

**lemma** *sumhr-minus-one-realpow-zero* [*simp*]:  $\bigwedge N. \text{sumhr } (0, N + N, \lambda i. (-1)^\wedge (i + 1)) = 0$

**unfolding** *sumhr-app*  
**by** *transfer (induct-tac N, auto)*

**lemma** *sumhr-interval-const*:

$(\forall n. m \leq \text{Suc } n \longrightarrow f \ n = r) \wedge m \leq na \implies$   
 $\text{sumhr } (\text{hypnat-of-nat } m, \text{hypnat-of-nat } na, f) = \text{hypreal-of-nat } (na - m) * \text{hypreal-of-real } r$

**unfolding** *sumhr-app* **by** *transfer simp*

**lemma** *starfunNat-sumr*:  $\bigwedge N. (*f* (\lambda n. \text{sum } f \ \{0..<n\})) \ N = \text{sumhr } (0, N, f)$

**unfolding** *sumhr-app* **by** *transfer (rule refl)*

**lemma** *sumhr-hrabs-approx [simp]*:  $\text{sumhr } (0, M, f) \approx \text{sumhr } (0, N, f) \implies |\text{sumhr } (M, N, f)| \approx 0$

**using** *linorder-less-linear [where x = M and y = N]*

**by** (*metis (no-types, lifting) abs-zero approx-hrabs approx-minus-iff approx-refl approx-sym sumhr-eq-bounds sumhr-less-bounds-zero sumhr-split-iff*)

## 11.2 Infinite sums: Standard and NS theorems

**lemma** *sums-NSsums-iff*:  $f \ \text{sums } l \longleftrightarrow f \ \text{NSsums } l$

**by** (*simp add: sums-def NSsums-def LIMSEQ-NSLIMSEQ-iff*)

**lemma** *summable-NSsummable-iff*:  $\text{summable } f \longleftrightarrow \text{NSsummable } f$

**by** (*simp add: summable-def NSsummable-def sums-NSsums-iff*)

**lemma** *suminf-NSsuminf-iff*:  $\text{suminf } f = \text{NSsuminf } f$

**by** (*simp add: suminf-def NSsuminf-def sums-NSsums-iff*)

**lemma** *NSsums-NSsummable*:  $f \ \text{NSsums } l \implies \text{NSsummable } f$

**unfolding** *NSsums-def NSsummable-def* **by** *blast*

**lemma** *NSsummable-NSsums*:  $\text{NSsummable } f \implies f \ \text{NSsums } (\text{NSsuminf } f)$

**unfolding** *NSsummable-def NSsuminf-def NSsums-def*

**by** (*blast intro: theI NSLIMSEQ-unique*)

**lemma** *NSsums-unique*:  $f \ \text{NSsums } s \implies s = \text{NSsuminf } f$

**by** (*simp add: suminf-NSsuminf-iff [symmetric] sums-NSsums-iff sums-unique*)

**lemma** *NSseries-zero*:  $\forall m. n \leq \text{Suc } m \longrightarrow f \ m = 0 \implies f \ \text{NSsums } (\text{sum } f \ \{..<n\})$

**by** (*auto simp add: sums-NSsums-iff [symmetric] not-le[symmetric] intro!: sums-finite*)

**lemma** *NSsummable-NSCauchy*:

$\text{NSsummable } f \longleftrightarrow (\forall M \in \text{HNatInfinite}. \forall N \in \text{HNatInfinite}. |\text{sumhr } (M, N, f)| \approx 0)$  (is ?L=?R)

**proof** –

**have** ?L =  $(\forall M \in \text{HNatInfinite}. \forall N \in \text{HNatInfinite}. \text{sumhr } (0, M, f) \approx \text{sumhr } (0, N, f))$

**by** (*auto simp add: summable-iff-convergent convergent-NSconvergent-iff NSCauchy-def*)

*starfunNat-sumr*  
*simp flip: NSCauchy-NSconvergent-iff summable-NSsummable-iff atLeast0LessThan)*  
**also have** ...  $\longleftrightarrow$  ?*R*  
**by** (*metis approx-hrabs-zero-cancel approx-minus-iff approx-refl approx-sym*  
*linorder-less-linear sumhr-hrabs-approx sumhr-split-diff*)  
**finally show** ?*thesis* .  
**qed**

Terms of a convergent series tend to zero.

**lemma** *NSsummable-NSLIMSEQ-zero: NSsummable f  $\implies$  f  $\longrightarrow_{NS}$  0*  
**by** (*metis HNatInfinite-add NSLIMSEQ-def NSsummable-NSCauchy approx-hrabs-zero-cancel*  
*star-of-zero sumhr-Suc*)

Nonstandard comparison test.

**lemma** *NSsummable-comparison-test:  $\exists N. \forall n. N \leq n \longrightarrow |f n| \leq g n \implies NSsummable$*   
*g  $\implies NSsummable f$*   
**by** (*metis real-norm-def summable-NSsummable-iff summable-comparison-test*)

**lemma** *NSsummable-rabs-comparison-test:*  
 $\exists N. \forall n. N \leq n \longrightarrow |f n| \leq g n \implies NSsummable g \implies NSsummable (\lambda k. |f k|)$   
**by** (*rule NSsummable-comparison-test*) *auto*

**end**

## 12 Limits and Continuity (Nonstandard)

**theory** *HLim*  
**imports** *Star*  
**abbrevs**  $----> = -\square \rightarrow_{NS}$   
**begin**

Nonstandard Definitions.

**definition** *NSLIM :: ('a::real-normed-vector  $\Rightarrow$  'b::real-normed-vector)  $\Rightarrow$  'a  $\Rightarrow$  'b*  
 $\Rightarrow$  *bool*  
 $(((-)/ -(-)/\rightarrow_{NS} (-)) [60, 0, 60] 60)$   
**where**  $f -a \rightarrow_{NS} L \longleftrightarrow (\forall x. x \neq \text{star-of } a \wedge x \approx \text{star-of } a \longrightarrow (*f* f) x \approx \text{star-of } L)$

**definition** *isNSCont :: ('a::real-normed-vector  $\Rightarrow$  'b::real-normed-vector)  $\Rightarrow$  'a  $\Rightarrow$*   
*bool*  
**where** — NS definition dispenses with limit notions  
 $isNSCont f a \longleftrightarrow (\forall y. y \approx \text{star-of } a \longrightarrow (*f* f) y \approx \text{star-of } (f a))$

**definition** *isNSUCont :: ('a::real-normed-vector  $\Rightarrow$  'b::real-normed-vector)  $\Rightarrow$  bool*  
**where**  $isNSUCont f \longleftrightarrow (\forall x y. x \approx y \longrightarrow (*f* f) x \approx (*f* f) y)$

## 12.1 Limits of Functions

**lemma** *NSLIM-I*:  $(\bigwedge x. x \neq \text{star-of } a \implies x \approx \text{star-of } a \implies \text{starfun } f \ x \approx \text{star-of } L) \implies f -a \rightarrow_{NS} L$   
**by** (*simp add: NSLIM-def*)

**lemma** *NSLIM-D*:  $f -a \rightarrow_{NS} L \implies x \neq \text{star-of } a \implies x \approx \text{star-of } a \implies \text{starfun } f \ x \approx \text{star-of } L$   
**by** (*simp add: NSLIM-def*)

Proving properties of limits using nonstandard definition. The properties hold for standard limits as well!

**lemma** *NSLIM-mult*:  $f -x \rightarrow_{NS} l \implies g -x \rightarrow_{NS} m \implies (\lambda x. f \ x * g \ x) -x \rightarrow_{NS} (l * m)$   
**for**  $l \ m :: 'a::\text{real-normed-algebra}$   
**by** (*auto simp add: NSLIM-def intro!: approx-mult-HFinite*)

**lemma** *starfun-scaleR* [*simp*]:  $\text{starfun } (\lambda x. f \ x *_R g \ x) = (\lambda x. \text{scaleHR } (\text{starfun } f \ x) (\text{starfun } g \ x))$   
**by** *transfer (rule refl)*

**lemma** *NSLIM-scaleR*:  $f -x \rightarrow_{NS} l \implies g -x \rightarrow_{NS} m \implies (\lambda x. f \ x *_R g \ x) -x \rightarrow_{NS} (l *_R m)$   
**by** (*auto simp add: NSLIM-def intro!: approx-scaleR-HFinite*)

**lemma** *NSLIM-add*:  $f -x \rightarrow_{NS} l \implies g -x \rightarrow_{NS} m \implies (\lambda x. f \ x + g \ x) -x \rightarrow_{NS} (l + m)$   
**by** (*auto simp add: NSLIM-def intro!: approx-add*)

**lemma** *NSLIM-const* [*simp*]:  $(\lambda x. k) -x \rightarrow_{NS} k$   
**by** (*simp add: NSLIM-def*)

**lemma** *NSLIM-minus*:  $f -a \rightarrow_{NS} L \implies (\lambda x. - f \ x) -a \rightarrow_{NS} -L$   
**by** (*simp add: NSLIM-def*)

**lemma** *NSLIM-diff*:  $f -x \rightarrow_{NS} l \implies g -x \rightarrow_{NS} m \implies (\lambda x. f \ x - g \ x) -x \rightarrow_{NS} (l - m)$   
**by** (*simp only: NSLIM-add NSLIM-minus diff-conv-add-uminus*)

**lemma** *NSLIM-add-minus*:  $f -x \rightarrow_{NS} l \implies g -x \rightarrow_{NS} m \implies (\lambda x. f \ x + - g \ x) -x \rightarrow_{NS} (l + -m)$   
**by** (*simp only: NSLIM-add NSLIM-minus*)

**lemma** *NSLIM-inverse*:  $f -a \rightarrow_{NS} L \implies L \neq 0 \implies (\lambda x. \text{inverse } (f \ x)) -a \rightarrow_{NS} (\text{inverse } L)$   
**for**  $L :: 'a::\text{real-normed-div-algebra}$   
**unfolding** *NSLIM-def* **by** (*metis (no-types) star-of-approx-inverse star-of-simps(6) starfun-inverse*)

**lemma** *NSLIM-zero*:

**assumes**  $f: f -a \rightarrow_{NS} l$   
**shows**  $(\lambda x. f(x) - l) -a \rightarrow_{NS} 0$   
**proof** –  
**have**  $(\lambda x. f x - l) -a \rightarrow_{NS} l - l$   
**by** (*rule NSLIM-diff [OF f NSLIM-const]*)  
**then show** *?thesis* **by** *simp*  
**qed**

**lemma** *NSLIM-zero-cancel*:  
**assumes**  $(\lambda x. f x - l) -x \rightarrow_{NS} 0$   
**shows**  $f -x \rightarrow_{NS} l$   
**proof** –  
**have**  $(\lambda x. f x - l + l) -x \rightarrow_{NS} 0 + l$   
**by** (*fast intro: assms NSLIM-const NSLIM-add*)  
**then show** *?thesis*  
**by** *simp*  
**qed**

**lemma** *NSLIM-const-eq*:  
**fixes**  $a :: 'a::real-normed-algebra-1$   
**assumes**  $(\lambda x. k) -a \rightarrow_{NS} l$   
**shows**  $k = l$   
**proof** –  
**have**  $\neg (\lambda x. k) -a \rightarrow_{NS} l$  **if**  $k \neq l$   
**proof** –  
**have** *star-of a + of-hypreal  $\varepsilon \approx$  star-of a*  
**by** (*simp add: approx-def*)  
**then show** *?thesis*  
**using** *epsilon-not-zero that* **by** (*force simp add: NSLIM-def*)  
**qed**  
**with** *assms* **show** *?thesis* **by** *metis*  
**qed**

**lemma** *NSLIM-unique*:  $f -a \rightarrow_{NS} l \implies f -a \rightarrow_{NS} M \implies l = M$   
**for**  $a :: 'a::real-normed-algebra-1$   
**by** (*drule (1) NSLIM-diff*) (*auto dest!: NSLIM-const-eq*)

**lemma** *NSLIM-mult-zero*:  $f -x \rightarrow_{NS} 0 \implies g -x \rightarrow_{NS} 0 \implies (\lambda x. f x * g x) -x \rightarrow_{NS} 0$   
**for**  $f g :: 'a::real-normed-vector \Rightarrow 'b::real-normed-algebra$   
**by** (*drule NSLIM-mult*) *auto*

**lemma** *NSLIM-self*:  $(\lambda x. x) -a \rightarrow_{NS} a$   
**by** (*simp add: NSLIM-def*)

### 12.1.1 Equivalence of *filterlim* and *NSLIM*

**lemma** *LIM-NSLIM*:  
**assumes**  $f: f -a \rightarrow L$



**shows**  $f - a \rightarrow_{NS} L$   
**proof** (rule *NSLIM-I*)  
**fix**  $x$   
**assume** *neg*:  $x \neq \text{star-of } a$   
**assume** *approx*:  $x \approx \text{star-of } a$   
**have** *starfun*  $f x - \text{star-of } L \in \text{Infinitesimal}$   
**proof** (rule *InfinitesimalI2*)  
**fix**  $r :: \text{real}$   
**assume**  $r: 0 < r$   
**from** *LIM-D* [*OF f r*] **obtain**  $s$   
**where**  $s: 0 < s$  **and** *less-r*:  $\bigwedge x. x \neq a \implies \text{norm } (x - a) < s \implies \text{norm } (f x - L) < r$   
**by** *fast*  
**from** *less-r* **have** *less-r'*:  
 $\bigwedge x. x \neq \text{star-of } a \implies \text{hnorm } (x - \text{star-of } a) < \text{star-of } s \implies$   
 $\text{hnorm } (\text{starfun } f x - \text{star-of } L) < \text{star-of } r$   
**by** *transfer*  
**from** *approx* **have**  $x - \text{star-of } a \in \text{Infinitesimal}$   
**by** (*simp only*: *approx-def*)  
**then** **have**  $\text{hnorm } (x - \text{star-of } a) < \text{star-of } s$   
**using**  $s$  **by** (rule *InfinitesimalD2*)  
**with** *neg* **show**  $\text{hnorm } (\text{starfun } f x - \text{star-of } L) < \text{star-of } r$   
**by** (rule *less-r'*)  
**qed**  
**then** **show**  $\text{starfun } f x \approx \text{star-of } L$   
**by** (*unfold approx-def*)  
**qed**

**lemma** *NSLIM-LIM*:  
**assumes**  $f: f - a \rightarrow_{NS} L$   
**shows**  $f - a \rightarrow L$   
**proof** (rule *LIM-I*)  
**fix**  $r :: \text{real}$   
**assume**  $r: 0 < r$   
**have**  $\exists s > 0. \forall x. x \neq \text{star-of } a \wedge \text{hnorm } (x - \text{star-of } a) < s \longrightarrow$   
 $\text{hnorm } (\text{starfun } f x - \text{star-of } L) < \text{star-of } r$   
**proof** (rule *exI*, *safe*)  
**show**  $0 < \varepsilon$   
**by** (rule *epsilon-gt-zero*)  
**next**  
**fix**  $x$   
**assume** *neg*:  $x \neq \text{star-of } a$   
**assume**  $\text{hnorm } (x - \text{star-of } a) < \varepsilon$   
**with** *Infinitesimal-epsilon* **have**  $x - \text{star-of } a \in \text{Infinitesimal}$   
**by** (rule *hnorm-less-Infinitesimal*)  
**then** **have**  $x \approx \text{star-of } a$   
**by** (*unfold approx-def*)  
**with** *f neg* **have**  $\text{starfun } f x \approx \text{star-of } L$   
**by** (rule *NSLIM-D*)

**then have**  $\text{starfun } f \ x - \text{star-of } L \in \text{Infinitesimal}$   
**by** (*unfold approx-def*)  
**then show**  $\text{hnorm } (\text{starfun } f \ x - \text{star-of } L) < \text{star-of } r$   
**using**  $r$  **by** (*rule InfinitesimalD2*)  
**qed**  
**then show**  $\exists s > 0. \forall x. x \neq a \wedge \text{norm } (x - a) < s \longrightarrow \text{norm } (f \ x - L) < r$   
**by** *transfer*  
**qed**

**theorem** *LIM-NSLIM-iff*:  $f -x \rightarrow L \longleftrightarrow f -x \rightarrow_{NS} L$   
**by** (*blast intro: LIM-NSLIM NSLIM-LIM*)

## 12.2 Continuity

**lemma** *isNSContD*:  $\text{isNSCont } f \ a \Longrightarrow y \approx \text{star-of } a \Longrightarrow (*f* \ f) \ y \approx \text{star-of } (f \ a)$   
**by** (*simp add: isNSCont-def*)

**lemma** *isNSCont-NSLIM*:  $\text{isNSCont } f \ a \Longrightarrow f -a \rightarrow_{NS} (f \ a)$   
**by** (*simp add: isNSCont-def NSLIM-def*)

**lemma** *NSLIM-isNSCont*:  $f -a \rightarrow_{NS} (f \ a) \Longrightarrow \text{isNSCont } f \ a$   
**by** (*force simp add: isNSCont-def NSLIM-def*)

NS continuity can be defined using NS Limit in similar fashion to standard definition of continuity.

**lemma** *isNSCont-NSLIM-iff*:  $\text{isNSCont } f \ a \longleftrightarrow f -a \rightarrow_{NS} (f \ a)$   
**by** (*blast intro: isNSCont-NSLIM NSLIM-isNSCont*)

Hence, NS continuity can be given in terms of standard limit.

**lemma** *isNSCont-LIM-iff*:  $(\text{isNSCont } f \ a) = (f -a \rightarrow (f \ a))$   
**by** (*simp add: LIM-NSLIM-iff isNSCont-NSLIM-iff*)

Moreover, it's trivial now that NS continuity is equivalent to standard continuity.

**lemma** *isNSCont-isCont-iff*:  $\text{isNSCont } f \ a \longleftrightarrow \text{isCont } f \ a$   
**by** (*simp add: isCont-def*) (*rule isNSCont-LIM-iff*)

Standard continuity  $\Longrightarrow$  NS continuity.

**lemma** *isCont-isNSCont*:  $\text{isCont } f \ a \Longrightarrow \text{isNSCont } f \ a$   
**by** (*erule isNSCont-isCont-iff [THEN iffD2]*)

NS continuity  $\Longrightarrow$  Standard continuity.

**lemma** *isNSCont-isCont*:  $\text{isNSCont } f \ a \Longrightarrow \text{isCont } f \ a$   
**by** (*erule isNSCont-isCont-iff [THEN iffD1]*)

Alternative definition of continuity.

Prove equivalence between NS limits – seems easier than using standard definition.

**lemma** *NSLIM-at0-iff*:  $f -a \rightarrow_{NS} L \iff (\lambda h. f (a + h)) -0 \rightarrow_{NS} L$   
**proof**  
**assume**  $f -a \rightarrow_{NS} L$   
**then show**  $(\lambda h. f (a + h)) -0 \rightarrow_{NS} L$   
**by** (*simp add: NSLIM-def*) (*metis (no-types) add-cancel-left-right approx-add-left-iff starfun-lambda-cancel*)  
**next**  
**assume**  $*$ :  $(\lambda h. f (a + h)) -0 \rightarrow_{NS} L$   
**show**  $f -a \rightarrow_{NS} L$   
**proof** (*clarsimp simp: NSLIM-def*)  
**fix**  $x$   
**assume**  $x \neq \text{star-of } a \approx \text{star-of } a$   
**then have**  $(** (\lambda h. f (a + h))) (- \text{star-of } a + x) \approx \text{star-of } L$   
**by** (*metis (no-types, lifting) \* NSLIM-D add.right-neutral add-minus-cancel approx-minus-iff2 star-zero-def*)  
**then show**  $(** f) x \approx \text{star-of } L$   
**by** (*simp add: starfun-lambda-cancel*)  
**qed**  
**qed**

**lemma** *isNSCont-minus*:  $\text{isNSCont } f \ a \implies \text{isNSCont } (\lambda x. - f \ x) \ a$   
**by** (*simp add: isNSCont-def*)

**lemma** *isNSCont-inverse*:  $\text{isNSCont } f \ x \implies f \ x \neq 0 \implies \text{isNSCont } (\lambda x. \text{inverse } (f \ x)) \ x$   
**for**  $f :: 'a::\text{real-normed-vector} \Rightarrow 'b::\text{real-normed-div-algebra}$   
**using** *NSLIM-inverse NSLIM-isNSCont isNSCont-NSLIM* **by** *blast*

**lemma** *isNSCont-const* [*simp*]:  $\text{isNSCont } (\lambda x. k) \ a$   
**by** (*simp add: isNSCont-def*)

**lemma** *isNSCont-abs* [*simp*]:  $\text{isNSCont } \text{abs } a$   
**for**  $a :: \text{real}$   
**by** (*auto simp: isNSCont-def intro: approx-hrabs simp: starfun-rabs-hrabs*)

### 12.3 Uniform Continuity

**lemma** *isNSUContD*:  $\text{isNSUCont } f \implies x \approx y \implies (** f) \ x \approx (** f) \ y$   
**by** (*simp add: isNSUCont-def*)

**lemma** *isUCont-isNSUCont*:  
**fixes**  $f :: 'a::\text{real-normed-vector} \Rightarrow 'b::\text{real-normed-vector}$   
**assumes**  $f$ : *isUCont*  $f$   
**shows** *isNSUCont*  $f$   
**unfolding** *isNSUCont-def*

**proof** *safe*  
**fix**  $x \ y :: 'a \ \text{star}$   
**assume** *approx*:  $x \approx y$   
**have**  $\text{starfun } f \ x - \text{starfun } f \ y \in \text{Infinitesimal}$

```

proof (rule InfinitesimalI2)
  fix r :: real
  assume r: 0 < r
  with f obtain s where s: 0 < s
    and less-r:  $\bigwedge x y. \text{norm } (x - y) < s \implies \text{norm } (f x - f y) < r$ 
    by (auto simp add: isUCont-def dist-norm)
  from less-r have less-r':
     $\bigwedge x y. \text{hnorm } (x - y) < \text{star-of } s \implies \text{hnorm } (\text{starfun } f x - \text{starfun } f y) <$ 
    star-of r
    by transfer
  from approx have x - y  $\in$  Infinitesimal
    by (unfold approx-def)
  then have hnorm (x - y) < star-of s
    using s by (rule InfinitesimalD2)
  then show hnorm (starfun f x - starfun f y) < star-of r
    by (rule less-r')
  qed
then show starfun f x  $\approx$  starfun f y
  by (unfold approx-def)
qed

```

**lemma** isNSUCont-isUCont:

```

  fixes f :: 'a::real-normed-vector  $\Rightarrow$  'b::real-normed-vector
  assumes f: isNSUCont f
  shows isUCont f
  unfolding isUCont-def dist-norm
proof safe
  fix r :: real
  assume r: 0 < r
  have  $\exists s > 0. \forall x y. \text{hnorm } (x - y) < s \longrightarrow \text{hnorm } (\text{starfun } f x - \text{starfun } f y) <$ 
  star-of r
  proof (rule exI, safe)
    show 0 <  $\varepsilon$ 
    by (rule epsilon-gt-zero)
  next
    fix x y :: 'a star
    assume hnorm (x - y) <  $\varepsilon$ 
    with Infinitesimal-epsilon have x - y  $\in$  Infinitesimal
      by (rule hnorm-less-Infinitesimal)
    then have x  $\approx$  y
      by (unfold approx-def)
    with f have starfun f x  $\approx$  starfun f y
      by (simp add: isNSUCont-def)
    then have starfun f x - starfun f y  $\in$  Infinitesimal
      by (unfold approx-def)
    then show hnorm (starfun f x - starfun f y) < star-of r
      using r by (rule InfinitesimalD2)
  qed
then show  $\exists s > 0. \forall x y. \text{norm } (x - y) < s \longrightarrow \text{norm } (f x - f y) < r$ 

```

by transfer  
qed

end

## 13 Differentiation (Nonstandard)

theory HDeriv  
imports HLim  
begin

Nonstandard Definitions.

**definition** *nsderiv* :: [*a*::real-normed-field  $\Rightarrow$  'a, 'a, 'a]  $\Rightarrow$  bool  
 ((NSDERIV (-)/ (-) /> (-) [1000, 1000, 60] 60)  
**where** NSDERIV *f x* /> *D*  $\longleftrightarrow$   
 ( $\forall h \in \text{Infinitesimal} - \{0\}. ((**f) (\text{star-of } x + h) - \text{star-of } (f x)) / h \approx \text{star-of } D$ )

**definition** *NSdifferentiable* :: [*a*::real-normed-field  $\Rightarrow$  'a, 'a]  $\Rightarrow$  bool  
 (infixl NSdifferentiable 60)  
**where** *f NSdifferentiable x*  $\longleftrightarrow (\exists D. \text{NSDERIV } f x /> D)$

**definition** *increment* :: (real  $\Rightarrow$  real)  $\Rightarrow$  real  $\Rightarrow$  hypreal  $\Rightarrow$  hypreal  
**where** *increment f x h* =  
 (SOME inc. *f NSdifferentiable x*  $\wedge$  inc = ( $**f$ ) (hypreal-of-real *x* + *h*) - hypreal-of-real (*f x*))

### 13.1 Derivatives

**lemma** *DERIV-NS-iff*: (*DERIV f x* /> *D*)  $\longleftrightarrow (\lambda h. (f (x + h) - f x) / h) - 0 \rightarrow_{NS} D$   
**by** (simp add: DERIV-def LIM-NSLIM-iff)

**lemma** *NS-DERIV-D*: *DERIV f x* /> *D*  $\Longrightarrow (\lambda h. (f (x + h) - f x) / h) - 0 \rightarrow_{NS} D$   
**by** (simp add: DERIV-def LIM-NSLIM-iff)

**lemma** *Infinitesimal-of-hypreal*:  
*x*  $\in$  Infinitesimal  $\Longrightarrow ((**f \text{ of-real } x)::'a::\text{real-normed-div-algebra star}) \in \text{Infinitesimal}$   
**by** (metis Infinitesimal-of-hypreal-iff of-hypreal-def)

**lemma** *of-hypreal-eq-0-iff*:  $\bigwedge x. ((**f \text{ of-real } x) = (0::'a::\text{real-algebra-1 star})) = (x = 0)$   
**by** transfer (rule of-real-eq-0-iff)

**lemma** *NSDeriv-unique*:  
**assumes** NSDERIV *f x* /> *D* NSDERIV *f x* /> *E*  
**shows** NSDERIV *f x* /> *D*  $\Longrightarrow$  NSDERIV *f x* /> *E*  $\Longrightarrow D = E$

**proof** –

**have**  $\exists s. (s::'a \text{ star}) \in \text{Infinitesimal} - \{0\}$   
**by** (*metis Diff-iff HDeriv-of-hypreal-eq-0-iff Infinitesimal-epsilon Infinitesimal-of-hypreal-epsilon-not-zero singletonD*)  
**with** *assms* **show** *?thesis*  
**by** (*meson approx-trans3 nsderiv-def star-of-approx-iff*)  
**qed**

First *NSDERIV* in terms of *NSLIM*.

First equivalence.

**lemma** *NSDERIV-NSLIM-iff*:  $(\text{NSDERIV } f x \text{ :> } D) \longleftrightarrow (\lambda h. (f (x + h) - f x) / h) - 0 \rightarrow_{NS} D$   
**by** (*auto simp add: nsderiv-def NSLIM-def starfun-lambda-cancel mem-infmal-iff*)

Second equivalence.

**lemma** *NSDERIV-NSLIM-iff2*:  $(\text{NSDERIV } f x \text{ :> } D) \longleftrightarrow (\lambda z. (f z - f x) / (z - x)) - x \rightarrow_{NS} D$   
**by** (*simp add: NSDERIV-NSLIM-iff DERIV-LIM-iff LIM-NSLIM-iff [symmetric]*)

While we're at it!

**lemma** *NSDERIV-iff2*:  
 $(\text{NSDERIV } f x \text{ :> } D) \longleftrightarrow$   
 $(\forall w. w \neq \text{star-of } x \wedge w \approx \text{star-of } x \longrightarrow (*f* (\lambda z. (f z - f x) / (z - x))) w \approx \text{star-of } D)$   
**by** (*simp add: NSDERIV-NSLIM-iff2 NSLIM-def*)

**lemma** *NSDERIVD5*:

$[\text{NSDERIV } f x \text{ :> } D; u \approx \text{hypreal-of-real } x] \implies$   
 $(*f* (\lambda z. f z - f x)) u \approx \text{hypreal-of-real } D * (u - \text{hypreal-of-real } x)$   
**unfolding** *NSDERIV-iff2*  
**apply** (*case-tac u = hypreal-of-real x, auto*)  
**by** (*metis (mono-tags, lifting) HFinite-star-of Infinitesimal-ratio approx-def approx-minus-iff approx-mult-subst approx-star-of-HFinite approx-sym mult-zero-right right-minus-eq*)

**lemma** *NSDERIVD4*:

$[\text{NSDERIV } f x \text{ :> } D; h \in \text{Infinitesimal}]$   
 $\implies (*f* f)(\text{hypreal-of-real } x + h) - \text{hypreal-of-real } (f x) \approx \text{hypreal-of-real } D * h$   
**apply** (*clarsimp simp add: nsderiv-def*)  
**apply** (*case-tac h = 0, simp*)  
**by** (*meson DiffI Infinitesimal-approx Infinitesimal-ratio Infinitesimal-star-of-mult2 approx-star-of-HFinite singletonD*)

Differentiability implies continuity nice and simple "algebraic" proof.

**lemma** *NSDERIV-isNSCont*:

**assumes**  $\text{NSDERIV } f x \text{ :> } D$  **shows** *isNSCont*  $f x$   
**unfolding** *isNSCont-NSLIM-iff NSLIM-def*

**proof** *clarify*

**fix**  $x'$   
**assume**  $x' \neq \text{star-of } x \ x' \approx \text{star-of } x$   
**then have**  $m0: x' - \text{star-of } x \in \text{Infinitesimal} - \{0\}$   
**using** *bex-Infinitesimal-iff by auto*  
**then have**  $(( *f* f) x' - \text{star-of } (f x)) / (x' - \text{star-of } x) \approx \text{star-of } D$   
**by** *(metis  $\langle x' \approx \text{star-of } x \rangle$  add-diff-cancel-left' assms bex-Infinitesimal-iff2 ns-deriv-def)*  
**then have**  $(( *f* f) x' - \text{star-of } (f x)) / (x' - \text{star-of } x) \in \text{HFinite}$   
**by** *(metis approx-star-of-HFinite)*  
**then show**  $(*f* f) x' \approx \text{star-of } (f x)$   
**by** *(metis (no-types) Diff-iff Infinitesimal-ratio m0 bex-Infinitesimal-iff insert-iff)*  
**qed**

Differentiation rules for combinations of functions follow from clear, straightforward, algebraic manipulations.

Constant function.

**lemma** *NSDERIV-const [simp]: NSDERIV  $(\lambda x. k) x := 0$*   
**by** *(simp add: NSDERIV-NSLIM-iff)*

Sum of functions- proved easily.

**lemma** *NSDERIV-add:*

**assumes** *NSDERIV  $f x := Da$  NSDERIV  $g x := Db$*   
**shows** *NSDERIV  $(\lambda x. f x + g x) x := Da + Db$*

**proof** –

**have**  *$((\lambda x. f x + g x) \text{ has-field-derivative } Da + Db) (at x)$*

**using** *assms DERIV-NS-iff NSDERIV-NSLIM-iff field-differentiable-add by blast*

**then show** *?thesis*

**by** *(simp add: DERIV-NS-iff NSDERIV-NSLIM-iff)*

**qed**

Product of functions - Proof is simple.

**lemma** *NSDERIV-mult:*

**assumes** *NSDERIV  $g x := Db$  NSDERIV  $f x := Da$*

**shows** *NSDERIV  $(\lambda x. f x * g x) x := (Da * g x) + (Db * f x)$*

**proof** –

**have**  *$(f \text{ has-field-derivative } Da) (at x) (g \text{ has-field-derivative } Db) (at x)$*

**using** *assms by (simp-all add: DERIV-NS-iff NSDERIV-NSLIM-iff)*

**then have**  *$((\lambda a. f a * g a) \text{ has-field-derivative } Da * g x + Db * f x) (at x)$*

**using** *DERIV-mult by blast*

**then show** *?thesis*

**by** *(simp add: DERIV-NS-iff NSDERIV-NSLIM-iff)*

**qed**

Multiplying by a constant.

**lemma** *NSDERIV-cmult*:  $NSDERIV f x \text{ :> } D \implies NSDERIV (\lambda x. c * f x) x \text{ :> } c * D$

**unfolding** *times-divide-eq-right* [*symmetric*] *NSDERIV-NSLIM-iff*  
*minus-mult-right right-diff-distrib* [*symmetric*]  
**by** (*erule NSLIM-const* [*THEN NSLIM-mult*])

Negation of function.

**lemma** *NSDERIV-minus*:  $NSDERIV f x \text{ :> } D \implies NSDERIV (\lambda x. - f x) x \text{ :> } - D$

**proof** (*simp add: NSDERIV-NSLIM-iff*)

**assume**  $(\lambda h. (f (x + h) - f x) / h) - 0 \rightarrow_{NS} D$

**then have** *deriv*:  $(\lambda h. - ((f(x+h) - f x) / h)) - 0 \rightarrow_{NS} - D$

**by** (*rule NSLIM-minus*)

**have**  $\forall h. - ((f (x + h) - f x) / h) = (- f (x + h) + f x) / h$

**by** (*simp add: minus-divide-left*)

**with** *deriv* **have**  $(\lambda h. (- f (x + h) + f x) / h) - 0 \rightarrow_{NS} - D$

**by** *simp*

**then show**  $(\lambda h. (f (x + h) - f x) / h) - 0 \rightarrow_{NS} D \implies (\lambda h. (f x - f (x + h)) / h) - 0 \rightarrow_{NS} - D$

**by** *simp*

**qed**

Subtraction.

**lemma** *NSDERIV-add-minus*:

$NSDERIV f x \text{ :> } Da \implies NSDERIV g x \text{ :> } Db \implies NSDERIV (\lambda x. f x + - g x) x \text{ :> } Da + - Db$

**by** (*blast dest: NSDERIV-add NSDERIV-minus*)

**lemma** *NSDERIV-diff*:

$NSDERIV f x \text{ :> } Da \implies NSDERIV g x \text{ :> } Db \implies NSDERIV (\lambda x. f x - g x) x \text{ :> } Da - Db$

**using** *NSDERIV-add-minus* [*of f x Da g Db*] **by** *simp*

Similarly to the above, the chain rule admits an entirely straightforward derivation. Compare this with Harrison’s HOL proof of the chain rule, which proved to be trickier and required an alternative characterisation of differentiability- the so-called Carathedory derivative. Our main problem is manipulation of terms.

## 13.2 Lemmas

**lemma** *NSDERIV-zero*:

$\llbracket NSDERIV g x \text{ :> } D; (*f* g) (star-of x + y) = star-of (g x); y \in Infinitesimal; y \neq 0 \rrbracket$

$\implies D = 0$

**by** (*force simp add: nsderiv-def*)

Can be proved differently using *NSLIM-isCont-iff*.



**lemma** *NSDERIV-approx*:

$NSDERIV f x :> D \implies h \in Infinitesimal \implies h \neq 0 \implies$

$( *f* f ) ( star-of x + h ) - star-of ( f x ) \approx 0$

**by** (*meson DiffI Infinitesimal-ratio approx-star-of-HFinite mem-infmal-iff ns-deriv-def singletonD*)

From one version of differentiability

$f x - f a \text{ ----- } \approx Db x - a$

**lemma** *NSDERIVD1*:

$\llbracket NSDERIV f (g x) :> Da;$

$( *f* g ) ( star-of x + y ) \neq star-of (g x);$

$( *f* g ) ( star-of x + y ) \approx star-of (g x) \rrbracket$

$\implies (( *f* f ) (( *f* g ) ( star-of x + y )) -$   
 $star-of ( f (g x) )) / (( *f* g ) ( star-of x + y ) - star-of (g x)) \approx$   
 $star-of Da$

**by** (*auto simp add: NSDERIV-NSLIM-iff2 NSLIM-def*)

From other version of differentiability

$f (x + h) - f x \text{ ----- } \approx Db h$

**lemma** *NSDERIVD2*:  $\llbracket NSDERIV g x :> Db; y \in Infinitesimal; y \neq 0 \rrbracket$

$\implies (( *f* g ) ( star-of(x) + y ) - star-of(g x)) / y$   
 $\approx star-of(Db)$

**by** (*auto simp add: NSDERIV-NSLIM-iff NSLIM-def mem-infmal-iff starfun-lambda-cancel*)

This proof uses both definitions of differentiability.

**lemma** *NSDERIV-chain*:

$NSDERIV f (g x) :> Da \implies NSDERIV g x :> Db \implies NSDERIV (f \circ g) x :>$   
 $Da * Db$

**using** *DERIV-NS-iff DERIV-chain NSDERIV-NSLIM-iff* **by** *blast*

Differentiation of natural number powers.

**lemma** *NSDERIV-Id* [*simp*]:  $NSDERIV (\lambda x. x) x :> 1$

**by** (*simp add: NSDERIV-NSLIM-iff NSLIM-def del: divide-self-if*)

**lemma** *NSDERIV-cmult-Id* [*simp*]:  $NSDERIV ((* c) x) :> c$

**using** *NSDERIV-Id [THEN NSDERIV-cmult]* **by** *simp*

**lemma** *NSDERIV-inverse*:

**fixes**  $x :: 'a::real-normed-field$

**assumes**  $x \neq 0$  — can't get rid of  $x \neq (0::'a)$  because it isn't continuous at zero

**shows**  $NSDERIV (\lambda x. inverse x) x :> - (inverse x \hat{ } Suc (Suc 0))$

**proof** —

{

**fix**  $h :: 'a star$

**assume**  $h-Inf: h \in Infinitesimal$

**from** *this assms* **have**  $not-0: star-of x + h \neq 0$

**by** (*rule Infinitesimal-add-not-zero*)

**assume**  $h \neq 0$

**from**  $h$ -Inf **have**  $h * \text{star-of } x \in \text{Infinitesimal}$   
**by** (rule *Infinitesimal-HFinite-mult*) *simp*  
**with** *assms* **have**  $\text{inverse } (- (h * \text{star-of } x) + - (\text{star-of } x * \text{star-of } x)) \approx$   
 $\text{inverse } (- (\text{star-of } x * \text{star-of } x))$   
**proof** –  
**have**  $- (h * \text{star-of } x) + - (\text{star-of } x * \text{star-of } x) \approx - (\text{star-of } x * \text{star-of } x)$   
**using**  $\langle h * \text{star-of } x \in \text{Infinitesimal} \rangle$  *assms* *beX-Infinitesimal-iff* **by** *fastforce*  
**then show** *?thesis*  
**by** (*metis* *assms* *mult-eq-0-iff* *neg-equal-0-iff-equal* *star-of-approx-inverse*  
*star-of-minus* *star-of-mult*)  
**qed**  
**moreover from** *not-0*  $\langle h \neq 0 \rangle$  *assms*  
**have**  $\text{inverse } (- (h * \text{star-of } x) + - (\text{star-of } x * \text{star-of } x))$   
 $= (\text{inverse } (\text{star-of } x + h) - \text{inverse } (\text{star-of } x)) / h$   
**by** (*simp* *add: division-ring-inverse-diff* *inverse-mult-distrib* [*symmetric*]  
*inverse-minus-eq* [*symmetric*] *algebra-simps*)  
**ultimately have**  $(\text{inverse } (\text{star-of } x + h) - \text{inverse } (\text{star-of } x)) / h \approx$   
 $- (\text{inverse } (\text{star-of } x) * \text{inverse } (\text{star-of } x))$   
**using** *assms* **by** *simp*  
**}**  
**then show** *?thesis* **by** (*simp* *add: nsderiv-def*)  
**qed**

### 13.2.1 Equivalence of NS and Standard definitions

**lemma** *divideR-eq-divide*:  $x /_R y = x / y$   
**by** (*simp* *add: divide-inverse* *mult commute*)

Now equivalence between *NSDERIV* and *DERIV*.

**lemma** *NSDERIV-DERIV-iff*:  $\text{NSDERIV } f x :> D \longleftrightarrow \text{DERIV } f x :> D$   
**by** (*simp* *add: DERIV-def* *NSDERIV-NSLIM-iff* *LIM-NSLIM-iff*)

NS version.

**lemma** *NSDERIV-pow*:  $\text{NSDERIV } (\lambda x. x \wedge n) x :> \text{real } n * (x \wedge (n - \text{Suc } 0))$   
**by** (*simp* *add: NSDERIV-DERIV-iff* *DERIV-pow*)

Derivative of inverse.

**lemma** *NSDERIV-inverse-fun*:  
 $\text{NSDERIV } f x :> d \implies f x \neq 0 \implies$   
 $\text{NSDERIV } (\lambda x. \text{inverse } (f x)) x :> (- (d * \text{inverse } (f x \wedge \text{Suc } (\text{Suc } 0))))$   
**for**  $x :: 'a::\{\text{real-normed-field}\}$   
**by** (*simp* *add: NSDERIV-DERIV-iff* *DERIV-inverse-fun* *del: power-Suc*)

Derivative of quotient.

**lemma** *NSDERIV-quotient*:  
**fixes**  $x :: 'a::\{\text{real-normed-field}\}$   
**shows**  $\text{NSDERIV } f x :> d \implies \text{NSDERIV } g x :> e \implies g x \neq 0 \implies$   
 $\text{NSDERIV } (\lambda y. f y / g y) x :> (d * g x - (e * f x)) / (g x \wedge \text{Suc } (\text{Suc } 0))$   
**by** (*simp* *add: NSDERIV-DERIV-iff* *DERIV-quotient* *del: power-Suc*)

**lemma** *CARAT-NSDERIV*:

$NSDERIV f x :> l \implies \exists g. (\forall z. f z - f x = g z * (z - x)) \wedge isNSCont g x \wedge g x = l$

**by** (*simp add: CARAT-DERIV NSDERIV-DERIV-iff isNSCont-isCont-iff*)

**lemma** *hypreal-eq-minus-iff3*:  $x = y + z \longleftrightarrow x + - z = y$

**for**  $x y z :: hypreal$

**by** *auto*

**lemma** *CARAT-DERIVD*:

**assumes** *all*:  $\forall z. f z - f x = g z * (z - x)$

**and** *nsc*:  $isNSCont g x$

**shows**  $NSDERIV f x :> g x$

**proof** –

**from** *nsc* **have**  $\forall w. w \neq \text{star-of } x \wedge w \approx \text{star-of } x \longrightarrow$

$( *f* g ) w * ( w - \text{star-of } x ) / ( w - \text{star-of } x ) \approx \text{star-of } ( g x )$

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

**with** *all* **show** *?thesis*

**by** (*simp add: NSDERIV-iff2 starfun-if-eq cong: if-cong*)

**qed**

### 13.2.2 Differentiability predicate

**lemma** *NSdifferentiableD*:  $f NSdifferentiable x \implies \exists D. NSDERIV f x :> D$

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

**lemma** *NSdifferentiableI*:  $NSDERIV f x :> D \implies f NSdifferentiable x$

**by** (*force simp add: NSdifferentiable-def*)

## 13.3 (NS) Increment

**lemma** *incrementI*:

$f NSdifferentiable x \implies$

$\text{increment } f x h = ( *f* f ) ( \text{hypreal-of-real } x + h ) - \text{hypreal-of-real } ( f x )$

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

**lemma** *incrementI2*:

$NSDERIV f x :> D \implies$

$\text{increment } f x h = ( *f* f ) ( \text{hypreal-of-real } x + h ) - \text{hypreal-of-real } ( f x )$

**by** (*erule NSdifferentiableI [THEN incrementI]*)

The Increment theorem – Keisler p. 65.

**lemma** *increment-thm*:

**assumes**  $NSDERIV f x :> D h \in \text{Infinitesimal } h \neq 0$

**shows**  $\exists e \in \text{Infinitesimal}. \text{increment } f x h = \text{hypreal-of-real } D * h + e * h$

**proof** –

**have** *inc*:  $\text{increment } f x h = ( *f* f ) ( \text{hypreal-of-real } x + h ) - \text{hypreal-of-real } ( f x )$

```

using assms(1) incrementI2 by auto
have ((*f* f) (hypreal-of-real x + h) - hypreal-of-real (f x)) / h  $\approx$  hypreal-of-real D
by (simp add: NSDERIVD2 assms)
then obtain y where y  $\in$  Infinitesimal
  ((*f* f) (hypreal-of-real x + h) - hypreal-of-real (f x)) / h = hypreal-of-real D
+ y
by (metis beX-Infinitesimal-iff2)
then have increment f x h / h = hypreal-of-real D + y
by (metis inc)
then show ?thesis
  by (metis (no-types) <y  $\in$  Infinitesimal> <h  $\neq$  0> distrib-right mult.commute
nonzero-mult-div-cancel-left times-divide-eq-right)
qed

```

```

lemma increment-approx-zero: NSDERIV f x :> D  $\implies$  h  $\approx$  0  $\implies$  h  $\neq$  0  $\implies$ 
increment f x h  $\approx$  0
by (simp add: NSDERIV-approx incrementI2 mem-infmal-iff)

```

**end**

## 14 Nonstandard Extensions of Transcendental Functions

```

theory HTranscendental
imports Complex-Main HSeries HDeriv
begin

```

### definition

```

exphr :: real  $\Rightarrow$  hypreal where
  — define exponential function using standard part
  exphr x  $\equiv$  st(sumhr (0, whn,  $\lambda n.$  inverse (fact n) * (x ^ n)))

```

### definition

```

sinhr :: real  $\Rightarrow$  hypreal where
  sinhr x  $\equiv$  st(sumhr (0, whn,  $\lambda n.$  sin-coeff n * x ^ n))

```

### definition

```

coshhr :: real  $\Rightarrow$  hypreal where
  coshhr x  $\equiv$  st(sumhr (0, whn,  $\lambda n.$  cos-coeff n * x ^ n))

```

### 14.1 Nonstandard Extension of Square Root Function

```

lemma STAR-sqrt-zero [simp]: (*f* sqrt) 0 = 0
by (simp add: starfun star-n-zero-num)

```

```

lemma STAR-sqrt-one [simp]: (*f* sqrt) 1 = 1
by (simp add: starfun star-n-one-num)

```

**lemma** *hypreal-sqrt-pow2-iff*:  $((\text{*f* sqrt})(x) \wedge 2 = x) = (0 \leq x)$

**proof** (*cases x*)

**case** (*star-n X*)

**then show** *?thesis*

**by** (*simp add: star-n-le star-n-zero-num starfun hrealpow star-n-eq-iff del: hpowr-Suc power-Suc*)

**qed**

**lemma** *hypreal-sqrt-gt-zero-pow2*:  $\bigwedge x. 0 < x \implies (\text{*f* sqrt})(x) \wedge 2 = x$

**by** *transfer simp*

**lemma** *hypreal-sqrt-pow2-gt-zero*:  $0 < x \implies 0 < (\text{*f* sqrt})(x) \wedge 2$

**by** (*frule hypreal-sqrt-gt-zero-pow2, auto*)

**lemma** *hypreal-sqrt-not-zero*:  $0 < x \implies (\text{*f* sqrt})(x) \neq 0$

**using** *hypreal-sqrt-gt-zero-pow2* **by** *fastforce*

**lemma** *hypreal-inverse-sqrt-pow2*:

$0 < x \implies \text{inverse}((\text{*f* sqrt})(x)) \wedge 2 = \text{inverse } x$

**by** (*simp add: hypreal-sqrt-gt-zero-pow2 power-inverse*)

**lemma** *hypreal-sqrt-mult-distrib*:

$\bigwedge x y. [0 < x; 0 < y] \implies$

$(\text{*f* sqrt})(x*y) = (\text{*f* sqrt})(x) * (\text{*f* sqrt})(y)$

**by** *transfer (auto intro: real-sqrt-mult)*

**lemma** *hypreal-sqrt-mult-distrib2*:

$[0 \leq x; 0 \leq y] \implies (\text{*f* sqrt})(x*y) = (\text{*f* sqrt})(x) * (\text{*f* sqrt})(y)$

**by** (*auto intro: hypreal-sqrt-mult-distrib simp add: order-le-less*)

**lemma** *hypreal-sqrt-approx-zero* [*simp*]:

**assumes**  $0 < x$

**shows**  $((\text{*f* sqrt}) x \approx 0) \longleftrightarrow (x \approx 0)$

**proof** –

**have**  $(\text{*f* sqrt}) x \in \text{Infinitesimal} \longleftrightarrow ((\text{*f* sqrt}) x)^2 \in \text{Infinitesimal}$

**by** (*metis Infinitesimal-hrealpow pos2 power2-eq-square Infinitesimal-square-iff*)

**also have**  $\dots \longleftrightarrow x \in \text{Infinitesimal}$

**by** (*simp add: asms hypreal-sqrt-gt-zero-pow2*)

**finally show** *?thesis*

**using** *mem-infmal-iff* **by** *blast*

**qed**

**lemma** *hypreal-sqrt-approx-zero2* [*simp*]:

$0 \leq x \implies ((\text{*f* sqrt})(x) \approx 0) = (x \approx 0)$

**by** (*auto simp add: order-le-less*)

**lemma** *hypreal-sqrt-gt-zero*:  $\bigwedge x. 0 < x \implies 0 < (\text{*f* sqrt})(x)$

**by** *transfer (simp add: real-sqrt-gt-zero)*

**lemma** *hypreal-sqrt-ge-zero*:  $0 \leq x \implies 0 \leq (*f* \text{ sqrt})(x)$   
**by** (*auto intro: hypreal-sqrt-gt-zero simp add: order-le-less*)

**lemma** *hypreal-sqrt-lessI*:  
 $\bigwedge x u. [0 < u; x < u^2] \implies (*f* \text{ sqrt}) x < u$   
**proof** *transfer*  
**show**  $\bigwedge x u. [0 < u; x < u^2] \implies \text{sqrt } x < u$   
**by** (*metis less-le real-sqrt-less-iff real-sqrt-pow2 real-sqrt-power*)  
**qed**

**lemma** *hypreal-sqrt-hrabs* [*simp*]:  $\bigwedge x. (*f* \text{ sqrt})(x^2) = |x|$   
**by** *transfer simp*

**lemma** *hypreal-sqrt-hrabs2* [*simp*]:  $\bigwedge x. (*f* \text{ sqrt})(x*x) = |x|$   
**by** *transfer simp*

**lemma** *hypreal-sqrt-hyperpow-hrabs* [*simp*]:  
 $\bigwedge x. (*f* \text{ sqrt})(x \text{ pow } (\text{hypnat-of-nat } 2)) = |x|$   
**by** *transfer simp*

**lemma** *star-sqrt-HFinite*:  $[x \in \text{HFinite}; 0 \leq x] \implies (*f* \text{ sqrt}) x \in \text{HFinite}$   
**by** (*metis HFinite-square-iff hypreal-sqrt-pow2-iff power2-eq-square*)

**lemma** *st-hypreal-sqrt*:  
**assumes**  $x \in \text{HFinite } 0 \leq x$   
**shows**  $st((*f* \text{ sqrt}) x) = (*f* \text{ sqrt})(st x)$   
**proof** (*rule power-inject-base*)  
**show**  $st((*f* \text{ sqrt}) x) \wedge \text{Suc } 1 = (*f* \text{ sqrt}) (st x) \wedge \text{Suc } 1$   
**using** *assms hypreal-sqrt-pow2-iff* [*of x*]  
**by** (*metis HFinite-square-iff hypreal-sqrt-hrabs2 power2-eq-square st-hrabs st-mult*)  
**show**  $0 \leq st((*f* \text{ sqrt}) x)$   
**by** (*simp add: assms hypreal-sqrt-ge-zero st-zero-le star-sqrt-HFinite*)  
**show**  $0 \leq (*f* \text{ sqrt}) (st x)$   
**by** (*simp add: assms hypreal-sqrt-ge-zero st-zero-le*)  
**qed**

**lemma** *hypreal-sqrt-sum-squares-ge1* [*simp*]:  $\bigwedge x y. x \leq (*f* \text{ sqrt})(x^2 + y^2)$   
**by** *transfer (rule real-sqrt-sum-squares-ge1)*

**lemma** *HFinite-hypreal-sqrt-imp-HFinite*:  
 $[0 \leq x; (*f* \text{ sqrt}) x \in \text{HFinite}] \implies x \in \text{HFinite}$   
**by** (*metis HFinite-mult hypreal-sqrt-pow2-iff power2-eq-square*)

**lemma** *HFinite-hypreal-sqrt-iff* [*simp*]:  
 $0 \leq x \implies ((*f* \text{ sqrt}) x \in \text{HFinite}) = (x \in \text{HFinite})$   
**by** (*blast intro: star-sqrt-HFinite HFinite-hypreal-sqrt-imp-HFinite*)

**lemma** *Infinitesimal-hypreal-sqrt*:

$\llbracket 0 \leq x; x \in \text{Infinitesimal} \rrbracket \implies (*f* \text{ sqrt}) x \in \text{Infinitesimal}$   
**by** (*simp add: mem-infmal-iff*)

**lemma** *Infinitesimal-hypreal-sqrt-imp-Infinitesimal*:

$\llbracket 0 \leq x; (*f* \text{ sqrt}) x \in \text{Infinitesimal} \rrbracket \implies x \in \text{Infinitesimal}$   
**using** *hypreal-sqrt-approx-zero2 mem-infmal-iff* **by** *blast*

**lemma** *Infinitesimal-hypreal-sqrt-iff [simp]*:

$0 \leq x \implies (( *f* \text{ sqrt}) x \in \text{Infinitesimal}) = (x \in \text{Infinitesimal})$

**by** (*blast intro: Infinitesimal-hypreal-sqrt-imp-Infinitesimal Infinitesimal-hypreal-sqrt*)

**lemma** *HInfinite-hypreal-sqrt*:

$\llbracket 0 \leq x; x \in \text{HInfinite} \rrbracket \implies (*f* \text{ sqrt}) x \in \text{HInfinite}$

**by** (*simp add: HInfinite-HFinite-iff*)

**lemma** *HInfinite-hypreal-sqrt-imp-HInfinite*:

$\llbracket 0 \leq x; (*f* \text{ sqrt}) x \in \text{HInfinite} \rrbracket \implies x \in \text{HInfinite}$

**using** *HFinite-hypreal-sqrt-iff HInfinite-HFinite-iff* **by** *blast*

**lemma** *HInfinite-hypreal-sqrt-iff [simp]*:

$0 \leq x \implies (( *f* \text{ sqrt}) x \in \text{HInfinite}) = (x \in \text{HInfinite})$

**by** (*blast intro: HInfinite-hypreal-sqrt HInfinite-hypreal-sqrt-imp-HInfinite*)

**lemma** *HFinite-exp [simp]*:

*sumhr* ( $0$ , *whn*,  $\lambda n.$  *inverse* (*fact*  $n$ ) \*  $x \wedge n$ )  $\in$  *HFinite*

**unfolding** *sumhr-app star-zero-def starfun2-star-of atLeast0LessThan*

**by** (*metis NSBseqD2 NSconvergent-NSBseq convergent-NSconvergent-iff summable-iff-convergent summable-exp*)

**lemma** *exphr-zero [simp]*: *exphr*  $0 = 1$

**proof** –

**have**  $\forall x > 1. 1 = \text{sumhr } (0, 1, \lambda n. \text{inverse } (\text{fact } n) * 0 \wedge n) + \text{sumhr } (1, x, \lambda n. \text{inverse } (\text{fact } n) * 0 \wedge n)$

**unfolding** *sumhr-app* **by** *transfer (simp add: power-0-left)*

**then have**  $\text{sumhr } (0, 1, \lambda n. \text{inverse } (\text{fact } n) * 0 \wedge n) + \text{sumhr } (1, \text{whn}, \lambda n. \text{inverse } (\text{fact } n) * 0 \wedge n) \approx 1$

**by** *auto*

**then show** *?thesis*

**unfolding** *exphr-def*

**using** *sumhr-split-add [OF hypnat-one-less-hypnat-omega] st-unique* **by** *auto*

**qed**

**lemma** *coshr-zero [simp]*: *coshr*  $0 = 1$

**proof** –

**have**  $\forall x > 1. 1 = \text{sumhr } (0, 1, \lambda n. \text{cos-coeff } n * 0 \wedge n) + \text{sumhr } (1, x, \lambda n. \text{cos-coeff } n * 0 \wedge n)$

**unfolding** *sumhr-app* **by** *transfer (simp add: power-0-left)*

**then have**  $\text{sumhr } (0, 1, \lambda n. \text{cos-coeff } n * 0 \wedge n) + \text{sumhr } (1, \text{whn}, \lambda n. \text{cos-coeff } n * 0 \wedge n) \approx 1$

```

  by auto
  then show ?thesis
    unfolding coshr-def
    using sumhr-split-add [OF hypnat-one-less-hypnat-omega] st-unique by auto
qed

```

```

lemma STAR-exp-zero-approx-one [simp]: ( *f* exp ) ( 0::hypreal )  $\approx$  1
  proof -
  have ( *f* exp ) ( 0::real star ) = 1
    by transfer simp
  then show ?thesis
    by auto
qed

```

```

lemma STAR-exp-Infinitesimal:
  assumes  $x \in \text{Infinitesimal}$  shows ( *f* exp ) (  $x::\text{hypreal}$  )  $\approx$  1
  proof (cases  $x = 0$ )
  case False
  have NSDERIV exp 0  $>$  1
    by (metis DERIV-exp NSDERIV-DERIV-iff exp-zero)
  then have ( *f* exp )  $x - 1$  /  $x \approx$  1
    using nsderiv-def False NSDERIVD2 assms by fastforce
  then have ( *f* exp )  $x - 1 \approx$   $x$ 
    using NSDERIVD4  $\langle$  NSDERIV exp 0  $>$  1  $\rangle$  assms by fastforce
  then show ?thesis
    by (meson Infinitesimal-approx approx-minus-iff approx-trans2 assms not-Infinitesimal-not-zero)
qed auto

```

```

lemma STAR-exp-epsilon [simp]: ( *f* exp )  $\varepsilon \approx$  1
  by (auto intro: STAR-exp-Infinitesimal)

```

```

lemma STAR-exp-add:
   $\bigwedge (x::'a:: \{ \text{banach, real-normed-field} \} \text{ star} ) y. ( *f* \text{exp} )( x + y ) = ( *f* \text{exp} ) x * ( *f* \text{exp} ) y$ 
  by transfer (rule exp-add)

```

```

lemma exphr-hypreal-of-real-exp-eq: exphr x = hypreal-of-real (exp x)
  proof -
  have (  $\lambda n. \text{inverse (fact n)} * x ^ n$  ) sums exp x
    using exp-converges [of x] by simp
  then have (  $\lambda n. \sum_{n < n}. \text{inverse (fact n)} * x ^ n$  )  $\longrightarrow_{NS}$  exp x
    using NSsums-def sums-NSsums-iff by blast
  then have hypreal-of-real (exp x)  $\approx$  sumhr ( 0, whn,  $\lambda n. \text{inverse (fact n)} * x ^ n$  )
  unfolding starfunNat-sumr [symmetric] atLeast0LessThan
  using HNatInfinite-whn NSLIMSEQ-def approx-sym by blast
  then show ?thesis
    unfolding exphr-def using st-eq-approx-iff by auto
qed

```



**lemma** *starfun-exp-ge-add-one-self* [*simp*]:  $\bigwedge x::\text{hypreal}. 0 \leq x \implies (1 + x) \leq (*f* \text{exp}) x$   
**by** *transfer* (*rule exp-ge-add-one-self-aux*)

exp maps infinities to infinities

**lemma** *starfun-exp-HInfinite*:  
**fixes**  $x :: \text{hypreal}$   
**assumes**  $x \in \text{HInfinite}$   $0 \leq x$   
**shows**  $(*f* \text{exp}) x \in \text{HInfinite}$   
**proof** –  
**have**  $x \leq 1 + x$   
**by** *simp*  
**also have**  $\dots \leq (*f* \text{exp}) x$   
**by** (*simp add: <0 ≤ x>*)  
**finally show** *?thesis*  
**using** *HInfinite-ge-HInfinite assms* **by** *blast*  
**qed**

**lemma** *starfun-exp-minus*:  
 $\bigwedge x::'a::\{\text{banach,real-normed-field}\} \text{star}. (*f* \text{exp}) (-x) = \text{inverse}(( *f* \text{exp}) x)$   
**by** *transfer* (*rule exp-minus*)

exp maps infinitesimals to infinitesimals

**lemma** *starfun-exp-Infinitesimal*:  
**fixes**  $x :: \text{hypreal}$   
**assumes**  $x \in \text{HInfinite}$   $x \leq 0$   
**shows**  $(*f* \text{exp}) x \in \text{Infinitesimal}$   
**proof** –  
**obtain**  $y$  **where**  $x = -y$   $y \geq 0$   
**by** (*metis abs-of-nonpos assms(2) eq-abs-iff'*)  
**then have**  $(*f* \text{exp}) y \in \text{HInfinite}$   
**using** *HInfinite-minus-iff assms(1) starfun-exp-HInfinite* **by** *blast*  
**then show** *?thesis*  
**by** (*simp add: HInfinite-inverse-Infinitesimal <x = - y> starfun-exp-minus*)  
**qed**

**lemma** *starfun-exp-gt-one* [*simp*]:  $\bigwedge x::\text{hypreal}. 0 < x \implies 1 < (*f* \text{exp}) x$   
**by** *transfer* (*rule exp-gt-one*)

**abbreviation** *real-ln* :: *real*  $\Rightarrow$  *real* **where**  
*real-ln*  $\equiv$  *ln*

**lemma** *starfun-ln-exp* [*simp*]:  $\bigwedge x. (*f* \text{real-ln}) (( *f* \text{exp}) x) = x$   
**by** *transfer* (*rule ln-exp*)

**lemma** *starfun-exp-ln-iff* [*simp*]:  $\bigwedge x. (( *f* \text{exp})(( *f* \text{real-ln}) x) = x) = (0 < x)$   
**by** *transfer* (*rule exp-ln-iff*)

**lemma** *starfun-exp-ln-eq*:  $\bigwedge u x. (*f* \text{ exp}) u = x \implies (*f* \text{ real-ln}) x = u$   
**by** *transfer (rule ln-unique)*

**lemma** *starfun-ln-less-self* [*simp*]:  $\bigwedge x. 0 < x \implies (*f* \text{ real-ln}) x < x$   
**by** *transfer (rule ln-less-self)*

**lemma** *starfun-ln-ge-zero* [*simp*]:  $\bigwedge x. 1 \leq x \implies 0 \leq (*f* \text{ real-ln}) x$   
**by** *transfer (rule ln-ge-zero)*

**lemma** *starfun-ln-gt-zero* [*simp*]:  $\bigwedge x. 1 < x \implies 0 < (*f* \text{ real-ln}) x$   
**by** *transfer (rule ln-gt-zero)*

**lemma** *starfun-ln-not-eq-zero* [*simp*]:  $\bigwedge x. \llbracket 0 < x; x \neq 1 \rrbracket \implies (*f* \text{ real-ln}) x \neq 0$   
**by** *transfer simp*

**lemma** *starfun-ln-HFinite*:  $\llbracket x \in \text{HFinite}; 1 \leq x \rrbracket \implies (*f* \text{ real-ln}) x \in \text{HFinite}$   
**by** (*metis HFinite-HInfinite-iff less-le-trans starfun-exp-HInfinite starfun-exp-ln-iff starfun-ln-ge-zero zero-less-one*)

**lemma** *starfun-ln-inverse*:  $\bigwedge x. 0 < x \implies (*f* \text{ real-ln}) (\text{inverse } x) = -(*f* \text{ ln}) x$   
**by** *transfer (rule ln-inverse)*

**lemma** *starfun-abs-exp-cancel*:  $\bigwedge x. |(*f* \text{ exp}) (x::\text{hypreal})| = (*f* \text{ exp}) x$   
**by** *transfer (rule abs-exp-cancel)*

**lemma** *starfun-exp-less-mono*:  $\bigwedge x y::\text{hypreal}. x < y \implies (*f* \text{ exp}) x < (*f* \text{ exp}) y$   
**by** *transfer (rule exp-less-mono)*

**lemma** *starfun-exp-HFinite*:  
**fixes**  $x :: \text{hypreal}$   
**assumes**  $x \in \text{HFinite}$   
**shows**  $(*f* \text{ exp}) x \in \text{HFinite}$   
**proof** –  
**obtain**  $u$  **where**  $u \in \mathbb{R} \mid x < u$   
**using** *HFiniteD assms* **by** *force*  
**with** *assms* **have**  $|(*f* \text{ exp}) x| < (*f* \text{ exp}) u$   
**using** *starfun-abs-exp-cancel starfun-exp-less-mono* **by** *auto*  
**with**  $\langle u \in \mathbb{R} \rangle$  **show** *?thesis*  
**by** (*force simp: HFinite-def Reals-eq-Standard*)  
**qed**

**lemma** *starfun-exp-add-HFinite-Infinitesimal-approx*:  
**fixes**  $x :: \text{hypreal}$   
**shows**  $\llbracket x \in \text{Infinitesimal}; z \in \text{HFinite} \rrbracket \implies (*f* \text{ exp}) (z + x::\text{hypreal}) \approx (*f* \text{ exp}) z$   
**using** *STAR-exp-Infinitesimal approx-mult2 starfun-exp-HFinite* **by** (*fastforce simp add: STAR-exp-add*)

**lemma** *starfun-ln-HInfinite*:

$\llbracket x \in HInfinite; 0 < x \rrbracket \implies ( ** real-ln ) x \in HInfinite$   
**by** (*metis HInfinite-HFinite-iff starfun-exp-HFinite starfun-exp-ln-iff*)

**lemma** *starfun-exp-HInfinite-Infinitesimal-disj*:

**fixes**  $x :: hypreal$   
**shows**  $x \in HInfinite \implies ( ** exp ) x \in HInfinite \vee ( ** exp ) (x::hypreal) \in Infinitesimal$   
**by** (*meson linear starfun-exp-HInfinite starfun-exp-Infinitesimal*)

**lemma** *starfun-ln-HFinite-not-Infinitesimal*:

$\llbracket x \in HFinite - Infinitesimal; 0 < x \rrbracket \implies ( ** real-ln ) x \in HFinite$   
**by** (*metis DiffD1 DiffD2 HInfinite-HFinite-iff starfun-exp-HInfinite-Infinitesimal-disj starfun-exp-ln-iff*)

**lemma** *starfun-ln-Infinitesimal-HInfinite*:

**assumes**  $x \in Infinitesimal$   $0 < x$   
**shows**  $( ** real-ln ) x \in HInfinite$   
**proof** –  
**have** *inverse*  $x \in HInfinite$   
**using** *Infinitesimal-inverse-HInfinite assms* **by** *blast*  
**then show** *?thesis*  
**using** *HInfinite-minus-iff assms(2) starfun-ln-HInfinite starfun-ln-inverse* **by** *fastforce*  
**qed**

**lemma** *starfun-ln-less-zero*:  $\bigwedge x. \llbracket 0 < x; x < 1 \rrbracket \implies ( ** real-ln ) x < 0$

**by** *transfer (rule ln-less-zero)*

**lemma** *starfun-ln-Infinitesimal-less-zero*:

$\llbracket x \in Infinitesimal; 0 < x \rrbracket \implies ( ** real-ln ) x < 0$   
**by** (*auto intro!: starfun-ln-less-zero simp add: Infinitesimal-def*)

**lemma** *starfun-ln-HInfinite-gt-zero*:

$\llbracket x \in HInfinite; 0 < x \rrbracket \implies 0 < ( ** real-ln ) x$   
**by** (*auto intro!: starfun-ln-gt-zero simp add: HInfinite-def*)

**lemma** *HFinite-sin [simp]*:  $sumhr (0, whn, \lambda n. sin-coeff n * x ^ n) \in HFinite$

**proof** –

**have** *summable*  $(\lambda i. sin-coeff i * x ^ i)$   
**using** *summable-norm-sin [of x]* **by** (*simp add: summable-rabs-cancel*)  
**then have**  $( ** ( \lambda n. \sum n < n. sin-coeff n * x ^ n ) ) whn \in HFinite$   
**unfolding** *summable-sums-iff sums-NSsums-iff NSsums-def NSLIMSEQ-def*  
**using** *HFinite-star-of HNatInfinite-whn approx-HFinite approx-sym* **by** *blast*  
**then show** *?thesis*  
**unfolding** *sumhr-app*

by (simp only: star-zero-def starfun2-star-of atLeast0LessThan)  
qed

lemma STAR-sin-zero [simp]: (\*f\* sin) 0 = 0  
by transfer (rule sin-zero)

lemma STAR-sin-Infinitesimal [simp]:  
fixes x :: 'a::{real-normed-field,banach} star  
assumes x ∈ Infinitesimal  
shows (\*f\* sin) x ≈ x  
proof (cases x = 0)  
case False  
have NSDERIV sin 0 :> 1  
by (metis DERIV-sin NSDERIV-DERIV-iff cos-zero)  
then have (\*f\* sin) x / x ≈ 1  
using False NSDERIVD2 assms by fastforce  
with assms show ?thesis  
unfolding star-one-def  
by (metis False Infinitesimal-approx Infinitesimal-ratio approx-star-of-HFinite)  
qed auto

lemma HFinite-cos [simp]: sumhr (0, whn, λn. cos-coeff n \* x ^ n) ∈ HFinite  
proof –

have summable (λi. cos-coeff i \* x ^ i)  
using summable-norm-cos [of x] by (simp add: summable-rabs-cancel)  
then have (\*f\* (λn. ∑ n<n. cos-coeff n \* x ^ n)) whn ∈ HFinite  
unfolding summable-sums-iff sums-NSsums-iff NSsums-def NSLIMSEQ-def  
using HFinite-star-of HNatInfinite-whn approx-HFinite approx-sym by blast  
then show ?thesis  
unfolding sumhr-app  
by (simp only: star-zero-def starfun2-star-of atLeast0LessThan)  
qed

lemma STAR-cos-zero [simp]: (\*f\* cos) 0 = 1  
by transfer (rule cos-zero)

lemma STAR-cos-Infinitesimal [simp]:  
fixes x :: 'a::{real-normed-field,banach} star  
assumes x ∈ Infinitesimal  
shows (\*f\* cos) x ≈ 1  
proof (cases x = 0)  
case False  
have NSDERIV cos 0 :> 0  
by (metis DERIV-cos NSDERIV-DERIV-iff add.inverse-neutral sin-zero)  
then have (\*f\* cos) x - 1 ≈ 0  
using NSDERIV-approx assms by fastforce  
with assms show ?thesis  
using approx-minus-iff by blast  
qed auto

**lemma** *STAR-tan-zero* [simp]:  $(** \tan) 0 = 0$   
 by transfer (rule tan-zero)

**lemma** *STAR-tan-Infinitesimal* [simp]:  
 assumes  $x \in \text{Infinitesimal}$   
 shows  $(** \tan) x \approx x$   
**proof** (cases  $x = 0$ )  
 case False  
 have  $\text{NSDERIV } \tan 0 :> 1$   
 using *DERIV-tan* [of 0] by (simp add: *NSDERIV-DERIV-iff*)  
 then have  $(** \tan) x / x \approx 1$   
 using False *NSDERIVD2 assms* by fastforce  
 with assms show ?thesis  
 unfolding *star-one-def*  
 by (metis False *Infinitesimal-approx Infinitesimal-ratio approx-star-of-HFinite*)  
**qed** auto

**lemma** *STAR-sin-cos-Infinitesimal-mult*:  
 fixes  $x :: 'a::\{\text{real-normed-field,banach}\}$  star  
 shows  $x \in \text{Infinitesimal} \implies (** \sin) x * (** \cos) x \approx x$   
 using *approx-mult-HFinite* [of  $(** \sin) x - (** \cos) x 1$ ]  
 by (simp add: *Infinitesimal-subset-HFinite [THEN subsetD]*)

**lemma** *HFinite-pi*:  $\text{hypreal-of-real } \pi \in \text{HFinite}$   
 by simp

**lemma** *STAR-sin-Infinitesimal-divide*:  
 fixes  $x :: 'a::\{\text{real-normed-field,banach}\}$  star  
 shows  $\llbracket x \in \text{Infinitesimal}; x \neq 0 \rrbracket \implies (** \sin) x / x \approx 1$   
 using *DERIV-sin* [of 0:: $'a$ ]  
 by (simp add: *NSDERIV-DERIV-iff [symmetric] nsderiv-def*)

## 14.2 Proving $\sin * (1/n) \times 1/(1/n) \approx 1$ for $n = \infty$

**lemma** *lemma-sin-pi*:  
 $n \in \text{HNatInfinite}$   
 $\implies (** \sin) (\text{inverse } (\text{hypreal-of-hypnat } n)) / (\text{inverse } (\text{hypreal-of-hypnat } n))$   
 $\approx 1$   
 by (simp add: *STAR-sin-Infinitesimal-divide zero-less-HNatInfinite*)

**lemma** *STAR-sin-inverse-HNatInfinite*:  
 $n \in \text{HNatInfinite}$   
 $\implies (** \sin) (\text{inverse } (\text{hypreal-of-hypnat } n)) * \text{hypreal-of-hypnat } n \approx 1$   
 by (metis *field-class.field-divide-inverse inverse-inverse-eq lemma-sin-pi*)

**lemma** *Infinitesimal-pi-divide-HNatInfinite*:  
 $N \in \text{HNatInfinite}$

$\implies \text{hypreal-of-real } \pi / (\text{hypreal-of-hypnat } N) \in \text{Infinitesimal}$   
**by** (*simp add: Infinitesimal-HFinite-mult2 field-class.field-divide-inverse*)

**lemma** *pi-divide-HNatInfinite-not-zero* [*simp*]:

$N \in \text{HNatInfinite} \implies \text{hypreal-of-real } \pi / (\text{hypreal-of-hypnat } N) \neq 0$   
**by** (*simp add: zero-less-HNatInfinite*)

**lemma** *STAR-sin-pi-divide-HNatInfinite-approx-pi*:

**assumes**  $n \in \text{HNatInfinite}$

**shows**  $(\text{hypreal-of-real } \pi / \text{hypreal-of-hypnat } n) * \text{hypreal-of-hypnat } n \approx \text{hypreal-of-real } \pi$

**proof** –

**have**  $(\text{hypreal-of-real } \pi / \text{hypreal-of-hypnat } n) / (\text{hypreal-of-real } \pi / \text{hypreal-of-hypnat } n) \approx 1$

**using** *Infinitesimal-pi-divide-HNatInfinite STAR-sin-Infinitesimal-divide assms pi-divide-HNatInfinite-not-zero* **by** *blast*

**then have**  $\text{hypreal-of-hypnat } n * \text{star-of } \sin \star (\text{hypreal-of-real } \pi / \text{hypreal-of-hypnat } n) / \text{hypreal-of-real } \pi \approx 1$

**by** (*simp add: mult.commute starfun-def*)

**then show** *?thesis*

**apply** (*simp add: starfun-def field-simps*)

**by** (*metis (no-types, lifting) approx-mult-subst-star-of approx-refl mult-cancel-right1 nonzero-eq-divide-eq pi-neq-zero star-of-eq-0*)

**qed**

**lemma** *STAR-sin-pi-divide-HNatInfinite-approx-pi2*:

$n \in \text{HNatInfinite}$

$\implies \text{hypreal-of-hypnat } n * (\text{hypreal-of-real } \pi / (\text{hypreal-of-hypnat } n)) \approx \text{hypreal-of-real } \pi$

**by** (*metis STAR-sin-pi-divide-HNatInfinite-approx-pi mult.commute*)

**lemma** *starfunNat-pi-divide-n-Infinitesimal*:

$N \in \text{HNatInfinite} \implies (\text{hypreal-of-real } \pi / \text{real } x) N \in \text{Infinitesimal}$

**by** (*simp add: Infinitesimal-HFinite-mult2 divide-inverse starfunNat-real-of-nat*)

**lemma** *STAR-sin-pi-divide-n-approx*:

**assumes**  $N \in \text{HNatInfinite}$

**shows**  $(\text{hypreal-of-real } \pi / \text{hypreal-of-hypnat } N) \approx \text{hypreal-of-real } \pi / (\text{hypreal-of-hypnat } N)$

**proof** –

**have**  $\exists s. (\text{hypreal-of-real } \pi / \text{hypreal-of-hypnat } N) \approx s \wedge \text{hypreal-of-real } \pi / \text{hypreal-of-hypnat } N \approx s$

**by** (*metis (lifting) Infinitesimal-approx Infinitesimal-pi-divide-HNatInfinite STAR-sin-Infinitesimal assms starfunNat-pi-divide-n-Infinitesimal*)

**then show** *?thesis*

**by** (*meson approx-trans2*)

**qed**

**lemma** *NSLIMSEQ-sin-pi*:  $(\lambda n. \text{real } n * \sin (\pi / \text{real } n)) \longrightarrow_{NS} \pi$

**proof** –

**have** \*: *hypreal-of-hypnat*  $N * (*f* \sin) ((*f* (\lambda x. \pi / \text{real } x)) N) \approx \text{hypreal-of-real } \pi$

**if**  $N \in \text{HNatInfinite}$

**for**  $N :: \text{nat star}$

**using** *that*

**by** *simp* (*metis STAR-sin-pi-divide-HNatInfinite-approx-pi2 starfunNat-real-of-nat*)

**show** *?thesis*

**by** (*simp add: NSLIMSEQ-def starfunNat-real-of-nat*) (*metis \* starfun-o2*)

**qed**

**lemma** *NSLIMSEQ-cos-one*:  $(\lambda n. \cos (\pi / \text{real } n)) \longrightarrow_{NS} 1$

**proof** –

**have**  $(*f* \cos) ((*f* (\lambda x. \pi / \text{real } x)) N) \approx 1$

**if**  $N \in \text{HNatInfinite}$  **for**  $N$

**using** *that STAR-cos-Infinitesimal starfunNat-pi-divide-n-Infinitesimal* **by** *blast*

**then show** *?thesis*

**by** (*simp add: NSLIMSEQ-def*) (*metis STAR-cos-Infinitesimal starfunNat-pi-divide-n-Infinitesimal starfun-o2*)

**qed**

**lemma** *NSLIMSEQ-sin-cos-pi*:

$(\lambda n. \text{real } n * \sin (\pi / \text{real } n) * \cos (\pi / \text{real } n)) \longrightarrow_{NS} \pi$

**using** *NSLIMSEQ-cos-one NSLIMSEQ-mult NSLIMSEQ-sin-pi* **by** *force*

A familiar approximation to  $\cos x$  when  $x$  is small

**lemma** *STAR-cos-Infinitesimal-approx*:

**fixes**  $x :: 'a :: \{\text{real-normed-field, banach}\} \text{ star}$

**shows**  $x \in \text{Infinitesimal} \implies (*f* \cos) x \approx 1 - x^2$

**by** (*metis Infinitesimal-square-iff STAR-cos-Infinitesimal approx-diff approx-sym diff-zero mem-infmal-iff power2-eq-square*)

**lemma** *STAR-cos-Infinitesimal-approx2*:

**fixes**  $x :: \text{hypreal}$

**assumes**  $x \in \text{Infinitesimal}$

**shows**  $(*f* \cos) x \approx 1 - (x^2)/2$

**proof** –

**have**  $1 \approx 1 - x^2 / 2$

**using** *assms*

**by** (*auto intro: Infinitesimal-SReal-divide simp add: Infinitesimal-approx-minus [symmetric] numeral-2-eq-2*)

**then show** *?thesis*

**using** *STAR-cos-Infinitesimal approx-trans assms* **by** *blast*

**qed**

**end**

## 15 Non-Standard Complex Analysis

```
theory NSCA
imports NSComplex HTranscendental
begin
```

**abbreviation**

```
SComplex :: hcomplex set where
SComplex ≡ Standard
```

**definition** — standard part map

```
stc :: hcomplex => hcomplex where
stc x = (SOME r. x ∈ HFinite ∧ r ∈ SComplex ∧ r ≈ x)
```

### 15.1 Closure Laws for SComplex, the Standard Complex Numbers

**lemma** *SComplex-minus-iff* [*simp*]:  $(-x \in SComplex) = (x \in SComplex)$   
**using** *Standard-minus* **by** *fastforce*

**lemma** *SComplex-add-cancel*:

```
 $\llbracket x + y \in SComplex; y \in SComplex \rrbracket \implies x \in SComplex$   

using Standard-diff by fastforce
```

**lemma** *SReal-hcmod-hcomplex-of-complex* [*simp*]:

```
hcmod (hcomplex-of-complex r) ∈ ℝ  

by (simp add: Reals-eq-Standard)
```

**lemma** *SReal-hcmod-numeral*: *hcmod* (*numeral* *w* :: *hcomplex*) ∈ ℝ  
**by** *simp*

**lemma** *SReal-hcmod-SComplex*:  $x \in SComplex \implies hcmod\ x \in \mathbb{R}$   
**by** (*simp* *add*: *Reals-eq-Standard*)

**lemma** *SComplex-divide-numeral*:

```
 $r \in SComplex \implies r / (\text{numeral } w :: \text{hcomplex}) \in SComplex$   

by simp
```

**lemma** *SComplex-UNIV-complex*:

```
{x. hcomplex-of-complex x ∈ SComplex} = (UNIV::complex set)  

by simp
```

**lemma** *SComplex-iff*:  $(x \in SComplex) = (\exists y. x = hcomplex-of-complex\ y)$   
**by** (*simp* *add*: *Standard-def image-def*)

**lemma** *hcomplex-of-complex-image*:

```
range hcomplex-of-complex = SComplex  

by (simp add: Standard-def)
```



**lemma** *inv-hcomplex-of-complex-image*: *inv hcomplex-of-complex* ‘*SComplex* = *UNIV*  
**by** (*auto simp add: Standard-def image-def*) (*metis inj-star-of inv-f-f*)

**lemma** *SComplex-hcomplex-of-complex-image*:  
 $\llbracket \exists x. x \in P; P \leq SComplex \rrbracket \implies \exists Q. P = hcomplex-of-complex \text{ ‘ } Q$   
**by** (*metis Standard-def subset-imageE*)

**lemma** *SComplex-SReal-dense*:  
 $\llbracket x \in SComplex; y \in SComplex; hmod x < hmod y \rrbracket \implies \exists r \in Reals. hmod x < r \wedge r < hmod y$   
**by** (*simp add: SReal-dense SReal-hmod-SComplex*)

## 15.2 The Finite Elements form a Subring

**lemma** *HFinite-hmod-hcomplex-of-complex* [*simp*]:  
 $hmod (hcomplex-of-complex r) \in HFinite$   
**by** (*auto intro!: SReal-subset-HFinite [THEN subsetD]*)

**lemma** *HFinite-hmod-iff* [*simp*]:  $hmod x \in HFinite \iff x \in HFinite$   
**by** (*simp add: HFinite-def*)

**lemma** *HFinite-bounded-hmod*:  
 $\llbracket x \in HFinite; y \leq hmod x; 0 \leq y \rrbracket \implies y \in HFinite$   
**using** *HFinite-bounded HFinite-hmod-iff* **by** *blast*

## 15.3 The Complex Infinitesimals form a Subring

**lemma** *Infinitesimal-hmod-iff*:  
 $(z \in Infinitesimal) = (hmod z \in Infinitesimal)$   
**by** (*simp add: Infinitesimal-def*)

**lemma** *HInfinite-hmod-iff*:  $(z \in HInfinite) = (hmod z \in HInfinite)$   
**by** (*simp add: HInfinite-def*)

**lemma** *HFinite-diff-Infinitesimal-hmod*:  
 $x \in HFinite - Infinitesimal \implies hmod x \in HFinite - Infinitesimal$   
**by** (*simp add: Infinitesimal-hmod-iff*)

**lemma** *hmod-less-Infinitesimal*:  
 $\llbracket e \in Infinitesimal; hmod x < hmod e \rrbracket \implies x \in Infinitesimal$   
**by** (*auto elim: hrabs-less-Infinitesimal simp add: Infinitesimal-hmod-iff*)

**lemma** *hmod-le-Infinitesimal*:  
 $\llbracket e \in Infinitesimal; hmod x \leq hmod e \rrbracket \implies x \in Infinitesimal$   
**by** (*auto elim: hrabs-le-Infinitesimal simp add: Infinitesimal-hmod-iff*)

## 15.4 The “Infinitely Close” Relation

**lemma** *approx-SComplex-mult-cancel-zero*:

$\llbracket a \in SComplex; a \neq 0; a*x \approx 0 \rrbracket \implies x \approx 0$   
**by** (*metis Infinitesimal-mult-disj SComplex-iff mem-infmal-iff star-of-Infinitesimal-iff-0 star-zero-def*)

**lemma** *approx-mult-SComplex1*:  $\llbracket a \in SComplex; x \approx 0 \rrbracket \implies x*a \approx 0$   
**using** *SComplex-iff approx-mult-subst-star-of* **by** *fastforce*

**lemma** *approx-mult-SComplex2*:  $\llbracket a \in SComplex; x \approx 0 \rrbracket \implies a*x \approx 0$   
**by** (*metis approx-mult-SComplex1 mult.commute*)

**lemma** *approx-mult-SComplex-zero-cancel-iff* [*simp*]:  
 $\llbracket a \in SComplex; a \neq 0 \rrbracket \implies (a*x \approx 0) = (x \approx 0)$   
**using** *approx-SComplex-mult-cancel-zero approx-mult-SComplex2* **by** *blast*

**lemma** *approx-SComplex-mult-cancel*:  
 $\llbracket a \in SComplex; a \neq 0; a*w \approx a*z \rrbracket \implies w \approx z$   
**by** (*metis approx-SComplex-mult-cancel-zero approx-minus-iff right-diff-distrib*)

**lemma** *approx-SComplex-mult-cancel-iff1* [*simp*]:  
 $\llbracket a \in SComplex; a \neq 0 \rrbracket \implies (a*w \approx a*z) = (w \approx z)$   
**by** (*metis HFinite-star-of SComplex-iff approx-SComplex-mult-cancel approx-mult2*)

**lemma** *approx-hcmod-approx-zero*:  $(x \approx y) = (hcmod (y - x) \approx 0)$   
**by** (*simp add: Infinitesimal-hcmod-iff approx-def hnorm-minus-commute*)

**lemma** *approx-approx-zero-iff*:  $(x \approx 0) = (hcmod x \approx 0)$   
**by** (*simp add: approx-hcmod-approx-zero*)

**lemma** *approx-minus-zero-cancel-iff* [*simp*]:  $(-x \approx 0) = (x \approx 0)$   
**by** (*simp add: approx-def*)

**lemma** *Infinitesimal-hcmod-add-diff*:  
 $u \approx 0 \implies hcmod(x + u) - hcmod x \in Infinitesimal$   
**by** (*metis add.commute add.left-neutral approx-add-right-iff approx-def approx-hnorm*)

**lemma** *approx-hcmod-add-hcmod*:  $u \approx 0 \implies hcmod(x + u) \approx hcmod x$   
**using** *Infinitesimal-hcmod-add-diff approx-def* **by** *blast*

## 15.5 Zero is the Only Infinitesimal Complex Number

**lemma** *Infinitesimal-less-SComplex*:  
 $\llbracket x \in SComplex; y \in Infinitesimal; 0 < hcmod x \rrbracket \implies hcmod y < hcmod x$   
**by** (*auto intro: Infinitesimal-less-SReal SReal-hcmod-SComplex simp add: Infinitesimal-hcmod-iff*)

**lemma** *SComplex-Int-Infinitesimal-zero*:  $SComplex Int Infinitesimal = \{0\}$   
**by** (*auto simp add: Standard-def Infinitesimal-hcmod-iff*)

**lemma** *SComplex-Infinitesimal-zero*:

$\llbracket x \in SComplex; x \in Infinitesimal \rrbracket \implies x = 0$   
**using** *SComplex-iff* **by** *auto*

**lemma** *SComplex-HFinite-diff-Infinitesimal*:

$\llbracket x \in SComplex; x \neq 0 \rrbracket \implies x \in HFinite - Infinitesimal$   
**using** *SComplex-iff* **by** *auto*

**lemma** *numeral-not-Infinitesimal* [*simp*]:

$numeral\ w \neq (0::hcomplex) \implies (numeral\ w::hcomplex) \notin Infinitesimal$   
**by** (*fast dest: Standard-numeral* [*THEN SComplex-Infinitesimal-zero*])

**lemma** *approx-SComplex-not-zero*:

$\llbracket y \in SComplex; x \approx y; y \neq 0 \rrbracket \implies x \neq 0$   
**by** (*auto dest: SComplex-Infinitesimal-zero approx-sym* [*THEN mem-infmal-iff*  
[*THEN iffD2*]])

**lemma** *SComplex-approx-iff*:

$\llbracket x \in SComplex; y \in SComplex \rrbracket \implies (x \approx y) = (x = y)$   
**by** (*auto simp add: Standard-def*)

**lemma** *approx-unique-complex*:

$\llbracket r \in SComplex; s \in SComplex; r \approx x; s \approx x \rrbracket \implies r = s$   
**by** (*blast intro: SComplex-approx-iff* [*THEN iffD1*] *approx-trans2*)

## 15.6 Properties of *hRe*, *hIm* and *HComplex*

**lemma** *abs-hRe-le-hcmod*:  $\bigwedge x. |hRe\ x| \leq hcmod\ x$

**by** *transfer* (*rule abs-Re-le-cmod*)

**lemma** *abs-hIm-le-hcmod*:  $\bigwedge x. |hIm\ x| \leq hcmod\ x$

**by** *transfer* (*rule abs-Im-le-cmod*)

**lemma** *Infinitesimal-hRe*:  $x \in Infinitesimal \implies hRe\ x \in Infinitesimal$

**using** *Infinitesimal-hcmod-iff abs-hRe-le-hcmod hrabs-le-Infinitesimal* **by** *blast*

**lemma** *Infinitesimal-hIm*:  $x \in Infinitesimal \implies hIm\ x \in Infinitesimal$

**using** *Infinitesimal-hcmod-iff abs-hIm-le-hcmod hrabs-le-Infinitesimal* **by** *blast*

**lemma** *Infinitesimal-HComplex*:

**assumes**  $x \in Infinitesimal$  **and**  $y \in Infinitesimal$   
**shows**  $HComplex\ x\ y \in Infinitesimal$

**proof** –

**have**  $hcmod\ (HComplex\ 0\ y) \in Infinitesimal$

**by** (*simp add: hcmod-i*)

**moreover have**  $hcmod\ (hcomplex-of-hypreal\ x) \in Infinitesimal$

**using** *Infinitesimal-hcmod-iff Infinitesimal-of-hypreal-iff*  $x$  **by** *blast*

**ultimately have**  $hcmod\ (HComplex\ x\ y) \in Infinitesimal$

by (metis *Infinesimal-add Infinesimal-hcmo-d-iff add.right-neutral hcomplex-of-hypreal-add-HComplex*)  
 then show ?thesis  
 by (simp add: *Infinesimal-hnorm-iff*)  
 qed

lemma *hcomplex-Infinesimal-iff*:  
 $(x \in \text{Infinesimal}) \longleftrightarrow (hRe\ x \in \text{Infinesimal} \wedge hIm\ x \in \text{Infinesimal})$   
 using *Infinesimal-HComplex Infinesimal-hIm Infinesimal-hRe* by fastforce

lemma *hRe-diff* [simp]:  $\bigwedge x\ y. hRe\ (x - y) = hRe\ x - hRe\ y$   
 by transfer simp

lemma *hIm-diff* [simp]:  $\bigwedge x\ y. hIm\ (x - y) = hIm\ x - hIm\ y$   
 by transfer simp

lemma *approx-hRe*:  $x \approx y \implies hRe\ x \approx hRe\ y$   
 unfolding *approx-def* by (drule *Infinesimal-hRe*) simp

lemma *approx-hIm*:  $x \approx y \implies hIm\ x \approx hIm\ y$   
 unfolding *approx-def* by (drule *Infinesimal-hIm*) simp

lemma *approx-HComplex*:  
 $\llbracket a \approx b; c \approx d \rrbracket \implies HComplex\ a\ c \approx HComplex\ b\ d$   
 unfolding *approx-def* by (simp add: *Infinesimal-HComplex*)

lemma *hcomplex-approx-iff*:  
 $(x \approx y) = (hRe\ x \approx hRe\ y \wedge hIm\ x \approx hIm\ y)$   
 unfolding *approx-def* by (simp add: *hcomplex-Infinesimal-iff*)

lemma *HFinite-hRe*:  $x \in HFinite \implies hRe\ x \in HFinite$   
 using *HFinite-bounded-hcmo-d-abs-ge-zero abs-hRe-le-hcmo-d* by blast

lemma *HFinite-hIm*:  $x \in HFinite \implies hIm\ x \in HFinite$   
 using *HFinite-bounded-hcmo-d-abs-ge-zero abs-hIm-le-hcmo-d* by blast

lemma *HFinite-HComplex*:  
 assumes  $x \in HFinite\ y \in HFinite$   
 shows  $HComplex\ x\ y \in HFinite$   
 proof -  
 have  $HComplex\ x\ 0 \in HFinite\ HComplex\ 0\ y \in HFinite$   
 using *HFinite-hcmo-d-iff assms hcmo-d-i* by fastforce+  
 then have  $HComplex\ x\ 0 + HComplex\ 0\ y \in HFinite$   
 using *HFinite-add* by blast  
 then show ?thesis  
 by simp  
 qed

lemma *hcomplex-HFinite-iff*:

$(x \in \mathit{HFinite}) = (\mathit{hRe } x \in \mathit{HFinite} \wedge \mathit{hIm } x \in \mathit{HFinite})$   
**using**  $\mathit{HFinite-HComplex} \mathit{HFinite-hIm} \mathit{HFinite-hRe}$  **by** *fastforce*

**lemma**  $\mathit{hcomplex-HInfinite-iff}$ :  
 $(x \in \mathit{HInfinite}) = (\mathit{hRe } x \in \mathit{HInfinite} \vee \mathit{hIm } x \in \mathit{HInfinite})$   
**by** (*simp add: HInfinite-HFinite-iff hcomplex-HFinite-iff*)

**lemma**  $\mathit{hcomplex-of-hypreal-approx-iff}$  [*simp*]:  
 $(\mathit{hcomplex-of-hypreal } x \approx \mathit{hcomplex-of-hypreal } z) = (x \approx z)$   
**by** (*simp add: hcomplex-approx-iff*)

**lemma**  $\mathit{stc-part-Ex}$ :  
**assumes**  $x \in \mathit{HFinite}$   
**shows**  $\exists t \in \mathit{SComplex}. x \approx t$   
**proof** –  
**let**  $?t = \mathit{HComplex} (st (\mathit{hRe } x)) (st (\mathit{hIm } x))$   
**have**  $?t \in \mathit{SComplex}$   
**using**  $\mathit{HFinite-hIm} \mathit{HFinite-hRe} \mathit{Reals-eq-Standard} \mathit{assms} \mathit{st-SReal}$  **by** *auto*  
**moreover** **have**  $x \approx ?t$   
**by** (*simp add: HFinite-hIm HFinite-hRe assms hcomplex-approx-iff st-HFinite st-eq-approx*)  
**ultimately show**  $?thesis ..$   
**qed**

**lemma**  $\mathit{stc-part-Ex1}$ :  $x \in \mathit{HFinite} \implies \exists !t. t \in \mathit{SComplex} \wedge x \approx t$   
**using**  $\mathit{approx-sym} \mathit{approx-unique-complex} \mathit{stc-part-Ex}$  **by** *blast*

## 15.7 Theorems About Monads

**lemma**  $\mathit{monad-zero-hcmod-iff}$ :  $(x \in \mathit{monad } 0) = (\mathit{hcmod } x \in \mathit{monad } 0)$   
**by** (*simp add: Infinitesimal-monad-zero-iff [symmetric] Infinitesimal-hcmod-iff*)

## 15.8 Theorems About Standard Part

**lemma**  $\mathit{stc-approx-self}$ :  $x \in \mathit{HFinite} \implies \mathit{stc } x \approx x$   
**unfolding**  $\mathit{stc-def}$   
**by** (*metis (no-types, lifting) approx-reorient someI-ex stc-part-Ex1*)

**lemma**  $\mathit{stc-SComplex}$ :  $x \in \mathit{HFinite} \implies \mathit{stc } x \in \mathit{SComplex}$   
**unfolding**  $\mathit{stc-def}$   
**by** (*metis (no-types, lifting) SComplex-iff approx-sym someI-ex stc-part-Ex*)

**lemma**  $\mathit{stc-HFinite}$ :  $x \in \mathit{HFinite} \implies \mathit{stc } x \in \mathit{HFinite}$   
**by** (*erule stc-SComplex [THEN Standard-subset-HFinite [THEN subsetD]]*)

**lemma**  $\mathit{stc-unique}$ :  $\llbracket y \in \mathit{SComplex}; y \approx x \rrbracket \implies \mathit{stc } x = y$   
**by** (*metis SComplex-approx-iff SComplex-iff approx-monad-iff approx-star-of-HFinite stc-SComplex stc-approx-self*)

**lemma** *stc-SComplex-eq* [*simp*]:  $x \in SComplex \implies stc\ x = x$   
**by** (*simp add: stc-unique*)

**lemma** *stc-eq-approx*:  
 $\llbracket x \in HFinite; y \in HFinite; stc\ x = stc\ y \rrbracket \implies x \approx y$   
**by** (*auto dest!: stc-approx-self elim!: approx-trans3*)

**lemma** *approx-stc-eq*:  
 $\llbracket x \in HFinite; y \in HFinite; x \approx y \rrbracket \implies stc\ x = stc\ y$   
**by** (*metis approx-sym approx-trans3 stc-part-Ex1 stc-unique*)

**lemma** *stc-eq-approx-iff*:  
 $\llbracket x \in HFinite; y \in HFinite \rrbracket \implies (x \approx y) = (stc\ x = stc\ y)$   
**by** (*blast intro: approx-stc-eq stc-eq-approx*)

**lemma** *stc-Infinitesimal-add-SComplex*:  
 $\llbracket x \in SComplex; e \in Infinitesimal \rrbracket \implies stc(x + e) = x$   
**using** *Infinitesimal-add-approx-self stc-unique* **by** *blast*

**lemma** *stc-Infinitesimal-add-SComplex2*:  
 $\llbracket x \in SComplex; e \in Infinitesimal \rrbracket \implies stc(e + x) = x$   
**using** *Infinitesimal-add-approx-self2 stc-unique* **by** *blast*

**lemma** *HFinite-stc-Infinitesimal-add*:  
 $x \in HFinite \implies \exists e \in Infinitesimal. x = stc(x) + e$   
**by** (*blast dest!: stc-approx-self [THEN approx-sym] bex-Infinitesimal-iff2 [THEN iffD2]*)

**lemma** *stc-add*:  
 $\llbracket x \in HFinite; y \in HFinite \rrbracket \implies stc\ (x + y) = stc(x) + stc(y)$   
**by** (*simp add: stc-unique stc-SComplex stc-approx-self approx-add*)

**lemma** *stc-zero*:  $stc\ 0 = 0$   
**by** *simp*

**lemma** *stc-one*:  $stc\ 1 = 1$   
**by** *simp*

**lemma** *stc-minus*:  $y \in HFinite \implies stc(-y) = -stc(y)$   
**by** (*simp add: stc-unique stc-SComplex stc-approx-self approx-minus*)

**lemma** *stc-diff*:  
 $\llbracket x \in HFinite; y \in HFinite \rrbracket \implies stc\ (x - y) = stc(x) - stc(y)$   
**by** (*simp add: stc-unique stc-SComplex stc-approx-self approx-diff*)

**lemma** *stc-mult*:  
 $\llbracket x \in HFinite; y \in HFinite \rrbracket$   
 $\implies stc\ (x * y) = stc(x) * stc(y)$   
**by** (*simp add: stc-unique stc-SComplex stc-approx-self approx-mult-HFinite*)

**lemma** *stc-Infinitesimal*:  $x \in \text{Infinitesimal} \implies \text{stc } x = 0$   
**by** (*simp add: stc-unique mem-infmal-iff*)

**lemma** *stc-not-Infinitesimal*:  $\text{stc}(x) \neq 0 \implies x \notin \text{Infinitesimal}$   
**by** (*fast intro: stc-Infinitesimal*)

**lemma** *stc-inverse*:  
 $\llbracket x \in \text{HFinite}; \text{stc } x \neq 0 \rrbracket \implies \text{stc}(\text{inverse } x) = \text{inverse } (\text{stc } x)$   
**by** (*simp add: stc-unique stc-SComplex stc-approx-self approx-inverse stc-not-Infinitesimal*)

**lemma** *stc-divide* [*simp*]:  
 $\llbracket x \in \text{HFinite}; y \in \text{HFinite}; \text{stc } y \neq 0 \rrbracket$   
 $\implies \text{stc}(x/y) = (\text{stc } x) / (\text{stc } y)$   
**by** (*simp add: divide-inverse stc-mult stc-not-Infinitesimal HFinite-inverse stc-inverse*)

**lemma** *stc-idempotent* [*simp*]:  $x \in \text{HFinite} \implies \text{stc}(\text{stc}(x)) = \text{stc}(x)$   
**by** (*blast intro: stc-HFinite stc-approx-self approx-stc-eq*)

**lemma** *HFinite-HFinite-hcomplex-of-hypreal*:  
 $z \in \text{HFinite} \implies \text{hcomplex-of-hypreal } z \in \text{HFinite}$   
**by** (*simp add: hcomplex-HFinite-iff*)

**lemma** *SComplex-SReal-hcomplex-of-hypreal*:  
 $x \in \mathbb{R} \implies \text{hcomplex-of-hypreal } x \in \text{SComplex}$   
**by** (*simp add: Reals-eq-Standard*)

**lemma** *stc-hcomplex-of-hypreal*:  
 $z \in \text{HFinite} \implies \text{stc}(\text{hcomplex-of-hypreal } z) = \text{hcomplex-of-hypreal } (\text{st } z)$   
**by** (*simp add: SComplex-SReal-hcomplex-of-hypreal st-SReal st-approx-self stc-unique*)

**lemma** *hmod-stc-eq*:  
**assumes**  $x \in \text{HFinite}$   
**shows**  $\text{hmod}(\text{stc } x) = \text{st}(\text{hmod } x)$   
**by** (*metis SReal-hmod-SComplex approx-HFinite approx-hnorm assms st-unique stc-SComplex-eq stc-eq-approx-iff stc-part-Ex*)

**lemma** *Infinitesimal-hcnj-iff* [*simp*]:  
 $(\text{hcnj } z \in \text{Infinitesimal}) \longleftrightarrow (z \in \text{Infinitesimal})$   
**by** (*simp add: Infinitesimal-hcmmod-iff*)

end

## 16 Star-transforms in NSA, Extending Sets of Complex Numbers and Complex Functions

**theory** *CStar*  
**imports** *NSCA*

begin

### 16.1 Properties of the \*-Transform Applied to Sets of Reals

**lemma** *STARC-hcomplex-of-complex-Int*:  $*s* X \cap SComplex = hcomplex-of-complex$   
 $' X$   
 by (auto simp: Standard-def)

**lemma** *lemma-not-hcomplexA*:  $x \notin hcomplex-of-complex ' A \implies \forall y \in A. x \neq$   
 $hcomplex-of-complex y$   
 by auto

### 16.2 Theorems about Nonstandard Extensions of Functions

**lemma** *starfunC-hcpow*:  $\bigwedge Z. (*f* (\lambda z. z \hat{\ } n)) Z = Z \text{ pow hypnat-of-nat } n$   
 by transfer (rule refl)

**lemma** *starfunCR-cmod*:  $*f* cmod = hcmod$   
 by transfer (rule refl)

### 16.3 Internal Functions - Some Redundancy With \*f\* Now

**lemma** *starfun-Re*:  $(*f* (\lambda x. Re (f x))) = (\lambda x. hRe (( *f* f) x))$   
 by transfer (rule refl)

**lemma** *starfun-Im*:  $(*f* (\lambda x. Im (f x))) = (\lambda x. hIm (( *f* f) x))$   
 by transfer (rule refl)

**lemma** *starfunC-eq-Re-Im-iff*:  
 $(*f* f) x = z \longleftrightarrow (*f* (\lambda x. Re (f x))) x = hRe z \wedge (*f* (\lambda x. Im (f x))) x =$   
 $hIm z$   
 by (simp add: hcomplex-hRe-hIm-cancel-iff starfun-Re starfun-Im)

**lemma** *starfunC-approx-Re-Im-iff*:  
 $(*f* f) x \approx z \longleftrightarrow (*f* (\lambda x. Re (f x))) x \approx hRe z \wedge (*f* (\lambda x. Im (f x))) x \approx$   
 $hIm z$   
 by (simp add: hcomplex-approx-iff starfun-Re starfun-Im)

end

## 17 Limits, Continuity and Differentiation for Complex Functions

**theory** *CLim*  
 imports *CStar*  
 begin

**declare** *epsilon-not-zero* [simp]



**lemma** *lemma-complex-mult-inverse-squared* [*simp*]:  $x \neq 0 \implies x * (\text{inverse } x)^2 = \text{inverse } x$   
**for**  $x :: \text{complex}$   
**by** (*simp add: numeral-2-eq-2*)

Changing the quantified variable. Install earlier?

**lemma** *all-shift*:  $(\forall x :: 'a :: \text{comm-ring-1}. P x) \longleftrightarrow (\forall x. P (x - a))$   
**by** (*metis add-diff-cancel*)

### 17.1 Limit of Complex to Complex Function

**lemma** *NSLIM-Re*:  $f -a \rightarrow_{NS} L \implies (\lambda x. \text{Re } (f x)) -a \rightarrow_{NS} \text{Re } L$   
**by** (*simp add: NSLIM-def starfunC-approx-Re-Im-iff hRe-hcomplex-of-complex*)

**lemma** *NSLIM-Im*:  $f -a \rightarrow_{NS} L \implies (\lambda x. \text{Im } (f x)) -a \rightarrow_{NS} \text{Im } L$   
**by** (*simp add: NSLIM-def starfunC-approx-Re-Im-iff hIm-hcomplex-of-complex*)

**lemma** *LIM-Re*:  $f -a \rightarrow L \implies (\lambda x. \text{Re } (f x)) -a \rightarrow \text{Re } L$   
**for**  $f :: 'a :: \text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: LIM-NSLIM-iff NSLIM-Re*)

**lemma** *LIM-Im*:  $f -a \rightarrow L \implies (\lambda x. \text{Im } (f x)) -a \rightarrow \text{Im } L$   
**for**  $f :: 'a :: \text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: LIM-NSLIM-iff NSLIM-Im*)

**lemma** *LIM-cnj*:  $f -a \rightarrow L \implies (\lambda x. \text{cnj } (f x)) -a \rightarrow \text{cnj } L$   
**for**  $f :: 'a :: \text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: LIM-eq complex-cnj-diff [symmetric] del: complex-cnj-diff*)

**lemma** *LIM-cnj-iff*:  $(\lambda x. \text{cnj } (f x)) -a \rightarrow \text{cnj } L \longleftrightarrow f -a \rightarrow L$   
**for**  $f :: 'a :: \text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: LIM-eq complex-cnj-diff [symmetric] del: complex-cnj-diff*)

**lemma** *starfun-norm*:  $( *f* (\lambda x. \text{norm } (f x))) = (\lambda x. \text{hnorm } (( *f* f) x))$   
**by** *transfer (rule refl)*

**lemma** *star-of-Re* [*simp*]:  $\text{star-of } (\text{Re } x) = \text{hRe } (\text{star-of } x)$   
**by** *transfer (rule refl)*

**lemma** *star-of-Im* [*simp*]:  $\text{star-of } (\text{Im } x) = \text{hIm } (\text{star-of } x)$   
**by** *transfer (rule refl)*

Another equivalence result.

**lemma** *NSCLIM-NSCRLIM-iff*:  $f -x \rightarrow_{NS} L \longleftrightarrow (\lambda y. \text{cmod } (f y - L)) -x \rightarrow_{NS} 0$   
**by** (*simp add: NSLIM-def starfun-norm approx-approx-zero-iff [symmetric] approx-minus-iff [symmetric]*)

Much, much easier standard proof.

**lemma** *CLIM-CRLIM-iff*:  $f -x \rightarrow L \longleftrightarrow (\lambda y. \text{cmod } (f y - L)) -x \rightarrow 0$   
**for**  $f :: 'a::\text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: LIM-eq*)

So this is nicer nonstandard proof.

**lemma** *NSCLIM-NSCRLIM-iff2*:  $f -x \rightarrow_{NS} L \longleftrightarrow (\lambda y. \text{cmod } (f y - L)) -x \rightarrow_{NS} 0$   
**by** (*simp add: LIM-NSLIM-iff [symmetric] CLIM-CRLIM-iff*)

**lemma** *NSLIM-NSCRLIM-Re-Im-iff*:  
 $f -a \rightarrow_{NS} L \longleftrightarrow (\lambda x. \text{Re } (f x)) -a \rightarrow_{NS} \text{Re } L \wedge (\lambda x. \text{Im } (f x)) -a \rightarrow_{NS} \text{Im } L$   
**apply** (*auto intro: NSLIM-Re NSLIM-Im*)  
**apply** (*auto simp add: NSLIM-def starfun-Re starfun-Im*)  
**apply** (*auto dest!: spec*)  
**apply** (*simp add: hcomplex-approx-iff*)  
**done**

**lemma** *LIM-CRLIM-Re-Im-iff*:  $f -a \rightarrow L \longleftrightarrow (\lambda x. \text{Re } (f x)) -a \rightarrow \text{Re } L \wedge (\lambda x. \text{Im } (f x)) -a \rightarrow \text{Im } L$   
**for**  $f :: 'a::\text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: LIM-NSLIM-iff NSLIM-NSCRLIM-Re-Im-iff*)

## 17.2 Continuity

**lemma** *NSLIM-isContc-iff*:  $f -a \rightarrow_{NS} f a \longleftrightarrow (\lambda h. f (a + h)) -0 \rightarrow_{NS} f a$   
**by** (*rule NSLIM-at0-iff*)

## 17.3 Functions from Complex to Reals

**lemma** *isNSContCR-cmod [simp]*: *isNSCont cmod a*  
**by** (*auto intro: approx-hnorm*)  
*simp: starfunCR-cmod hmod-hcomplex-of-complex [symmetric] isNSCont-def*)

**lemma** *isContCR-cmod [simp]*: *isCont cmod a*  
**by** (*simp add: isNSCont-isCont-iff [symmetric]*)

**lemma** *isCont-Re*: *isCont f a  $\implies$  isCont  $(\lambda x. \text{Re } (f x)) a$*   
**for**  $f :: 'a::\text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: isCont-def LIM-Re*)

**lemma** *isCont-Im*: *isCont f a  $\implies$  isCont  $(\lambda x. \text{Im } (f x)) a$*   
**for**  $f :: 'a::\text{real-normed-vector} \Rightarrow \text{complex}$   
**by** (*simp add: isCont-def LIM-Im*)

## 17.4 Differentiation of Natural Number Powers

**lemma** *CDERIV-pow [simp]*: *DERIV  $(\lambda x. x \wedge n) x :> \text{complex-of-real } (\text{real } n) * (x \wedge (n - \text{Suc } 0))$*

```

apply (induct n)
  apply (drule-tac [2] DERIV-ident [THEN DERIV-mult])
  apply (auto simp add: distrib-right of-nat-Suc)
apply (case-tac n)
  apply (auto simp add: ac-simps)
done

```

Nonstandard version.

**lemma** NSCDERIV-pow:  $NSDERIV (\lambda x. x \wedge n) x := \text{complex-of-real (real } n) * (x \wedge (n - 1))$   
**by** (metis CDERIV-pow NSDERIV-DERIV-iff One-nat-def)

Can't relax the premise  $x \neq (0::'a)$ : it isn't continuous at zero.

**lemma** NSCDERIV-inverse:  $x \neq 0 \implies NSDERIV (\lambda x. \text{inverse } x) x := - (\text{inverse } x)^2$   
**for**  $x :: \text{complex}$   
**unfolding** numeral-2-eq-2 **by** (rule NSDERIV-inverse)

**lemma** CDERIV-inverse:  $x \neq 0 \implies DERIV (\lambda x. \text{inverse } x) x := - (\text{inverse } x)^2$   
**for**  $x :: \text{complex}$   
**unfolding** numeral-2-eq-2 **by** (rule DERIV-inverse)

## 17.5 Derivative of Reciprocals (Function *inverse*)

**lemma** CDERIV-inverse-fun:  
 $DERIV f x := d \implies f x \neq 0 \implies DERIV (\lambda x. \text{inverse } (f x)) x := - (d * \text{inverse } ((f x)^2))$   
**for**  $x :: \text{complex}$   
**unfolding** numeral-2-eq-2 **by** (rule DERIV-inverse-fun)

**lemma** NSCDERIV-inverse-fun:  
 $NSDERIV f x := d \implies f x \neq 0 \implies NSDERIV (\lambda x. \text{inverse } (f x)) x := - (d * \text{inverse } ((f x)^2))$   
**for**  $x :: \text{complex}$   
**unfolding** numeral-2-eq-2 **by** (rule NSDERIV-inverse-fun)

## 17.6 Derivative of Quotient

**lemma** CDERIV-quotient:  
 $DERIV f x := d \implies DERIV g x := e \implies g(x) \neq 0 \implies$   
 $DERIV (\lambda y. f y / g y) x := (d * g x - (e * f x)) / (g x)^2$   
**for**  $x :: \text{complex}$   
**unfolding** numeral-2-eq-2 **by** (rule DERIV-quotient)

**lemma** NSCDERIV-quotient:  
 $NSDERIV f x := d \implies NSDERIV g x := e \implies g x \neq (0::\text{complex}) \implies$   
 $NSDERIV (\lambda y. f y / g y) x := (d * g x - (e * f x)) / (g x)^2$   
**unfolding** numeral-2-eq-2 **by** (rule NSDERIV-quotient)

## 17.7 Caratheodory Formulation of Derivative at a Point: Standard Proof

**lemma** *CARAT-CDERIVD*:

$(\forall z. f z - f x = g z * (z - x)) \wedge \text{isNSCont } g x \wedge g x = l \implies \text{NSDERIV } f x :> l$   
 by *clarify (rule CARAT-DERIVD)*

**end**

## 18 Logarithms: Non-Standard Version

**theory** *HLog*

**imports** *HTranscendental*

**begin**

**definition** *powhr* :: *hypreal*  $\Rightarrow$  *hypreal*  $\Rightarrow$  *hypreal* (**infixr** *powhr* 80)

**where** [*transfer-unfold*]:  $x \text{ powhr } a = \text{starfun2 } (\text{powr}) x a$

**definition** *hlog* :: *hypreal*  $\Rightarrow$  *hypreal*  $\Rightarrow$  *hypreal*

**where** [*transfer-unfold*]:  $\text{hlog } a x = \text{starfun2 } \text{log } a x$

**lemma** *powhr*:  $(\text{star-n } X) \text{ powhr } (\text{star-n } Y) = \text{star-n } (\lambda n. (X n) \text{ powr } (Y n))$

**by** (*simp add: powhr-def starfun2-star-n*)

**lemma** *powhr-one-eq-one* [*simp*]:  $\bigwedge a. 1 \text{ powhr } a = 1$

**by** *transfer simp*

**lemma** *powhr-mult*:  $\bigwedge a x y. 0 < x \implies 0 < y \implies (x * y) \text{ powhr } a = (x \text{ powhr } a)$

$* (y \text{ powhr } a)$

**by** *transfer (simp add: powr-mult)*

**lemma** *powhr-gt-zero* [*simp*]:  $\bigwedge a x. 0 < x \text{ powhr } a \longleftrightarrow x \neq 0$

**by** *transfer simp*

**lemma** *powhr-not-zero* [*simp*]:  $\bigwedge a x. x \text{ powhr } a \neq 0 \longleftrightarrow x \neq 0$

**by** *transfer simp*

**lemma** *powhr-divide*:  $\bigwedge a x y. 0 \leq x \implies 0 \leq y \implies (x / y) \text{ powhr } a = (x \text{ powhr } a) / (y \text{ powhr } a)$

**by** *transfer (rule powr-divide)*

**lemma** *powhr-add*:  $\bigwedge a b x. x \text{ powhr } (a + b) = (x \text{ powhr } a) * (x \text{ powhr } b)$

**by** *transfer (rule powr-add)*

**lemma** *powhr-powhr*:  $\bigwedge a b x. (x \text{ powhr } a) \text{ powhr } b = x \text{ powhr } (a * b)$

**by** *transfer (rule powr-powr)*

**lemma** *powhr-powhr-swap*:  $\bigwedge a b x. (x \text{ powhr } a) \text{ powhr } b = (x \text{ powhr } b) \text{ powhr } a$

**by** *transfer (rule powr-powr-swap)*

**lemma powhr-minus:**  $\bigwedge a x. x \text{ powhr } (- a) = \text{inverse } (x \text{ powhr } a)$   
**by** *transfer (rule powr-minus)*

**lemma powhr-minus-divide:**  $x \text{ powhr } (- a) = 1 / (x \text{ powhr } a)$   
**by** *(simp add: divide-inverse powhr-minus)*

**lemma powhr-less-mono:**  $\bigwedge a b x. a < b \implies 1 < x \implies x \text{ powhr } a < x \text{ powhr } b$   
**by** *transfer simp*

**lemma powhr-less-cancel:**  $\bigwedge a b x. x \text{ powhr } a < x \text{ powhr } b \implies 1 < x \implies a < b$   
**by** *transfer simp*

**lemma powhr-less-cancel-iff [simp]:**  $1 < x \implies x \text{ powhr } a < x \text{ powhr } b \longleftrightarrow a < b$   
**by** *(blast intro: powhr-less-cancel powhr-less-mono)*

**lemma powhr-le-cancel-iff [simp]:**  $1 < x \implies x \text{ powhr } a \leq x \text{ powhr } b \longleftrightarrow a \leq b$   
**by** *(simp add: linorder-not-less [symmetric])*

**lemma hlog:**  $\text{hlog } (\text{star-}n X) (\text{star-}n Y) = \text{star-}n (\lambda n. \text{log } (X n) (Y n))$   
**by** *(simp add: hlog-def starfun2-star-n)*

**lemma hlog-starfun-ln:**  $\bigwedge x. (*f* \text{ ln}) x = \text{hlog } (( *f* \text{ exp}) 1) x$   
**by** *transfer (rule log-ln)*

**lemma powhr-hlog-cancel [simp]:**  $\bigwedge a x. 0 < a \implies a \neq 1 \implies 0 < x \implies a \text{ powhr } (\text{hlog } a x) = x$   
**by** *transfer simp*

**lemma hlog-powhr-cancel [simp]:**  $\bigwedge a y. 0 < a \implies a \neq 1 \implies \text{hlog } a (a \text{ powhr } y) = y$   
**by** *transfer simp*

**lemma hlog-mult:**  
 $\bigwedge a x y. 0 < a \implies a \neq 1 \implies 0 < x \implies 0 < y \implies \text{hlog } a (x * y) = \text{hlog } a x + \text{hlog } a y$   
**by** *transfer (rule log-mult)*

**lemma hlog-as-starfun:**  $\bigwedge a x. 0 < a \implies a \neq 1 \implies \text{hlog } a x = (*f* \text{ ln}) x / (*f* \text{ ln}) a$   
**by** *transfer (simp add: log-def)*

**lemma hlog-eq-div-starfun-ln-mult-hlog:**  
 $\bigwedge a b x. 0 < a \implies a \neq 1 \implies 0 < b \implies b \neq 1 \implies 0 < x \implies \text{hlog } a x = (( *f* \text{ ln}) b / (*f* \text{ ln}) a) * \text{hlog } b x$   
**by** *transfer (rule log-eq-div-ln-mult-log)*

**lemma powhr-as-starfun:**  $\bigwedge a x. x \text{ powhr } a = (\text{if } x = 0 \text{ then } 0 \text{ else } (*f* \text{ exp}) (a * (*f* \text{ real-ln}) x))$

**by** *transfer (simp add: powr-def)*

**lemma** *HInfinite-powhr:*

$x \in HInfinite \implies 0 < x \implies a \in HFinite - Infinitesimal \implies 0 < a \implies x \text{ powhr } a \in HInfinite$

**by** (*auto intro!: starfun-ln-ge-zero starfun-ln-HInfinite  
HInfinite-HFinite-not-Infinitesimal-mult2 starfun-exp-HInfinite  
simp add: order-less-imp-le HInfinite-gt-zero-gt-one powhr-as-starfun zero-le-mult-iff*)

**lemma** *hlog-hrabs-HInfinite-Infinitesimal:*

$x \in HFinite - Infinitesimal \implies a \in HInfinite \implies 0 < a \implies hlog a |x| \in Infinitesimal$

**apply** (*frule HInfinite-gt-zero-gt-one*)  
**apply** (*auto intro!: starfun-ln-HFinite-not-Infinitesimal  
HInfinite-inverse-Infinitesimal Infinitesimal-HFinite-mult2  
simp add: starfun-ln-HInfinite not-Infinitesimal-not-zero  
hlog-as-starfun divide-inverse*)

**done**

**lemma** *hlog-HInfinite-as-starfun:*  $a \in HInfinite \implies 0 < a \implies hlog a x = (*f* ln) x / (*f* ln) a$

**by** (*rule hlog-as-starfun auto*)

**lemma** *hlog-one [simp]:*  $\bigwedge a. hlog a 1 = 0$

**by** *transfer simp*

**lemma** *hlog-eq-one [simp]:*  $\bigwedge a. 0 < a \implies a \neq 1 \implies hlog a a = 1$

**by** *transfer (rule log-eq-one)*

**lemma** *hlog-inverse:*  $0 < a \implies a \neq 1 \implies 0 < x \implies hlog a (inverse x) = - hlog a x$

**by** (*rule add-left-cancel [of hlog a x, THEN iffD1] (simp add: hlog-mult [symmetric])*)

**lemma** *hlog-divide:*  $0 < a \implies a \neq 1 \implies 0 < x \implies 0 < y \implies hlog a (x / y) = hlog a x - hlog a y$

**by** (*simp add: hlog-mult hlog-inverse divide-inverse*)

**lemma** *hlog-less-cancel-iff [simp]:*

$\bigwedge a x y. 1 < a \implies 0 < x \implies 0 < y \implies hlog a x < hlog a y \iff x < y$

**by** *transfer simp*

**lemma** *hlog-le-cancel-iff [simp]:*  $1 < a \implies 0 < x \implies 0 < y \implies hlog a x \leq hlog a y \iff x \leq y$

**by** (*simp add: linorder-not-less [symmetric]*)

**end**

**theory** *Hyperreal*

```
imports HLog  
begin
```

```
end  
theory Hypercomplex  
imports CLim Hyperreal  
begin
```

```
end
```

```
theory Nonstandard-Analysis  
imports Hypercomplex  
begin
```

```
end
```