

The Hereditarily Finite Sets

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May 26, 2024

Abstract

The theory of hereditarily finite sets is formalised, following the development of Świerczkowski [2]. An HF set is a finite collection of other HF sets; they enjoy an induction principle and satisfy all the axioms of ZF set theory apart from the axiom of infinity, which is negated. All constructions that are possible in ZF set theory (Cartesian products, disjoint sums, natural numbers, functions) without using infinite sets are possible here. The definition of addition for the HF sets follows Kirby [1].

This development forms the foundation for the Isabelle proof of Gödel's incompleteness theorems, which has been formalised separately.

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Chapter 1

The Hereditarily Finite Sets

```
theory HF
imports HOL-Library.Nat-Bijection
abbrevs <: =  $\in$ 
       and  $\sim$ <: =  $\notin$ 
begin
```

From "Finite sets and Gödel's Incompleteness Theorems" by S. Swierczkowski. Thanks for Brian Huffman for this development, up to the cases and induct rules.

1.1 Basic Definitions and Lemmas

```
typedef hf = UNIV :: nat set <proof>
```

```
definition hfset :: hf  $\Rightarrow$  hf set
  where hfset a = Abs-hf ' set-decode (Rep-hf a)
```

```
definition HF :: hf set  $\Rightarrow$  hf
  where HF A = Abs-hf (set-encode (Rep-hf ' A))
```

```
definition hinsert :: hf  $\Rightarrow$  hf  $\Rightarrow$  hf
  where hinsert a b = HF (insert a (hfset b))
```

```
definition hmem :: hf  $\Rightarrow$  hf  $\Rightarrow$  bool (infixl  $\in$  50)
  where hmem a b  $\longleftrightarrow$  a  $\in$  hfset b
```

```
abbreviation not-hmem :: hf  $\Rightarrow$  hf  $\Rightarrow$  bool (infixl  $\notin$  50)
  where a  $\notin$  b  $\equiv$   $\neg$  a  $\in$  b
```

```
notation (ASCII)
  hmem (infixl <: 50)
```

```
instantiation hf :: zero
begin
```

definition *Zero-hf-def*: $0 = HF \{\}$
instance $\langle proof \rangle$
end

lemma *Abs-hf-0* [*simp*]: $Abs-hf\ 0 = 0$
 $\langle proof \rangle$

HF Set enumerations

abbreviation *inserthf* :: $hf \Rightarrow hf \Rightarrow hf$ (**infixl** $\triangleleft 60$)
where $y \triangleleft x \equiv hinsert\ x\ y$

syntax (*ASCII*)
 $-HF\inset :: args \Rightarrow hf \quad (\{|(-)|\})$

syntax
 $-HF\inset :: args \Rightarrow hf \quad (\{\!-\!\})$

translations
 $\{\!x, y\!\} \rightleftharpoons \{\!y\!\} \triangleleft x$
 $\{\!x\!\} \rightleftharpoons 0 \triangleleft x$

lemma *finite-hfset* [*simp*]: $finite\ (hfset\ a)$
 $\langle proof \rangle$

lemma *HF-hfset* [*simp*]: $HF\ (hfset\ a) = a$
 $\langle proof \rangle$

lemma *hfset-HF* [*simp*]: $finite\ A \Longrightarrow hfset\ (HF\ A) = A$
 $\langle proof \rangle$

lemma *inj-on-HF*: $inj\ on\ HF\ (Collect\ finite)$
 $\langle proof \rangle$

lemma *hmem-hempty* [*simp*]: $a \notin 0$
 $\langle proof \rangle$

lemmas *hemptyE* [*elim!*] = *hmem-hempty* [*THEN notE*]

lemma *hmem-hinsert* [*iff*]:
 $hmem\ a\ (c \triangleleft b) \longleftrightarrow a = b \vee a \in c$
 $\langle proof \rangle$

lemma *hf-ext*: $a = b \longleftrightarrow (\forall x. x \in a \longleftrightarrow x \in b)$
 $\langle proof \rangle$

lemma *finite-cases* [*consumes 1, case-names empty insert*]:
 $\llbracket finite\ F; F = \{\} \rrbracket \Longrightarrow P; \bigwedge A\ x. \llbracket F = insert\ x\ A; x \notin A; finite\ A \rrbracket \Longrightarrow P \Longrightarrow P$
 $\langle proof \rangle$

lemma *hf-cases* [*cases type: hf, case-names 0 hinsert*]:
obtains $y = 0 \mid a\ b$ **where** $y = b \triangleleft a$ **and** $a \notin b$

<proof>

lemma *Rep-hf-hinsert*:

assumes $a \notin b$ **shows** $\text{Rep-hf } (\text{hinsert } a \ b) = 2 \wedge (\text{Rep-hf } a) + \text{Rep-hf } b$

<proof>

1.2 Verifying the Axioms of HF

HF1

lemma *empty-iff*: $z=0 \longleftrightarrow (\forall x. x \notin z)$

<proof>

HF2

lemma *hinsert-iff*: $z = x \triangleleft y \longleftrightarrow (\forall u. u \in z \longleftrightarrow u \in x \vee u = y)$

<proof>

HF induction

lemma *hf-induct* [*induct type: hf, case-names 0 hinsert*]:

assumes [*simp*]: $P \ 0$

$\bigwedge x \ y. \llbracket P \ x; P \ y; x \notin y \rrbracket \Longrightarrow P \ (y \triangleleft x)$

shows $P \ z$

<proof>

HF3

lemma *hf-induct-ax*: $\llbracket P \ 0; \forall x. P \ x \longrightarrow (\forall y. P \ y \longrightarrow P \ (x \triangleleft y)) \rrbracket \Longrightarrow P \ x$

<proof>

lemma *hf-equalityI* [*intro*]: $(\bigwedge x. x \in a \longleftrightarrow x \in b) \Longrightarrow a = b$

<proof>

lemma *hinsert-nonempty* [*simp*]: $A \triangleleft a \neq 0$

<proof>

lemma *hinsert-commute*: $(z \triangleleft y) \triangleleft x = (z \triangleleft x) \triangleleft y$

<proof>

lemma *hmem-HF-iff* [*simp*]: $x \in \text{HF } A \longleftrightarrow x \in A \wedge \text{finite } A$

<proof>

1.3 Ordered Pairs, from ZF/ZF.thy

lemma *singleton-eq-iff* [*iff*]: $\{a\} = \{b\} \longleftrightarrow a=b$

<proof>

lemma *doubleton-eq-iff*: $\{a,b\} = \{c,d\} \longleftrightarrow (a=c \wedge b=d) \vee (a=d \wedge b=c)$

<proof>

definition $hpair :: hf \Rightarrow hf \Rightarrow hf$
where $hpair\ a\ b = \{\{a\}, \{a, b\}\}$

definition $hfst :: hf \Rightarrow hf$
where $hfst\ p \equiv THE\ x.\ \exists y.\ p = hpair\ x\ y$

definition $hsnd :: hf \Rightarrow hf$
where $hsnd\ p \equiv THE\ y.\ \exists x.\ p = hpair\ x\ y$

definition $hsplit :: [[hf, hf] \Rightarrow 'a, hf] \Rightarrow 'a::\{\}$ — for pattern-matching
where $hsplit\ c \equiv \lambda p.\ c\ (hfst\ p)\ (hsnd\ p)$

Ordered Pairs, from ZF/ZF.thy

nonterminal hfs

syntax (ASCII)

-*Tuple* $:: [hf, hfs] \Rightarrow hf \quad (<(-, / -)>)$

-*hpattern* $:: [pttrn, patterns] \Rightarrow pttrn \quad (<(-, / ->)$

syntax

$:: hf \Rightarrow hfs \quad (-)$

-*Enum* $:: [hf, hfs] \Rightarrow hfs \quad (-, / -)$

-*Tuple* $:: [hf, hfs] \Rightarrow hf \quad (((-, / -)))$

-*hpattern* $:: [pttrn, patterns] \Rightarrow pttrn \quad (((-, / -))$

translations

$\langle x, y, z \rangle \quad \rightleftharpoons \langle x, \langle y, z \rangle \rangle$

$\langle x, y \rangle \quad \rightleftharpoons CONST\ hpair\ x\ y$

$\langle x, y, z \rangle \quad \rightleftharpoons \langle x, \langle y, z \rangle \rangle$

$\lambda \langle x, y, zs \rangle.\ b \quad \rightleftharpoons CONST\ hsplit(\lambda x\ \langle y, zs \rangle.\ b)$

$\lambda \langle x, y \rangle.\ b \quad \rightleftharpoons CONST\ hsplit(\lambda x\ y.\ b)$

lemma $hpair\text{-}def'$: $hpair\ a\ b = \{\{a, a\}, \{a, b\}\}$
<proof>

lemma $hpair\text{-}iff$ [*simp*]: $hpair\ a\ b = hpair\ a'\ b' \longleftrightarrow a=a' \wedge b=b'$
<proof>

lemmas $hpair\text{-}inject = hpair\text{-}iff$ [*THEN iffD1, THEN conjE, elim!*]

lemma $hfst\text{-}conv$ [*simp*]: $hfst\ \langle a, b \rangle = a$
<proof>

lemma $hsnd\text{-}conv$ [*simp*]: $hsnd\ \langle a, b \rangle = b$
<proof>

lemma $hsplit$ [*simp*]: $hsplit\ c\ \langle a, b \rangle = c\ a\ b$
<proof>

1.4 Unions, Comprehensions, Intersections

1.4.1 Unions

Theorem 1.5 (Existence of the union of two sets).

lemma *binary-union*: $\exists z. \forall u. u \in z \longleftrightarrow u \in x \vee u \in y$
<proof>

Theorem 1.6 (Existence of the union of a set of sets).

lemma *union-of-set*: $\exists z. \forall u. u \in z \longleftrightarrow (\exists y. y \in x \wedge u \in y)$
<proof>

1.4.2 Set comprehensions

Theorem 1.7, comprehension scheme

lemma *comprehension*: $\exists z. \forall u. u \in z \longleftrightarrow u \in x \wedge P u$
<proof>

definition *HCollect* :: $(hf \Rightarrow bool) \Rightarrow hf \Rightarrow hf$ — comprehension
where *HCollect* $P A = (THE z. \forall u. u \in z = (P u \wedge u \in A))$

syntax (*ASCII*)

-HCollect :: $idt \Rightarrow hf \Rightarrow bool \Rightarrow hf$ ((1 $\{\}$ - <:/ -/ - $\}$)

syntax

-HCollect :: $idt \Rightarrow hf \Rightarrow bool \Rightarrow hf$ ((1 $\{\}$ - \in / -/ - $\}$)

translations

$\{x \in A. P\} \rightleftharpoons CONST HCollect (\lambda x. P) A$

lemma *HCollect-iff* [*iff*]: $hmem x (HCollect P A) \longleftrightarrow P x \wedge x \in A$
<proof>

lemma *HCollectI*: $a \in A \Longrightarrow P a \Longrightarrow hmem a \{x \in A. P x\}$
<proof>

lemma *HCollectE*:

assumes $a \in \{x \in A. P x\}$ **obtains** $a \in A P a$
<proof>

lemma *HCollect-empty* [*simp*]: $HCollect P 0 = 0$
<proof>

1.4.3 Union operators

instantiation *hf* :: *sup*

begin

definition *sup* $a b = (THE z. \forall u. u \in z \longleftrightarrow u \in a \vee u \in b)$

instance *<proof>*

end

abbreviation $hunion :: hf \Rightarrow hf \Rightarrow hf$ (**infixl** \sqcup 65) **where**
 $hunion \equiv sup$

lemma $hunion\text{-iff}$ [*iff*]: $hmem\ x\ (a \sqcup b) \longleftrightarrow x \in a \vee x \in b$
 $\langle proof \rangle$

definition $HUnion :: hf \Rightarrow hf$ (\sqcup -[900] 900)
where $HUnion\ A = (THE\ z.\ \forall u.\ u \in z \longleftrightarrow (\exists y.\ y \in A \wedge u \in y))$

lemma $HUnion\text{-iff}$ [*iff*]: $hmem\ x\ (\sqcup\ A) \longleftrightarrow (\exists y.\ y \in A \wedge x \in y)$
 $\langle proof \rangle$

lemma $HUnion\text{-hempty}$ [*simp*]: $\sqcup\ 0 = 0$
 $\langle proof \rangle$

lemma $HUnion\text{-hinsert}$ [*simp*]: $\sqcup\ (A \triangleleft a) = a \sqcup \sqcup\ A$
 $\langle proof \rangle$

lemma $HUnion\text{-hunion}$ [*simp*]: $\sqcup\ (A \sqcup B) = \sqcup\ A \sqcup \sqcup\ B$
 $\langle proof \rangle$

1.4.4 Definition 1.8, Intersections

instantiation $hf :: inf$

begin

definition $inf\ a\ b = \{x \in a.\ x \in b\}$

instance $\langle proof \rangle$

end

abbreviation $hinter :: hf \Rightarrow hf \Rightarrow hf$ (**infixl** \sqcap 70) **where**
 $hinter \equiv inf$

lemma $hinter\text{-iff}$ [*iff*]: $hmem\ u\ (x \sqcap y) \longleftrightarrow u \in x \wedge u \in y$
 $\langle proof \rangle$

definition $HInter :: hf \Rightarrow hf$ (\sqcap -[900] 900)
where $HInter(A) = \{x \in HUnion(A).\ \forall y.\ y \in A \longrightarrow x \in y\}$

lemma $HInter\text{-hempty}$ [*iff*]: $\sqcap\ 0 = 0$
 $\langle proof \rangle$

lemma $HInter\text{-iff}$ [*simp*]: $A \neq 0 \Longrightarrow hmem\ x\ (\sqcap\ A) \longleftrightarrow (\forall y.\ y \in A \longrightarrow x \in y)$
 $\langle proof \rangle$

lemma $HInter\text{-hinsert}$ [*simp*]: $A \neq 0 \Longrightarrow \sqcap\ (A \triangleleft a) = a \sqcap \sqcap\ A$
 $\langle proof \rangle$

1.4.5 Set Difference

instantiation $hf :: minus$

begin
definition $A - B = \{x \in A. x \notin B\}$
instance $\langle proof \rangle$
end

lemma *hdiff-iff* [*iff*]: $hmem\ u\ (x - y) \longleftrightarrow u \in x \wedge u \notin y$
 $\langle proof \rangle$

lemma *hdiff-zero* [*simp*]: **fixes** $x :: hf$ **shows** $(x - 0) = x$
 $\langle proof \rangle$

lemma *zero-hdiff* [*simp*]: **fixes** $x :: hf$ **shows** $(0 - x) = 0$
 $\langle proof \rangle$

lemma *hdiff-insert*: $A - (B \triangleleft a) = A - B - \{a\}$
 $\langle proof \rangle$

lemma *hinsert-hdiff-if*:
 $(A \triangleleft x) - B = (if\ x \in B\ then\ A - B\ else\ (A - B) \triangleleft x)$
 $\langle proof \rangle$

1.5 Replacement

Theorem 1.9 (Replacement Scheme).

lemma *replacement*:
 $(\forall u\ v\ v'.\ u \in x \longrightarrow R\ u\ v \longrightarrow R\ u\ v' \longrightarrow v' = v) \implies \exists z. \forall v. v \in z \longleftrightarrow (\exists u. u \in x \wedge R\ u\ v)$
 $\langle proof \rangle$

lemma *replacement-fun*: $\exists z. \forall v. v \in z \longleftrightarrow (\exists u. u \in x \wedge v = f\ u)$
 $\langle proof \rangle$

definition *PrimReplace* :: $hf \Rightarrow (hf \Rightarrow hf \Rightarrow bool) \Rightarrow hf$
where *PrimReplace* $A\ R = (THE\ z. \forall v. v \in z \longleftrightarrow (\exists u. u \in A \wedge R\ u\ v))$

definition *Replace* :: $hf \Rightarrow (hf \Rightarrow hf \Rightarrow bool) \Rightarrow hf$
where *Replace* $A\ R = PrimReplace\ A\ (\lambda x\ y. (\exists! z. R\ x\ z) \wedge R\ x\ y)$

definition *RepFun* :: $hf \Rightarrow (hf \Rightarrow hf) \Rightarrow hf$
where *RepFun* $A\ f = Replace\ A\ (\lambda x\ y. y = f\ x)$

syntax (*ASCII*)

$-HReplace$:: $[pttrn, pptrn, hf, bool] \Rightarrow hf\ ((1\ \{|\cdot\ -<:\ -,\ -|\})$
 $-HRepFun$:: $[hf, pptrn, hf] \Rightarrow hf\ ((1\ \{|\cdot\ -<:\ -|\})\ [51,0,51])$
 $-HINTER$:: $[pttrn, hf, hf] \Rightarrow hf\ ((3INT\ -<:\ -/\ -)\ 10)$
 $-HUNION$:: $[pttrn, hf, hf] \Rightarrow hf\ ((3UN\ -<:\ -/\ -)\ 10)$

syntax

$-HReplace :: [pttrn, pttrn, hf, bool] \Rightarrow hf \ ((1 \{- ./ - \in -, -\})$
 $-HRepFun :: [hf, pttrn, hf] \Rightarrow hf \ ((1 \{- ./ - \in -\}) [51,0,51])$
 $-HINTER :: [pttrn, hf, hf] \Rightarrow hf \ ((3 \sqcap - \in - / -) 10)$
 $-HUNION :: [pttrn, hf, hf] \Rightarrow hf \ ((3 \sqcup - \in - / -) 10)$

translations

$\{y. x \in A, Q\} \Rightarrow CONST Replace A (\lambda x y. Q)$
 $\{b. x \in A\} \Rightarrow CONST RepFun A (\lambda x. b)$
 $\sqcap x \in A. B \Rightarrow CONST HInter(CONST RepFun A (\lambda x. B))$
 $\sqcup x \in A. B \Rightarrow CONST HUnion(CONST RepFun A (\lambda x. B))$

lemma PrimReplace-iff:

assumes $sv: \forall u v v'. u \in A \longrightarrow R u v \longrightarrow R u v' \longrightarrow v'=v$
shows $v \in (PrimReplace A R) \longleftrightarrow (\exists u. u \in A \wedge R u v)$
 $\langle proof \rangle$

lemma Replace-iff [iff]:

$v \in Replace A R \longleftrightarrow (\exists u. u \in A \wedge R u v \wedge (\forall y. R u y \longrightarrow y=v))$
 $\langle proof \rangle$

lemma Replace-0 [simp]: $Replace 0 R = 0$

$\langle proof \rangle$

lemma Replace-hunion [simp]: $Replace (A \sqcup B) R = Replace A R \sqcup Replace B R$

$\langle proof \rangle$

lemma Replace-cong [cong]:

$\llbracket A=B; \bigwedge x y. x \in B \Longrightarrow P x y \longleftrightarrow Q x y \rrbracket \Longrightarrow Replace A P = Replace B Q$
 $\langle proof \rangle$

lemma RepFun-iff [iff]: $v \in (RepFun A f) \longleftrightarrow (\exists u. u \in A \wedge v = f u)$

$\langle proof \rangle$

lemma RepFun-cong [cong]:

$\llbracket A=B; \bigwedge x. x \in B \Longrightarrow f(x)=g(x) \rrbracket \Longrightarrow RepFun A f = RepFun B g$
 $\langle proof \rangle$

lemma triv-RepFun [simp]: $RepFun A (\lambda x. x) = A$

$\langle proof \rangle$

lemma RepFun-0 [simp]: $RepFun 0 f = 0$

$\langle proof \rangle$

lemma RepFun-hinsert [simp]: $RepFun (hinsert a b) f = hinsert (f a) (RepFun b f)$

$\langle proof \rangle$

lemma RepFun-hunion [simp]:

$RepFun (A \sqcup B) f = RepFun A f \sqcup RepFun B f$

<proof>

lemma *HF-HUnion*: $\llbracket \text{finite } A; \bigwedge x. x \in A \implies \text{finite } (B\ x) \rrbracket \implies \text{HF } (\bigcup x \in A. B\ x)$
 $= (\bigsqcup x \in \text{HF } A. \text{HF } (B\ x))$
<proof>

1.6 Subset relation and the Lattice Properties

Definition 1.10 (Subset relation).

instantiation *hf* :: *order*

begin

definition *less-eq-hf* **where** $A \leq B \iff (\forall x. x \in A \longrightarrow x \in B)$

definition *less-hf* **where** $A < B \iff A \leq B \wedge A \neq (B::\text{hf})$

instance *<proof>*

end

1.6.1 Rules for subsets

lemma *hsubsetI* [*intro!*]:

$(\bigwedge x. x \in A \implies x \in B) \implies A \leq B$

<proof>

Classical elimination rule

lemma *hsubsetCE* [*elim*]: $\llbracket A \leq B; c \notin A \implies P; c \in B \implies P \rrbracket \implies P$

<proof>

Rule in Modus Ponens style

lemma *hsubsetD* [*elim*]: $\llbracket A \leq B; c \in A \rrbracket \implies c \in B$

<proof>

Sometimes useful with premises in this order

lemma *rev-hsubsetD*: $\llbracket c \in A; A \leq B \rrbracket \implies c \in B$

<proof>

lemma *contra-hsubsetD*: $\llbracket A \leq B; c \notin B \rrbracket \implies c \notin A$

<proof>

lemma *rev-contra-hsubsetD*: $\llbracket c \notin B; A \leq B \rrbracket \implies c \notin A$

<proof>

lemma *hf-equalityE*:

fixes $A :: \text{hf}$ **shows** $A = B \implies (A \leq B \implies B \leq A \implies P) \implies P$

<proof>

1.6.2 Lattice properties

instantiation *hf* :: *distrib-lattice*

begin
instance $\langle proof \rangle$
end

instantiation $hf :: bounded-lattice-bot$
begin
definition $bot = (0::hf)$
instance $\langle proof \rangle$
end

lemma *hinter-hempty-left* [simp]: $0 \sqcap A = 0$
 $\langle proof \rangle$

lemma *hinter-hempty-right* [simp]: $A \sqcap 0 = 0$
 $\langle proof \rangle$

lemma *hunion-hempty-left* [simp]: $0 \sqcup A = A$
 $\langle proof \rangle$

lemma *hunion-hempty-right* [simp]: $A \sqcup 0 = A$
 $\langle proof \rangle$

lemma *less-eq-hempty* [simp]: $u \leq 0 \longleftrightarrow u = (0::hf)$
 $\langle proof \rangle$

lemma *less-eq-insert1-iff* [iff]: $(hinsert\ x\ y) \leq z \longleftrightarrow x \in z \wedge y \leq z$
 $\langle proof \rangle$

lemma *less-eq-insert2-iff*:
 $z \leq (hinsert\ x\ y) \longleftrightarrow z \leq y \vee (\exists u. hinsert\ x\ u = z \wedge x \notin u \wedge u \leq y)$
 $\langle proof \rangle$

lemma *zero-le* [simp]: $0 \leq (x::hf)$
 $\langle proof \rangle$

lemma *hinsert-eq-sup*: $b \triangleleft a = b \sqcup \{a\}$
 $\langle proof \rangle$

lemma *hunion-hinsert-left*: $hinsert\ x\ A \sqcup B = hinsert\ x\ (A \sqcup B)$
 $\langle proof \rangle$

lemma *hunion-hinsert-right*: $B \sqcup hinsert\ x\ A = hinsert\ x\ (B \sqcup A)$
 $\langle proof \rangle$

lemma *hinter-hinsert-left*: $hinsert\ x\ A \sqcap B = (if\ x \in B\ then\ hinsert\ x\ (A \sqcap B)\ else\ A \sqcap B)$
 $\langle proof \rangle$

lemma *hinter-hinsert-right*: $B \sqcap hinsert\ x\ A = (if\ x \in B\ then\ hinsert\ x\ (B \sqcap A))$

else $B \sqcap A$
<proof>

1.7 Foundation, Cardinality, Powersets

1.7.1 Foundation

Theorem 1.13: Foundation (Regularity) Property.

lemma *foundation*:

assumes $z \neq 0$ **shows** $\exists w. w \in z \wedge w \sqcap z = 0$
<proof>

lemma *hmem-not-refl*: $x \notin x$
<proof>

lemma *hmem-not-sym*: $\neg (x \in y \wedge y \in x)$
<proof>

lemma *hmem-ne*: $x \in y \implies x \neq y$
<proof>

lemma *hmem-Sup-ne*: $x \in y \implies \sqcup x \neq y$
<proof>

lemma *hpair-neq-fst*: $\langle a, b \rangle \neq a$
<proof>

lemma *hpair-neq-snd*: $\langle a, b \rangle \neq b$
<proof>

lemma *hpair-nonzero* [*simp*]: $\langle x, y \rangle \neq 0$
<proof>

lemma *zero-notin-hpair*: $0 \notin \langle x, y \rangle$
<proof>

1.7.2 Cardinality

First we need to hack the underlying representation

lemma *hfset-0* [*simp*]: $hfset\ 0 = \{\}$
<proof>

lemma *hfset-hinsert*: $hfset\ (b \triangleleft a) = insert\ a\ (hfset\ b)$
<proof>

lemma *hfset-hdiff*: $hfset\ (x - y) = hfset\ x - hfset\ y$
<proof>

definition $hcard :: hf \Rightarrow nat$
where $hcard\ x = card\ (hfset\ x)$

lemma $hcard-0$ [simp]: $hcard\ 0 = 0$
 ⟨proof⟩

lemma $hcard-hinsert-if$: $hcard\ (hinsert\ x\ y) = (if\ x \in y\ then\ hcard\ y\ else\ Suc\ (hcard\ y))$
 ⟨proof⟩

lemma $hcard-union-inter$: $hcard\ (x \sqcup y) + hcard\ (x \sqcap y) = hcard\ x + hcard\ y$
 ⟨proof⟩

lemma $hcard-hdiff1-less$: $x \in z \implies hcard\ (z - \{x\}) < hcard\ z$
 ⟨proof⟩

1.7.3 Powerset Operator

Theorem 1.11 (Existence of the power set).

lemma $powerset$: $\exists z. \forall u. u \in z \longleftrightarrow u \leq x$
 ⟨proof⟩

definition $HPow :: hf \Rightarrow hf$
where $HPow\ x = (THE\ z. \forall u. u \in z \longleftrightarrow u \leq x)$

lemma $HPow-iff$ [iff]: $u \in HPow\ x \longleftrightarrow u \leq x$
 ⟨proof⟩

lemma $HPow-mono$: $x \leq y \implies HPow\ x \leq HPow\ y$
 ⟨proof⟩

lemma $HPow-mono-strict$: $x < y \implies HPow\ x < HPow\ y$
 ⟨proof⟩

lemma $HPow-mono-iff$ [simp]: $HPow\ x \leq HPow\ y \longleftrightarrow x \leq y$
 ⟨proof⟩

lemma $HPow-mono-strict-iff$ [simp]: $HPow\ x < HPow\ y \longleftrightarrow x < y$
 ⟨proof⟩

1.8 Bounded Quantifiers

definition $HBall :: hf \Rightarrow (hf \Rightarrow bool) \Rightarrow bool$ **where**
 $HBall\ A\ P \longleftrightarrow (\forall x. x \in A \longrightarrow P\ x)$ — bounded universal quantifiers

definition $HBeX :: hf \Rightarrow (hf \Rightarrow bool) \Rightarrow bool$ **where**
 $HBeX\ A\ P \longleftrightarrow (\exists x. x \in A \wedge P\ x)$ — bounded existential quantifiers

syntax (*ASCII*)

-*HBall* :: *pttrn* \Rightarrow *hf* \Rightarrow *bool* \Rightarrow *bool* ($(\exists ALL \text{ -<:-./ -}) [0, 0, 10] 10$)
-*HBex* :: *pttrn* \Rightarrow *hf* \Rightarrow *bool* \Rightarrow *bool* ($(\exists EX \text{ -<:-./ -}) [0, 0, 10] 10$)
-*HBex1* :: *pttrn* \Rightarrow *hf* \Rightarrow *bool* \Rightarrow *bool* ($(\exists EX! \text{ -<:-./ -}) [0, 0, 10] 10$)

syntax

-*HBall* :: *pttrn* \Rightarrow *hf* \Rightarrow *bool* \Rightarrow *bool* ($(\exists \forall \text{ -}\in\text{-./ -}) [0, 0, 10] 10$)
-*HBex* :: *pttrn* \Rightarrow *hf* \Rightarrow *bool* \Rightarrow *bool* ($(\exists \exists \text{ -}\in\text{-./ -}) [0, 0, 10] 10$)
-*HBex1* :: *pttrn* \Rightarrow *hf* \Rightarrow *bool* \Rightarrow *bool* ($(\exists \exists! \text{ -}\in\text{-./ -}) [0, 0, 10] 10$)

translations

$\forall x \in A. P \Leftrightarrow CONST\ HBall\ A\ (\lambda x. P)$
 $\exists x \in A. P \Leftrightarrow CONST\ HBex\ A\ (\lambda x. P)$
 $\exists !x \in A. P \rightarrow \exists !x. x \in A \wedge P$

lemma *hball-cong* [*cong*]:

$\llbracket A=A'; \bigwedge x. x \in A' \Rightarrow P(x) \longleftrightarrow P'(x) \rrbracket \Rightarrow (\forall x \in A. P(x)) \longleftrightarrow (\forall x \in A'. P'(x))$
<proof>

lemma *hballI* [*intro!*]: $(\bigwedge x. x \in A \Rightarrow P\ x) \Rightarrow \forall x \in A. P\ x$

<proof>

lemma *hbspec* [*dest?*]: $\forall x \in A. P\ x \Rightarrow x \in A \Rightarrow P\ x$

<proof>

lemma *hballE* [*elim*]: $\forall x \in A. P\ x \Rightarrow (P\ x \Rightarrow Q) \Rightarrow (x \notin A \Rightarrow Q) \Rightarrow Q$

<proof>

lemma *hbex-cong* [*cong*]:

$\llbracket A=A'; \bigwedge x. x \in A' \Rightarrow P(x) \longleftrightarrow P'(x) \rrbracket \Rightarrow (\exists x \in A. P(x)) \longleftrightarrow (\exists x \in A'. P'(x))$
<proof>

lemma *hbexI* [*intro*]: $P\ x \Rightarrow x \in A \Rightarrow \exists x \in A. P\ x$

and *rev-hbexI* [*intro?*]: $x \in A \Rightarrow P\ x \Rightarrow \exists x \in A. P\ x$

and *bexCI*: $(\forall x \in A. \neg P\ x \Rightarrow P\ a) \Rightarrow a \in A \Rightarrow \exists x \in A. P\ x$

and *hbexE* [*elim!*]: $\exists x \in A. P\ x \Rightarrow (\bigwedge x. x \in A \Rightarrow P\ x \Rightarrow Q) \Rightarrow Q$

<proof>

lemma *hball-triv* [*simp*]: $(\forall x \in A. P) = ((\exists x. x \in A) \rightarrow P)$

and *hbex-triv* [*simp*]: $(\exists x \in A. P) = ((\exists x. x \in A) \wedge P)$

— Dual form for existentials.

<proof>

lemma *hbex-triv-one-point1* [*simp*]: $(\exists x \in A. x = a) = (a \in A)$

<proof>

lemma *hbex-triv-one-point2* [*simp*]: $(\exists x \in A. a = x) = (a \in A)$

<proof>

lemma *hbex-one-point1* [*simp*]: $(\exists x \in A. x = a \wedge P x) = (a \in A \wedge P a)$
 ⟨*proof*⟩

lemma *hbex-one-point2* [*simp*]: $(\exists x \in A. a = x \wedge P x) = (a \in A \wedge P a)$
 ⟨*proof*⟩

lemma *hball-one-point1* [*simp*]: $(\forall x \in A. x = a \longrightarrow P x) = (a \in A \longrightarrow P a)$
 ⟨*proof*⟩

lemma *hball-one-point2* [*simp*]: $(\forall x \in A. a = x \longrightarrow P x) = (a \in A \longrightarrow P a)$
 ⟨*proof*⟩

lemma *hball-conj-distrib*:
 $(\forall x \in A. P x \wedge Q x) \longleftrightarrow ((\forall x \in A. P x) \wedge (\forall x \in A. Q x))$
 ⟨*proof*⟩

lemma *hbex-disj-distrib*:
 $(\exists x \in A. P x \vee Q x) \longleftrightarrow ((\exists x \in A. P x) \vee (\exists x \in A. Q x))$
 ⟨*proof*⟩

lemma *hb-all-simps* [*simp, no-atp*]:
 $\bigwedge A P Q. (\forall x \in A. P x \vee Q) \longleftrightarrow ((\forall x \in A. P x) \vee Q)$
 $\bigwedge A P Q. (\forall x \in A. P \vee Q x) \longleftrightarrow (P \vee (\forall x \in A. Q x))$
 $\bigwedge A P Q. (\forall x \in A. P \longrightarrow Q x) \longleftrightarrow (P \longrightarrow (\forall x \in A. Q x))$
 $\bigwedge A P Q. (\forall x \in A. P x \longrightarrow Q) \longleftrightarrow ((\exists x \in A. P x) \longrightarrow Q)$
 $\bigwedge P. (\forall x \in \emptyset. P x) \longleftrightarrow \text{True}$
 $\bigwedge a B P. (\forall x \in B \triangleleft a. P x) \longleftrightarrow (P a \wedge (\forall x \in B. P x))$
 $\bigwedge P Q. (\forall x \in \text{HCollect } Q A. P x) \longleftrightarrow (\forall x \in A. Q x \longrightarrow P x)$
 $\bigwedge A P. (\neg (\forall x \in A. P x)) \longleftrightarrow (\exists x \in A. \neg P x)$
 ⟨*proof*⟩

lemma *hb-ex-simps* [*simp, no-atp*]:
 $\bigwedge A P Q. (\exists x \in A. P x \wedge Q) \longleftrightarrow ((\exists x \in A. P x) \wedge Q)$
 $\bigwedge A P Q. (\exists x \in A. P \wedge Q x) \longleftrightarrow (P \wedge (\exists x \in A. Q x))$
 $\bigwedge P. (\exists x \in \emptyset. P x) \longleftrightarrow \text{False}$
 $\bigwedge a B P. (\exists x \in B \triangleleft a. P x) \longleftrightarrow (P a \vee (\exists x \in B. P x))$
 $\bigwedge P Q. (\exists x \in \text{HCollect } Q A. P x) \longleftrightarrow (\exists x \in A. Q x \wedge P x)$
 $\bigwedge A P. (\neg (\exists x \in A. P x)) \longleftrightarrow (\forall x \in A. \neg P x)$
 ⟨*proof*⟩

lemma *le-HCollect-iff*: $A \leq \{x \in B. P x\} \longleftrightarrow A \leq B \wedge (\forall x \in A. P x)$
 ⟨*proof*⟩

1.9 Relations and Functions

definition *is-hpair* :: $hf \Rightarrow bool$
 where *is-hpair* $z = (\exists x y. z = \langle x, y \rangle)$

definition *hconverse* :: $hf \Rightarrow hf$

where $hconverse(r) = \{z. w \in r, \exists x y. w = \langle x, y \rangle \wedge z = \langle y, x \rangle\}$

definition $hdomain :: hf \Rightarrow hf$

where $hdomain(r) = \{x. w \in r, \exists y. w = \langle x, y \rangle\}$

definition $hrange :: hf \Rightarrow hf$

where $hrange(r) = hdomain(hconverse(r))$

definition $hrelation :: hf \Rightarrow bool$

where $hrelation(r) = (\forall z. z \in r \longrightarrow is-hpair\ z)$

definition $hrestrict :: hf \Rightarrow hf \Rightarrow hf$

— Restrict the relation r to the domain A

where $hrestrict\ r\ A = \{z \in r. \exists x \in A. \exists y. z = \langle x, y \rangle\}$

definition $nonrestrict :: hf \Rightarrow hf \Rightarrow hf$

where $nonrestrict\ r\ A = \{z \in r. \forall x \in A. \forall y. z \neq \langle x, y \rangle\}$

definition $hfunction :: hf \Rightarrow bool$

where $hfunction(r) = (\forall x y. \langle x, y \rangle \in r \longrightarrow (\forall y'. \langle x, y' \rangle \in r \longrightarrow y = y'))$

definition $app :: hf \Rightarrow hf \Rightarrow hf$

where $app\ f\ x = (THE\ y. \langle x, y \rangle \in f)$

lemma $hrestrict-iff$ [*iff*]:

$z \in hrestrict\ r\ A \longleftrightarrow z \in r \wedge (\exists x y. z = \langle x, y \rangle \wedge x \in A)$

<proof>

lemma $hrelation-0$ [*simp*]: $hrelation\ 0$

<proof>

lemma $hrelation-restr$ [*iff*]: $hrelation\ (hrestrict\ r\ x)$

<proof>

lemma $hrelation-hunion$ [*simp*]: $hrelation\ (f \sqcup g) \longleftrightarrow hrelation\ f \wedge hrelation\ g$

<proof>

lemma $hfunction-restr$: $hfunction\ r \Longrightarrow hfunction\ (hrestrict\ r\ x)$

<proof>

lemma $hdomain-restr$ [*simp*]: $hdomain\ (hrestrict\ r\ x) = hdomain\ r \sqcap x$

<proof>

lemma $hdomain-0$ [*simp*]: $hdomain\ 0 = 0$

<proof>

lemma $hdomain-ins$ [*simp*]: $hdomain\ (r \triangleleft \langle x, y \rangle) = hdomain\ r \triangleleft x$

<proof>

lemma *hdomain-hunion* [simp]: $hdomain (f \sqcup g) = hdomain f \sqcup hdomain g$
 ⟨proof⟩

lemma *hdomain-not-mem* [iff]: $\langle hdomain r, a \rangle \notin r$
 ⟨proof⟩

lemma *app-singleton* [simp]: $app \{\langle x, y \rangle\} x = y$
 ⟨proof⟩

lemma *app-equality*: $hfunction f \implies \langle x, y \rangle \in f \implies app f x = y$
 ⟨proof⟩

lemma *app-ins2*: $x' \neq x \implies app (f \triangleleft \langle x, y \rangle) x' = app f x'$
 ⟨proof⟩

lemma *hfunction-0* [simp]: $hfunction 0$
 ⟨proof⟩

lemma *hfunction-ins*: $hfunction f \implies x \notin hdomain f \implies hfunction (f \triangleleft \langle x, y \rangle)$
 ⟨proof⟩

lemma *hdomainI*: $\langle x, y \rangle \in f \implies x \in hdomain f$
 ⟨proof⟩

lemma *hfunction-hunion*: $hdomain f \sqcap hdomain g = 0$
 $\implies hfunction (f \sqcup g) \longleftrightarrow hfunction f \wedge hfunction g$
 ⟨proof⟩

lemma *app-hrestrict* [simp]: $x \in A \implies app (hrestrict f A) x = app f x$
 ⟨proof⟩

1.10 Operations on families of sets

definition *HLambda* :: $hf \Rightarrow (hf \Rightarrow hf) \Rightarrow hf$
 where $HLambda A b = RepFun A (\lambda x. \langle x, b x \rangle)$

definition *HSigma* :: $hf \Rightarrow (hf \Rightarrow hf) \Rightarrow hf$
 where $HSigma A B = (\bigsqcup x \in A. \bigsqcup y \in B(x). \{\langle x, y \rangle\})$

definition *HPi* :: $hf \Rightarrow (hf \Rightarrow hf) \Rightarrow hf$
 where $HPi A B = \{f \in HPow(HSigma A B). A \leq hdomain(f) \wedge hfunction(f)\}$

syntax (*ASCII*)

-*PROD* :: $[pttrn, hf, hf] \Rightarrow hf$ (($\exists PROD$ -<:./ -) 10)

-*SUM* :: $[pttrn, hf, hf] \Rightarrow hf$ (($\exists SUM$ -<:./ -) 10)

-*lam* :: $[pttrn, hf, hf] \Rightarrow hf$ (($\exists lam$ -<:./ -) 10)

syntax

-*PROD* :: $[pttrn, hf, hf] \Rightarrow hf$ (($\exists \prod$ -<:./ -) 10)

-SUM :: [pttrn, hf, hf] ⇒ hf ((∑ -∈-./ -) 10)
-lam :: [pttrn, hf, hf] ⇒ hf ((λ-∈-./ -) 10)

translations

$\prod x \in A. B \Rightarrow \text{CONST HPi } A (\lambda x. B)$
 $\sum x \in A. B \Rightarrow \text{CONST HSigma } A (\lambda x. B)$
 $\lambda x \in A. f \Rightarrow \text{CONST HLambda } A (\lambda x. f)$

1.10.1 Rules for Unions and Intersections of families

lemma HUN-iff [simp]: $b \in (\bigsqcup x \in A. B(x)) \longleftrightarrow (\exists x \in A. b \in B(x))$
⟨proof⟩

lemma HUN-I: $\llbracket a \in A; b \in B(a) \rrbracket \Longrightarrow b \in (\bigsqcup x \in A. B(x))$
⟨proof⟩

lemma HUN-E [elim!]: **assumes** $b \in (\bigsqcup x \in A. B(x))$ **obtains** x **where** $x \in A$ $b \in B(x)$
⟨proof⟩

lemma HINT-iff: $b \in (\prod x \in A. B(x)) \longleftrightarrow (\forall x \in A. b \in B(x)) \wedge A \neq 0$
⟨proof⟩

lemma HINT-I: $\llbracket \bigwedge x. x \in A \Longrightarrow b \in B(x); A \neq 0 \rrbracket \Longrightarrow b \in (\prod x \in A. B(x))$
⟨proof⟩

lemma HINT-E: $\llbracket b \in (\prod x \in A. B(x)); a \in A \rrbracket \Longrightarrow b \in B(a)$
⟨proof⟩

1.10.2 Generalized Cartesian product

lemma HSigma-iff [simp]: $\langle a, b \rangle \in \text{HSigma } A B \longleftrightarrow a \in A \wedge b \in B(a)$
⟨proof⟩

lemma HSigmaI [intro!]: $\llbracket a \in A; b \in B(a) \rrbracket \Longrightarrow \langle a, b \rangle \in \text{HSigma } A B$
⟨proof⟩

lemmas HSigmaD1 = HSigma-iff [THEN iffD1, THEN conjunct1]

lemmas HSigmaD2 = HSigma-iff [THEN iffD1, THEN conjunct2]

The general elimination rule

lemma HSigmaE [elim!]:
assumes $c \in \text{HSigma } A B$
obtains $x y$ **where** $x \in A$ $y \in B(x)$ $c = \langle x, y \rangle$
⟨proof⟩

lemma HSigmaE2 [elim!]:
assumes $\langle a, b \rangle \in \text{HSigma } A B$ **obtains** $a \in A$ **and** $b \in B(a)$
⟨proof⟩

lemma *HSigma-empty1* [*simp*]: $HSigma\ 0\ B = 0$
 ⟨*proof*⟩

instantiation *hf* :: *times*
begin
definition $A * B = HSigma\ A\ (\lambda x. B)$
instance ⟨*proof*⟩
end

lemma *times-iff* [*simp*]: $\langle a, b \rangle \in A * B \longleftrightarrow a \in A \wedge b \in B$
 ⟨*proof*⟩

lemma *timesI* [*intro!*]: $\llbracket a \in A; b \in B \rrbracket \implies \langle a, b \rangle \in A * B$
 ⟨*proof*⟩

lemmas *timesD1* = *times-iff* [*THEN iffD1, THEN conjunct1*]
lemmas *timesD2* = *times-iff* [*THEN iffD1, THEN conjunct2*]

The general elimination rule

lemma *timesE* [*elim!*]:
assumes $c: c \in A * B$
obtains $x\ y$ **where** $x \in A\ y \in B\ c = \langle x, y \rangle$ ⟨*proof*⟩

...and a specific one

lemma *timesE2* [*elim!*]:
assumes $\langle a, b \rangle \in A * B$ **obtains** $a \in A$ **and** $b \in B$
 ⟨*proof*⟩

lemma *times-empty1* [*simp*]: $0 * B = (0::hf)$
 ⟨*proof*⟩

lemma *times-empty2* [*simp*]: $A * 0 = (0::hf)$
 ⟨*proof*⟩

lemma *times-empty-iff*: $A * B = 0 \longleftrightarrow A = 0 \vee B = (0::hf)$
 ⟨*proof*⟩

instantiation *hf* :: *mult-zero*
begin
instance ⟨*proof*⟩
end

1.11 Disjoint Sum

instantiation *hf* :: *zero-neq-one*
begin
definition *One-hf-def*: $1 = \{0\}$
instance ⟨*proof*⟩
end

instantiation $hf :: plus$

begin

definition $A + B = (\{0\} * A) \sqcup (\{1\} * B)$

instance $\langle proof \rangle$

end

definition $Inl :: hf \Rightarrow hf$ **where**

$Inl(a) \equiv \langle 0, a \rangle$

definition $Inr :: hf \Rightarrow hf$ **where**

$Inr(b) \equiv \langle 1, b \rangle$

lemmas $sum-defs = plus-hf-def Inl-def Inr-def$

lemma $Inl-nonzero$ $[simp]: Inl\ x \neq 0$

$\langle proof \rangle$

lemma $Inr-nonzero$ $[simp]: Inr\ x \neq 0$

$\langle proof \rangle$

Introduction rules for the injections (as equivalences)

lemma $Inl-in-sum-iff$ $[iff]: Inl(a) \in A+B \longleftrightarrow a \in A$

$\langle proof \rangle$

lemma $Inr-in-sum-iff$ $[iff]: Inr(b) \in A+B \longleftrightarrow b \in B$

$\langle proof \rangle$

Elimination rule

lemma $sumE$ $[elim!]:$

assumes $u: u \in A+B$

obtains x **where** $x \in A\ u = Inl(x) \mid y$ **where** $y \in B\ u = Inr(y)$ $\langle proof \rangle$

Injection and freeness equivalences, for rewriting

lemma $Inl-iff$ $[iff]: Inl(a) = Inl(b) \longleftrightarrow a = b$

$\langle proof \rangle$

lemma $Inr-iff$ $[iff]: Inr(a) = Inr(b) \longleftrightarrow a = b$

$\langle proof \rangle$

lemma $Inl-Inr-iff$ $[iff]: Inl(a) = Inr(b) \longleftrightarrow False$

$\langle proof \rangle$

lemma $Inr-Inl-iff$ $[iff]: Inr(b) = Inl(a) \longleftrightarrow False$

$\langle proof \rangle$

lemma $sum-empty$ $[simp]: 0 + 0 = (0::hf)$

$\langle proof \rangle$

lemma *sum-iff*: $u \in A+B \longleftrightarrow (\exists x. x \in A \wedge u = \text{Inl}(x)) \vee (\exists y. y \in B \wedge u = \text{Inr}(y))$
 ⟨proof⟩

lemma *sum-subset-iff*:
fixes $A :: hf$ **shows** $A+B \leq C+D \longleftrightarrow A \leq C \wedge B \leq D$
 ⟨proof⟩

lemma *sum-equal-iff*:
fixes $A :: hf$ **shows** $A+B = C+D \longleftrightarrow A=C \wedge B=D$
 ⟨proof⟩

definition *is-hsum* :: $hf \Rightarrow bool$
where $is-hsum\ z = (\exists x. z = \text{Inl}\ x \vee z = \text{Inr}\ x)$

definition *sum-case* :: $(hf \Rightarrow 'a) \Rightarrow (hf \Rightarrow 'a) \Rightarrow hf \Rightarrow 'a$
where
 $sum-case\ f\ g\ a \equiv$
 $THE\ z. (\forall x. a = \text{Inl}\ x \longrightarrow z = f\ x) \wedge (\forall y. a = \text{Inr}\ y \longrightarrow z = g\ y) \wedge (\neg$
 $is-hsum\ a \longrightarrow z = \text{undefined})$

lemma *sum-case-Inl* [*simp*]: $sum-case\ f\ g\ (\text{Inl}\ x) = f\ x$
 ⟨proof⟩

lemma *sum-case-Inr* [*simp*]: $sum-case\ f\ g\ (\text{Inr}\ y) = g\ y$
 ⟨proof⟩

lemma *sum-case-non* [*simp*]: $\neg is-hsum\ a \Longrightarrow sum-case\ f\ g\ a = \text{undefined}$
 ⟨proof⟩

lemma *is-hsum-cases*: $(\exists x. z = \text{Inl}\ x \vee z = \text{Inr}\ x) \vee \neg is-hsum\ z$
 ⟨proof⟩

lemma *sum-case-split*:
 $P\ (sum-case\ f\ g\ a) \longleftrightarrow (\forall x. a = \text{Inl}\ x \longrightarrow P(f\ x)) \wedge (\forall y. a = \text{Inr}\ y \longrightarrow P(g$
 $y)) \wedge (\neg is-hsum\ a \longrightarrow P\ \text{undefined})$
 ⟨proof⟩

lemma *sum-case-split-asm*:
 $P\ (sum-case\ f\ g\ a) \longleftrightarrow \neg ((\exists x. a = \text{Inl}\ x \wedge \neg P(f\ x)) \vee (\exists y. a = \text{Inr}\ y \wedge \neg$
 $P(g\ y)) \vee (\neg is-hsum\ a \wedge \neg P\ \text{undefined}))$
 ⟨proof⟩

end

Chapter 2

Ordinals, Sequences and Ordinal Recursion

theory *Ordinal* imports *HF*
begin

2.1 Ordinals

2.1.1 Basic Definitions

Definition 2.1. We say that x is transitive if every element of x is a subset of x .

definition

Transset :: *hf* \Rightarrow *bool* **where**
 $Transset(x) \equiv \forall y. y \in x \longrightarrow y \leq x$

lemma *Transset-sup*: $Transset\ x \Longrightarrow Transset\ y \Longrightarrow Transset\ (x \sqcup y)$
<proof>

lemma *Transset-inf*: $Transset\ x \Longrightarrow Transset\ y \Longrightarrow Transset\ (x \sqcap y)$
<proof>

lemma *Transset-hinsert*: $Transset\ x \Longrightarrow y \leq x \Longrightarrow Transset\ (x \triangleleft y)$
<proof>

In HF, the ordinals are simply the natural numbers. But the definitions are the same as for transfinite ordinals.

definition

Ord :: *hf* \Rightarrow *bool* **where**
 $Ord(k) \equiv Transset(k) \wedge (\forall x \in k. Transset(x))$

2.1.2 Definition 2.2 (Successor).

definition

$succ :: hf \Rightarrow hf$ **where**
 $succ(x) \equiv hinsert\ x\ x$

lemma *succ-iff* [simp]: $x \in succ\ y \longleftrightarrow x=y \vee x \in y$
 ⟨proof⟩

lemma *succ-ne-self* [simp]: $i \neq succ\ i$
 ⟨proof⟩

lemma *succ-notin-self*: $succ\ i \notin i$
 ⟨proof⟩

lemma *succE* [elim?]: **assumes** $x \in succ\ y$ **obtains** $x=y \mid x \in y$
 ⟨proof⟩

lemma *hmem-succ-ne*: $succ\ x \in y \Longrightarrow x \neq y$
 ⟨proof⟩

lemma *hball-succ* [simp]: $(\forall x \in succ\ k. P\ x) \longleftrightarrow P\ k \wedge (\forall x \in k. P\ x)$
 ⟨proof⟩

lemma *hbex-succ* [simp]: $(\exists x \in succ\ k. P\ x) \longleftrightarrow P\ k \vee (\exists x \in k. P\ x)$
 ⟨proof⟩

lemma *One-hf-eq-succ*: $1 = succ\ 0$
 ⟨proof⟩

lemma *zero-hmem-one* [iff]: $x \in 1 \longleftrightarrow x = 0$
 ⟨proof⟩

lemma *hball-One* [simp]: $(\forall x \in 1. P\ x) = P\ 0$
 ⟨proof⟩

lemma *hbex-One* [simp]: $(\exists x \in 1. P\ x) = P\ 0$
 ⟨proof⟩

lemma *hpair-neq-succ* [simp]: $\langle x, y \rangle \neq succ\ k$
 ⟨proof⟩

lemma *succ-neq-hpair* [simp]: $succ\ k \neq \langle x, y \rangle$
 ⟨proof⟩

lemma *hpair-neq-one* [simp]: $\langle x, y \rangle \neq 1$
 ⟨proof⟩

lemma *one-neq-hpair* [simp]: $1 \neq \langle x, y \rangle$
 ⟨proof⟩

lemma *hmem-succ-self* [simp]: $k \in succ\ k$

<proof>

lemma *hmem-succ*: $l \in k \implies l \in \text{succ } k$
<proof>

Theorem 2.3.

lemma *Ord-0 [iff]*: *Ord 0*
<proof>

lemma *Ord-succ*: $\text{Ord}(k) \implies \text{Ord}(\text{succ}(k))$
<proof>

lemma *Ord-1 [iff]*: *Ord 1*
<proof>

lemma *OrdmemD*: $\text{Ord}(k) \implies j \in k \implies j \leq k$
<proof>

lemma *Ord-trans*: $\llbracket i \in j; j \in k; \text{Ord}(k) \rrbracket \implies i \in k$
<proof>

lemma *hmem-0-Ord*:
assumes $k: \text{Ord}(k)$ and $knz: k \neq 0$ shows $0 \in k$
<proof>

lemma *Ord-in-Ord*: $\llbracket \text{Ord}(k); m \in k \rrbracket \implies \text{Ord}(m)$
<proof>

2.1.3 Induction, Linearity, etc.

lemma *Ord-induct [consumes 1, case-names step]*:
assumes $k: \text{Ord}(k)$
and *step*: $\bigwedge x. \llbracket \text{Ord}(x); \bigwedge y. y \in x \implies P(y) \rrbracket \implies P(x)$
shows $P(k)$
<proof>

Theorem 2.4 (Comparability of ordinals).

lemma *Ord-linear*: $\text{Ord}(k) \implies \text{Ord}(l) \implies k \in l \vee k=l \vee l \in k$
<proof>

The trichotomy law for ordinals

lemma *Ord-linear-lt*:
assumes $o: \text{Ord}(k) \text{ Ord}(l)$
obtains $(lt) k \in l \mid (eq) k=l \mid (gt) l \in k$
<proof>

lemma *Ord-linear2*:
assumes $o: \text{Ord}(k) \text{ Ord}(l)$
obtains $(lt) k \in l \mid (ge) l \leq k$

<proof>

lemma *Ord-linear-le*:

assumes $o: \text{Ord}(k) \ \text{Ord}(l)$

obtains $(le) \ k \leq l \mid (ge) \ l \leq k$

<proof>

lemma *hunion-less-iff* [simp]: $[[\text{Ord } i; \text{Ord } j]] \implies i \sqcup j < k \longleftrightarrow i < k \wedge j < k$

<proof>

Theorem 2.5

lemma *Ord-mem-iff-lt*: $\text{Ord}(k) \implies \text{Ord}(l) \implies k \in l \longleftrightarrow k < l$

<proof>

lemma *le-succE*: $\text{succ } i \leq \text{succ } j \implies i \leq j$

<proof>

lemma *le-succ-iff*: $\text{Ord } i \implies \text{Ord } j \implies \text{succ } i \leq \text{succ } j \longleftrightarrow i \leq j$

<proof>

lemma *succ-inject-iff* [iff]: $\text{succ } i = \text{succ } j \longleftrightarrow i = j$

<proof>

lemma *mem-succ-iff* [simp]: $\text{Ord } j \implies \text{succ } i \in \text{succ } j \longleftrightarrow i \in j$

<proof>

lemma *Ord-mem-succ-cases*:

assumes $\text{Ord}(k) \ l \in k$

shows $\text{succ } l = k \vee \text{succ } l \in k$

<proof>

2.1.4 Supremum and Infimum

lemma *Ord-Union* [intro,simp]: $[[\bigwedge i. i \in A \implies \text{Ord}(i)]] \implies \text{Ord}(\bigsqcup A)$

<proof>

lemma *Ord-Inter* [intro,simp]:

assumes $\bigwedge i. i \in A \implies \text{Ord}(i)$ **shows** $\text{Ord}(\bigsqcap A)$

<proof>

Theorem 2.7. Every set x of ordinals is ordered by the binary relation $<$. Moreover if $x \neq 0$ then x has a smallest and a largest element.

lemma *hmem-Sup-Ords*: $[[A \neq 0; \bigwedge i. i \in A \implies \text{Ord}(i)]] \implies \bigsqcup A \in A$

<proof>

lemma *hmem-Inf-Ords*: $[[A \neq 0; \bigwedge i. i \in A \implies \text{Ord}(i)]] \implies \bigsqcap A \in A$

<proof>

lemma *Ord-pred*: $[[\text{Ord}(k); k \neq 0]] \implies \text{succ}(\bigsqcup k) = k$

<proof>

lemma *Ord-cases* [*cases type: hf, case-names 0 succ*]:
 assumes *Ok: Ord(k)*
 obtains $k = 0 \mid l$ **where** *Ord l succ l = k*
<proof>

lemma *Ord-induct2* [*consumes 1, case-names 0 succ, induct type: hf*]:
 assumes *k: Ord(k)*
 and $P: P\ 0 \wedge k. Ord\ k \implies P\ k \implies P\ (succ\ k)$
 shows $P\ k$
<proof>

lemma *Ord-succ-iff* [*iff*]: $Ord\ (succ\ k) = Ord\ k$
<proof>

lemma [*simp*]: $succ\ k \neq 0$
<proof>

lemma *Ord-Sup-succ-eq* [*simp*]: $Ord\ k \implies \sqcup (succ\ k) = k$
<proof>

lemma *Ord-lt-succ-iff-le*: $Ord\ k \implies Ord\ l \implies k < succ\ l \iff k \leq l$
<proof>

lemma *zero-in-Ord*: $Ord\ k \implies k=0 \vee 0 \in k$
<proof>

lemma *hpair-neq-Ord*: $Ord\ k \implies \langle x,y \rangle \neq k$
<proof>

lemma *hpair-neq-Ord'*: **assumes** *k: Ord k* **shows** $k \neq \langle x,y \rangle$
<proof>

lemma *Not-Ord-hpair* [*iff*]: $\neg Ord\ \langle x,y \rangle$
<proof>

lemma *is-hpair* [*simp*]: $is-hpair\ \langle x,y \rangle$
<proof>

lemma *Ord-not-hpair*: $Ord\ x \implies \neg is-hpair\ x$
<proof>

lemma *zero-in-succ* [*simp,intro*]: $Ord\ i \implies 0 \in succ\ i$
<proof>

2.1.5 Converting Between Ordinals and Natural Numbers

fun *ord-of* :: $nat \Rightarrow hf$

where

$ord\text{-of } 0 = 0$
| $ord\text{-of } (Suc\ k) = succ\ (ord\text{-of } k)$

lemma *Ord-ord-of [simp]: Ord (ord-of k)*
<proof>

lemma *ord-of-inject [iff]: ord-of i = ord-of j \longleftrightarrow i=j*
<proof>

lemma *ord-of-minus-1: n > 0 \implies ord-of n = succ (ord-of (n - 1))*
<proof>

definition *nat-of-ord :: hf \Rightarrow nat*
where *nat-of-ord x = (THE n. x = ord-of n)*

lemma *nat-of-ord-ord-of [simp]: nat-of-ord (ord-of n) = n*
<proof>

lemma *nat-of-ord-0 [simp]: nat-of-ord 0 = 0*
<proof>

lemma *ord-of-nat-of-ord [simp]: Ord x \implies ord-of (nat-of-ord x) = x*
<proof>

lemma *nat-of-ord-inject: Ord x \implies Ord y \implies nat-of-ord x = nat-of-ord y \longleftrightarrow x = y*
<proof>

lemma *nat-of-ord-succ [simp]: Ord x \implies nat-of-ord (succ x) = Suc (nat-of-ord x)*
<proof>

lemma *inj-ord-of: inj-on ord-of A*
<proof>

lemma *hfset-ord-of: hfset (ord-of n) = ord-of ‘ {0.. $<n$ }*
<proof>

lemma *bij-betw-ord-of: bij-betw ord-of {0.. $<n$ } (hfset (ord-of n))*
<proof>

lemma *bij-betw-ord-ofI:*
bij-betw h A {0.. $<n$ } \implies bij-betw (ord-of \circ h) A (hfset (ord-of n))
<proof>

2.2 Sequences and Ordinal Recursion

Definition 3.2 (Sequence).

definition $Seq :: hf \Rightarrow hf \Rightarrow bool$
where $Seq\ s\ k \longleftrightarrow hrelation\ s \wedge hfunction\ s \wedge k \leq hdomain\ s$

lemma $Seq-0$ [iff]: $Seq\ 0\ 0$
 ⟨proof⟩

lemma $Seq-succ-D$: $Seq\ s\ (succ\ k) \Longrightarrow Seq\ s\ k$
 ⟨proof⟩

lemma $Seq-Ord-D$: $Seq\ s\ k \Longrightarrow l \in k \Longrightarrow Ord\ k \Longrightarrow Seq\ s\ l$
 ⟨proof⟩

lemma $Seq-restr$: $Seq\ s\ (succ\ k) \Longrightarrow Seq\ (hrestrict\ s\ k)\ k$
 ⟨proof⟩

lemma $Seq-Ord-restr$: $\llbracket Seq\ s\ k; l \in k; Ord\ k \rrbracket \Longrightarrow Seq\ (hrestrict\ s\ l)\ l$
 ⟨proof⟩

lemma $Seq-ins$: $\llbracket Seq\ s\ k; k \notin hdomain\ s \rrbracket \Longrightarrow Seq\ (s \triangleleft \langle k, y \rangle)\ (succ\ k)$
 ⟨proof⟩

definition $insf :: hf \Rightarrow hf \Rightarrow hf \Rightarrow hf$
where $insf\ s\ k\ y \equiv nonrestrict\ s\ \{\!|k|\!\} \triangleleft \langle k, y \rangle$

lemma $hrelation-insf$: $hrelation\ s \Longrightarrow hrelation\ (insf\ s\ k\ y)$
 ⟨proof⟩

lemma $hfunction-insf$: $hfunction\ s \Longrightarrow hfunction\ (insf\ s\ k\ y)$
 ⟨proof⟩

lemma $hdomain-insf$: $k \leq hdomain\ s \Longrightarrow succ\ k \leq hdomain\ (insf\ s\ k\ y)$
 ⟨proof⟩

lemma $Seq-insf$: $Seq\ s\ k \Longrightarrow Seq\ (insf\ s\ k\ y)\ (succ\ k)$
 ⟨proof⟩

lemma $Seq-succ-iff$: $Seq\ s\ (succ\ k) \longleftrightarrow Seq\ s\ k \wedge (\exists y. \langle k, y \rangle \in s)$
 ⟨proof⟩

lemma $nonrestrictD$: $a \in nonrestrict\ s\ X \Longrightarrow a \in s$
 ⟨proof⟩

lemma $hpair-in-nonrestrict-iff$ [simp]:
 $\langle a, b \rangle \in nonrestrict\ s\ X \longleftrightarrow \langle a, b \rangle \in s \wedge \neg a \in X$
 ⟨proof⟩

lemma $app-nonrestrict-Seq$: $Seq\ s\ k \Longrightarrow z \notin X \Longrightarrow app\ (nonrestrict\ s\ X)\ z = app\ s\ z$
 ⟨proof⟩

lemma *app-insf-Seq*: $Seq\ s\ k \implies app\ (insf\ s\ k\ y)\ k = y$
 ⟨proof⟩

lemma *app-insf2-Seq*: $Seq\ s\ k \implies k' \neq k \implies app\ (insf\ s\ k\ y)\ k' = app\ s\ k'$
 ⟨proof⟩

lemma *app-insf-Seq-if*: $Seq\ s\ k \implies app\ (insf\ s\ k\ y)\ k' = (if\ k' = k\ then\ y\ else\ app\ s\ k')$
 ⟨proof⟩

lemma *Seq-imp-eq-app*: $\llbracket Seq\ s\ d; \langle x, y \rangle \in s \rrbracket \implies app\ s\ x = y$
 ⟨proof⟩

lemma *Seq-iff-app*: $\llbracket Seq\ s\ d; x \in d \rrbracket \implies \langle x, y \rangle \in s \longleftrightarrow app\ s\ x = y$
 ⟨proof⟩

lemma *Exists-iff-app*: $Seq\ s\ d \implies x \in d \implies (\exists y. \langle x, y \rangle \in s \wedge P\ y) = P\ (app\ s\ x)$
 ⟨proof⟩

lemma *Ord-trans2*: $\llbracket i2 \in i; i \in j; j \in k; Ord\ k \rrbracket \implies i2 \in k$
 ⟨proof⟩

definition *ord-rec-Seq* :: $hf \Rightarrow (hf \Rightarrow hf) \Rightarrow hf \Rightarrow hf \Rightarrow hf \Rightarrow bool$
where

$ord-rec-Seq\ T\ G\ s\ k\ y \longleftrightarrow$
 $(Seq\ s\ k \wedge y = G\ (app\ s\ (\bigsqcup k)) \wedge app\ s\ 0 = T \wedge$
 $(\forall n. succ\ n \in k \longrightarrow app\ s\ (succ\ n) = G\ (app\ s\ n)))$

lemma *Seq-succ-insf*:

assumes s : $Seq\ s\ (succ\ k)$ **shows** $\exists y. s = insf\ s\ k\ y$
 ⟨proof⟩

lemma *ord-rec-Seq-succ-iff*:

assumes k : $Ord\ k$ **and** knz : $k \neq 0$
shows $ord-rec-Seq\ T\ G\ s\ (succ\ k)\ z \longleftrightarrow (\exists s'\ y. ord-rec-Seq\ T\ G\ s'\ k\ y \wedge z = G\ y \wedge s = insf\ s'\ k\ y)$
 ⟨proof⟩

lemma *ord-rec-Seq-functional*:

$Ord\ k \implies k \neq 0 \implies ord-rec-Seq\ T\ G\ s\ k\ y \implies ord-rec-Seq\ T\ G\ s'\ k\ y' \implies y' = y$
 ⟨proof⟩

definition *ord-recp* :: $hf \Rightarrow (hf \Rightarrow hf) \Rightarrow (hf \Rightarrow hf) \Rightarrow hf \Rightarrow hf \Rightarrow bool$

where

$ord-recp\ T\ G\ H\ x\ y =$
 $(if\ x=0\ then\ y = T$

else
 if $\text{Ord}(x)$ then $\exists s. \text{ord-rec-Seq } T \ G \ H \ s \ x \ y$
 else $y = H \ x$

lemma *ord-rec-functional*: $\text{ord-rec } T \ G \ H \ x \ y \implies \text{ord-rec } T \ G \ H \ x \ y' \implies y' = y$
<proof>

lemma *ord-rec-succ-iff*:
assumes $k: \text{Ord } k$ **shows** $\text{ord-rec } T \ G \ H \ (\text{succ } k) \ z \longleftrightarrow (\exists y. z = G \ y \wedge \text{ord-rec } T \ G \ H \ k \ y)$
<proof>

definition *ord-rec* :: $hf \Rightarrow (hf \Rightarrow hf) \Rightarrow (hf \Rightarrow hf) \Rightarrow hf \Rightarrow hf$
where
 $\text{ord-rec } T \ G \ H \ x = (\text{THE } y. \text{ord-rec } T \ G \ H \ x \ y)$

lemma *ord-rec-0* [*simp*]: $\text{ord-rec } T \ G \ H \ 0 = T$
<proof>

lemma *ord-rec-total*: $\exists y. \text{ord-rec } T \ G \ H \ x \ y$
<proof>

lemma *ord-rec-succ* [*simp*]:
assumes $k: \text{Ord } k$ **shows** $\text{ord-rec } T \ G \ H \ (\text{succ } k) = G \ (\text{ord-rec } T \ G \ H \ k)$
<proof>

lemma *ord-rec-non* [*simp*]: $\neg \text{Ord } x \implies \text{ord-rec } T \ G \ H \ x = H \ x$
<proof>

end

Chapter 3

V-Sets, Epsilon Closure, Ranks

theory *Rank* **imports** *Ordinal*
begin

3.1 V-sets

Definition 4.1

definition *Vset* :: *hf* \Rightarrow *hf*
where *Vset* *x* = *ord-rec* 0 *HPow* ($\lambda z. 0$) *x*

lemma *Vset-0* [*simp*]: *Vset* 0 = 0
<proof>

lemma *Vset-succ* [*simp*]: *Ord* *k* \Longrightarrow *Vset* (*succ* *k*) = *HPow* (*Vset* *k*)
<proof>

lemma *Vset-non* [*simp*]: \neg *Ord* *x* \Longrightarrow *Vset* *x* = 0
<proof>

Theorem 4.2(a)

lemma *Vset-mono-strict*:
assumes *Ord* *m* *n* \in *m* **shows** *Vset* *n* < *Vset* *m*
<proof>

lemma *Vset-mono*: $[[$ *Ord* *m*; *n* \leq *m*]] \Longrightarrow *Vset* *n* \leq *Vset* *m*
<proof>

Theorem 4.2(b)

lemma *Vset-Transset*: *Ord* *m* \Longrightarrow *Transset* (*Vset* *m*)
<proof>

lemma *Ord-sup* [*simp*]: *Ord* *k* \Longrightarrow *Ord* *l* \Longrightarrow *Ord* (*k* \sqcup *l*)

<proof>

lemma *Ord-inf [simp]*: $Ord\ k \implies Ord\ l \implies Ord\ (k \sqcap l)$
<proof>

Theorem 4.3

lemma *Vset-universal*: $\exists n. Ord\ n \wedge x \in Vset\ n$
<proof>

3.2 Least Ordinal Operator

Definition 4.4. For every x , let $rank(x)$ be the least ordinal n such that...

lemma *Ord-minimal*:
 $Ord\ k \implies P\ k \implies \exists n. Ord\ n \wedge P\ n \wedge (\forall m. Ord\ m \wedge P\ m \implies n \leq m)$
<proof>

lemma *OrdLeastI*: $Ord\ k \implies P\ k \implies P(LEAST\ n. Ord\ n \wedge P\ n)$
<proof>

lemma *OrdLeast-le*: $Ord\ k \implies P\ k \implies (LEAST\ n. Ord\ n \wedge P\ n) \leq k$
<proof>

lemma *OrdLeast-Ord*:
assumes $Ord\ k\ P\ k$ **shows** $Ord(LEAST\ n. Ord\ n \wedge P\ n)$
<proof>

3.3 Rank Function

definition $rank :: hf \Rightarrow hf$
where $rank\ x = (LEAST\ n. Ord\ n \wedge x \in Vset\ (succ\ n))$

lemma *[simp]*: $rank\ 0 = 0$
<proof>

lemma *in-Vset-rank*: $a \in Vset(succ(rank\ a))$
<proof>

lemma *Ord-rank [simp]*: $Ord\ (rank\ a)$
<proof>

lemma *le-Vset-rank*: $a \leq Vset(rank\ a)$
<proof>

lemma *VsetI*: $succ(rank\ a) \leq k \implies Ord\ k \implies a \in Vset\ k$
<proof>

lemma *Vset-succ-rank-le*: $Ord\ k \implies a \in Vset\ (succ\ k) \implies rank\ a \leq k$
<proof>

lemma *Vset-rank-lt*: **assumes** $a: a \in Vset\ k$ **shows** $rank\ a < k$
 ⟨*proof*⟩

Theorem 4.5

theorem *rank-lt*: $a \in b \implies rank(a) < rank(b)$
 ⟨*proof*⟩

lemma *rank-mono*: $x \leq y \implies rank\ x \leq rank\ y$
 ⟨*proof*⟩

lemma *rank-sup* [*simp*]: $rank\ (a \sqcup b) = rank\ a \sqcup rank\ b$
 ⟨*proof*⟩

lemma *rank-singleton* [*simp*]: $rank\ \{a\} = succ(rank\ a)$
 ⟨*proof*⟩

lemma *rank-hinsert* [*simp*]: $rank\ (b \triangleleft a) = rank\ b \sqcup succ(rank\ a)$
 ⟨*proof*⟩

Definition 4.6. The transitive closure of x is the minimal transitive set y such that $x \leq y$.

3.4 Epsilon Closure

definition

eclose $:: hf \Rightarrow hf$ **where**
 $eclose\ X = \bigcap \{Y \in HPow(Vset\ (rank\ X)).\ Transset\ Y \wedge X \leq Y\}$

lemma *eclose-facts*:

shows *Transset-eclose*: $Transset\ (eclose\ X)$

and *le-eclose*: $X \leq eclose\ X$

⟨*proof*⟩

lemma *eclose-minimal*:

assumes $Y: Transset\ Y\ X \leq Y$ **shows** $eclose\ X \leq Y$

⟨*proof*⟩

lemma *eclose-0* [*simp*]: $eclose\ 0 = 0$

⟨*proof*⟩

lemma *eclose-sup* [*simp*]: $eclose\ (a \sqcup b) = eclose\ a \sqcup eclose\ b$

⟨*proof*⟩

lemma *eclose-singleton* [*simp*]: $eclose\ \{a\} = (eclose\ a) \triangleleft a$

⟨*proof*⟩

lemma *eclose-hinsert* [*simp*]: $eclose\ (b \triangleleft a) = eclose\ b \sqcup (eclose\ a \triangleleft a)$

⟨*proof*⟩

lemma *eclose-succ* [simp]: $eclose (succ a) = eclose a \triangleleft a$
 ⟨proof⟩

lemma *fst-in-eclose* [simp]: $x \in eclose \langle x, y \rangle$
 ⟨proof⟩

lemma *snd-in-eclose* [simp]: $y \in eclose \langle x, y \rangle$
 ⟨proof⟩

Theorem 4.7. $rank(x) = rank(cl(x))$.

lemma *rank-eclose* [simp]: $rank (eclose x) = rank x$
 ⟨proof⟩

3.5 Epsilon-Recursion

Theorem 4.9. Definition of a function by recursion on rank.

lemma *hmem-induct* [case-names step]:
assumes *ih*: $\bigwedge x. (\bigwedge y. y \in x \implies P y) \implies P x$ **shows** $P x$
 ⟨proof⟩

definition
hmem-rel :: $(hf * hf)$ set **where**
hmem-rel = $transcl \{(x,y). x \in y\}$

lemma *wf-hmem-rel*: *wf hmem-rel*
 ⟨proof⟩

lemma *hmem-eclose-le*: $y \in x \implies eclose y \leq eclose x$
 ⟨proof⟩

lemma *hmem-rel-iff-hmem-eclose*: $(x,y) \in hmem-rel \iff x \in eclose y$
 ⟨proof⟩

definition *hmemrec* :: $((hf \Rightarrow 'a) \Rightarrow hf \Rightarrow 'a) \Rightarrow hf \Rightarrow 'a$ **where**
hmemrec $G \equiv wfrec hmem-rel G$

definition *ecut* :: $(hf \Rightarrow 'a) \Rightarrow hf \Rightarrow hf \Rightarrow 'a$ **where**
ecut $f x \equiv (\lambda y. \text{if } y \in eclose x \text{ then } f y \text{ else undefined})$

lemma *hmemrec*: $hmemrec G a = G (ecut (hmemrec G) a) a$
 ⟨proof⟩

This form avoids giant explosions in proofs.

lemma *def-hmemrec*: $f \equiv hmemrec G \implies f a = G (ecut (hmemrec G) a) a$
 ⟨proof⟩

lemma *ecut-apply*: $y \in eclose x \implies ecut f x y = f y$

<proof>

lemma *RepFun-ecut*: $y \leq z \implies \text{RepFun } y (\text{ecut } f z) = \text{RepFun } y f$
<proof>

Now, a stronger induction rule, for the transitive closure of membership

lemma *hmem-rel-induct* [*case-names step*]:

assumes *ih*: $\bigwedge x. (\bigwedge y. (y, x) \in \text{hmem-rel} \implies P y) \implies P x$ **shows** $P x$
<proof>

lemma *rank-HUnion-less*: $x \neq 0 \implies \text{rank } (\bigsqcup x) < \text{rank } x$
<proof>

corollary *Sup-ne*: $x \neq 0 \implies \bigsqcup x \neq x$
<proof>

end

Chapter 4

An Application: Finite Automata

```
theory Finite-Automata imports Ordinal  
begin
```

The point of this example is that the HF sets are closed under disjoint sums and Cartesian products, allowing the theory of finite state machines to be developed without issues of polymorphism or any tricky encodings of states.

```
record 'a fsm = states :: hf  
          init :: hf  
          final :: hf  
          next :: hf  $\Rightarrow$  'a  $\Rightarrow$  hf  $\Rightarrow$  bool
```

```
inductive reaches :: ['a fsm, hf, 'a list, hf]  $\Rightarrow$  bool
```

```
where
```

```
  Nil: st  $\in$  states fsm  $\implies$  reaches fsm st [] st  
  | Cons: [next fsm st x st''; reaches fsm st'' xs st'; st  $\in$  states fsm]  $\implies$  reaches  
  fsm st (x#xs) st'
```

```
declare reaches.intros [intro]
```

```
inductive-simps reaches-Nil [simp]: reaches fsm st [] st'
```

```
inductive-simps reaches-Cons [simp]: reaches fsm st (x#xs) st'
```

```
lemma reaches-imp-states: reaches fsm st xs st'  $\implies$  st  $\in$  states fsm  $\wedge$  st'  $\in$  states  
fsm
```

```
  <proof>
```

```
lemma reaches-append-iff:
```

```
  reaches fsm st (xs@ys) st'  $\iff$  ( $\exists$  st''. reaches fsm st xs st''  $\wedge$  reaches fsm st''  
ys st')
```

```
  <proof>
```

```
definition accepts :: 'a fsm  $\Rightarrow$  'a list  $\Rightarrow$  bool where
```

$accepts\ fsm\ xs \equiv \exists st\ st'.\ reaches\ fsm\ st\ xs\ st' \wedge st \in init\ fsm \wedge st' \in final\ fsm$

definition *regular* :: 'a list set \Rightarrow bool **where**
 $regular\ S \equiv \exists fsm.\ S = \{xs.\ accepts\ fsm\ xs\}$

definition *Null* **where**
 $Null = (\states = 0,\ init = 0,\ final = 0,\ next = \lambda st\ x\ st'.\ False)$

theorem *regular-empty*: $regular\ \{\}$
 $\langle proof \rangle$

abbreviation *NullStr* **where**
 $NullStr \equiv (\states = 1,\ init = 1,\ final = 1,\ next = \lambda st\ x\ st'.\ False)$

theorem *regular-emptystr*: $regular\ \{\}\}$
 $\langle proof \rangle$

abbreviation *SingStr* **where**
 $SingStr\ a \equiv (\states = \{0,\ 1\},\ init = \{0\},\ final = \{1\},\ next = \lambda st\ x\ st'.\ st=0 \wedge x=a \wedge st'=1)$

theorem *regular-singstr*: $regular\ \{[a]\}$
 $\langle proof \rangle$

definition *Reverse* **where**
 $Reverse\ fsm = (\states = states\ fsm,\ init = final\ fsm,\ final = init\ fsm,\ next = \lambda st\ x\ st'.\ next\ fsm\ st'\ x\ st)$

lemma *Reverse-Reverse-ident* [*simp*]: $Reverse\ (Reverse\ fsm) = fsm$
 $\langle proof \rangle$

lemma *reaches-Reverse-iff* [*simp*]:
 $reaches\ (Reverse\ fsm)\ st\ (rev\ xs)\ st' \longleftrightarrow reaches\ fsm\ st'\ xs\ st$
 $\langle proof \rangle$

lemma *reaches-Reverse-iff2* [*simp*]:
 $reaches\ (Reverse\ fsm)\ st'\ xs\ st \longleftrightarrow reaches\ fsm\ st\ (rev\ xs)\ st'$
 $\langle proof \rangle$

lemma [*simp*]: $init\ (Reverse\ fsm) = final\ fsm$
 $\langle proof \rangle$

lemma [*simp*]: $final\ (Reverse\ fsm) = init\ fsm$
 $\langle proof \rangle$

lemma *accepts-Reverse*: $rev\ \{xs.\ accepts\ fsm\ xs\} = \{xs.\ accepts\ (Reverse\ fsm)\ xs\}$
 $\langle proof \rangle$

theorem *regular-rev*: $regular\ S \implies regular\ (rev\ 'S)$
 ⟨proof⟩

definition *Times where*

$Times\ fsm1\ fsm2 = (\downarrow states = states\ fsm1 * states\ fsm2,$
 $init = init\ fsm1 * init\ fsm2,$
 $final = final\ fsm1 * final\ fsm2,$
 $next = \lambda st\ x\ st'. (\exists st1\ st2\ st1'\ st2'. st = \langle st1, st2 \rangle \wedge st' =$
 $\langle st1', st2' \rangle \wedge$
 $next\ fsm1\ st1\ x\ st1' \wedge next\ fsm2\ st2\ x\ st2'))$

lemma *states-Times* [simp]: $states\ (Times\ fsm1\ fsm2) = states\ fsm1 * states\ fsm2$
 ⟨proof⟩

lemma *init-Times* [simp]: $init\ (Times\ fsm1\ fsm2) = init\ fsm1 * init\ fsm2$
 ⟨proof⟩

lemma *final-Times* [simp]: $final\ (Times\ fsm1\ fsm2) = final\ fsm1 * final\ fsm2$
 ⟨proof⟩

lemma *next-Times*: $next\ (Times\ fsm1\ fsm2)\ \langle st1, st2 \rangle\ x\ st' \longleftrightarrow$
 $(\exists st1'\ st2'. st' = \langle st1', st2' \rangle \wedge next\ fsm1\ st1\ x\ st1' \wedge next\ fsm2\ st2\ x\ st2')$
 ⟨proof⟩

lemma *reaches-Times-iff* [simp]:
 $reaches\ (Times\ fsm1\ fsm2)\ \langle st1, st2 \rangle\ xs\ \langle st1', st2' \rangle \longleftrightarrow$
 $reaches\ fsm1\ st1\ xs\ st1' \wedge reaches\ fsm2\ st2\ xs\ st2'$
 ⟨proof⟩

lemma *accepts-Times-iff* [simp]:
 $accepts\ (Times\ fsm1\ fsm2)\ xs \longleftrightarrow accepts\ fsm1\ xs \wedge accepts\ fsm2\ xs$
 ⟨proof⟩

theorem *regular-Int*:

assumes S : *regular* S **and** T : *regular* T **shows** *regular* $(S \cap T)$
 ⟨proof⟩

definition *Plus where*

$Plus\ fsm1\ fsm2 = (\downarrow states = states\ fsm1 + states\ fsm2,$
 $init = init\ fsm1 + init\ fsm2,$
 $final = final\ fsm1 + final\ fsm2,$
 $next = \lambda st\ x\ st'. (\exists st1\ st1'. st = Inl\ st1 \wedge st' = Inl\ st1' \wedge next$
 $fsm1\ st1\ x\ st1') \vee$
 $(\exists st2\ st2'. st = Inr\ st2 \wedge st' = Inr\ st2' \wedge next$
 $fsm2\ st2\ x\ st2'))$

lemma *states-Plus* [simp]: $states\ (Plus\ fsm1\ fsm2) = states\ fsm1 + states\ fsm2$
 ⟨proof⟩

lemma *init-Plus* [*simp*]: $\text{init } (\text{Plus fsm1 fsm2}) = \text{init fsm1} + \text{init fsm2}$
<proof>

lemma *final-Plus* [*simp*]: $\text{final } (\text{Plus fsm1 fsm2}) = \text{final fsm1} + \text{final fsm2}$
<proof>

lemma *next-Plus1*: $\text{next } (\text{Plus fsm1 fsm2}) (\text{Inl st1}) x st' \longleftrightarrow (\exists st1'. st' = \text{Inl } st1' \wedge \text{next fsm1 st1 x st1}')$
<proof>

lemma *next-Plus2*: $\text{next } (\text{Plus fsm1 fsm2}) (\text{Inr st2}) x st' \longleftrightarrow (\exists st2'. st' = \text{Inr } st2' \wedge \text{next fsm2 st2 x st2}')$
<proof>

lemma *reaches-Plus-iff1* [*simp*]:
 $\text{reaches } (\text{Plus fsm1 fsm2}) (\text{Inl st1}) xs st' \longleftrightarrow$
 $(\exists st1'. st' = \text{Inl } st1' \wedge \text{reaches fsm1 st1 xs st1}')$
<proof>

lemma *reaches-Plus-iff2* [*simp*]:
 $\text{reaches } (\text{Plus fsm1 fsm2}) (\text{Inr st2}) xs st' \longleftrightarrow$
 $(\exists st2'. st' = \text{Inr } st2' \wedge \text{reaches fsm2 st2 xs st2}')$
<proof>

lemma *reaches-Plus-iff* [*simp*]:
 $\text{reaches } (\text{Plus fsm1 fsm2}) st xs st' \longleftrightarrow$
 $(\exists st1 st1'. st = \text{Inl } st1 \wedge st' = \text{Inl } st1' \wedge \text{reaches fsm1 st1 xs st1}') \vee$
 $(\exists st2 st2'. st = \text{Inr } st2 \wedge st' = \text{Inr } st2' \wedge \text{reaches fsm2 st2 xs st2}')$
<proof>

lemma *accepts-Plus-iff* [*simp*]:
 $\text{accepts } (\text{Plus fsm1 fsm2}) xs \longleftrightarrow \text{accepts fsm1 xs} \vee \text{accepts fsm2 xs}$
<proof>

lemma *regular-Un*:
assumes *S*: regular *S* and *T*: regular *T* **shows** regular (*S* \cup *T*)
<proof>

end

theory *Finitary*

imports *Ordinal*

begin

class *finitary* =

fixes *hf-of* :: 'a \Rightarrow hf

assumes *inj*: *inj hf-of*

begin

lemma *hf-of-eq-iff* [*simp*]: $\text{hf-of } x = \text{hf-of } y \longleftrightarrow x=y$

<proof>

end

instantiation *unit* :: *finitary*

begin

definition *hf-of-unit-def*: *hf-of* (*u::unit*) $\equiv 0$

instance

<proof>

end

instantiation *bool* :: *finitary*

begin

definition *hf-of-bool-def*: *hf-of* *b* \equiv *if* *b* *then* 1 *else* 0

instance

<proof>

end

instantiation *nat* :: *finitary*

begin

definition *hf-of-nat-def*: *hf-of* \equiv *ord-of*

instance

<proof>

end

instantiation *int* :: *finitary*

begin

definition *hf-of-int-def*:

hf-of *i* \equiv *if* $i \geq 0$ (*int*) *then* $\langle 0, \text{hf-of} (\text{nat } i) \rangle$ *else* $\langle 1, \text{hf-of} (\text{nat } (-i)) \rangle$

instance

<proof>

end

Strings are char lists, and are not considered separately.

instantiation *char* :: *finitary*

begin

definition *hf-of-char-def*:

hf-of *x* \equiv *hf-of* (*of-char* *x* :: *nat*)

instance

<proof>

end

instantiation *prod* :: (*finitary*,*finitary*) *finitary*

begin

definition *hf-of-prod-def*:

hf-of $\equiv \lambda(x,y). \langle \text{hf-of } x, \text{hf-of } y \rangle$

instance

<proof>

end

instantiation *sum* :: (*finitary*,*finitary*) *finitary*

```

begin
  definition hf-of-sum-def:
    hf-of  $\equiv$  case-sum (HF.Inl o hf-of) (HF.Inr o hf-of)
  instance
    <proof>
end

instantiation option :: (finitary) finitary
begin
  definition hf-of-option-def:
    hf-of  $\equiv$  case-option 0 ( $\lambda x.$  {hf-of x})
  instance
    <proof>
end

instantiation list :: (finitary) finitary
begin
  primrec hf-of-list where
    hf-of-list Nil = 0
  | hf-of-list (x#xs) = <hf-of x, hf-of-list xs>

lemma [simp]: fixes x :: 'a list shows hf-of x = hf-of y  $\implies$  x = y
  <proof>

instance
  <proof>
end

end

```

Chapter 5

Addition, Sequences and their Concatenation

theory *OrdArith* imports *Rank*
begin

5.1 Generalised Addition — Also for Ordinals

Source: Laurence Kirby, Addition and multiplication of sets *Math. Log. Quart.* 53, No. 1, 52-65 (2007) / DOI 10.1002/malq.200610026 <http://faculty.baruch.cuny.edu/lkirby/mlqarticlejan2007.pdf>

definition

$\text{hadd} \quad :: hf \Rightarrow hf \Rightarrow hf \quad (\text{infixl } @+ \ 65) \quad \text{where}$
 $\text{hadd } x \equiv \text{hmemrec } (\lambda f z. x \sqcup \text{RepFun } z f)$

lemma *hadd*: $x @+ y = x \sqcup \text{RepFun } y (\lambda z. x @+ z)$
<proof>

lemma *hmem-hadd-E*:

assumes $l \in x @+ y$
obtains $l \in x \mid z \text{ where } z \in y \ l = x @+ z$
<proof>

lemma *hadd-0-right* [*simp*]: $x @+ 0 = x$
<proof>

lemma *hadd-hinsert-right*: $x @+ \text{hinsert } y z = \text{hinsert } (x @+ y) (x @+ z)$
<proof>

lemma *hadd-succ-right* [*simp*]: $x @+ \text{succ } y = \text{succ } (x @+ y)$
<proof>

lemma *not-add-less-right*: $\neg (x @+ y < x)$
<proof>

lemma *not-add-mem-right*: $\neg (x @+ y \in x)$

<proof>

lemma *hadd-0-left [simp]*: $0 @+ x = x$

<proof>

lemma *hadd-succ-left [simp]*: $Ord\ y \implies succ\ x @+ y = succ\ (x @+ y)$

<proof>

lemma *hadd-assoc*: $(x @+ y) @+ z = x @+ (y @+ z)$

<proof>

lemma *RepFun-hadd-disjoint*: $x \sqcap RepFun\ y\ ((@+) x) = 0$

<proof>

5.1.1 Cancellation laws for addition

lemma *Rep-le-Cancel*: $x \sqcup RepFun\ y\ ((@+) x) \leq x \sqcup RepFun\ z\ ((@+) x)$
 $\implies RepFun\ y\ ((@+) x) \leq RepFun\ z\ ((@+) x)$

<proof>

lemma *hadd-cancel-right [simp]*: $x @+ y = x @+ z \longleftrightarrow y = z$

<proof>

lemma *RepFun-hadd-cancel*: $RepFun\ y\ (\lambda z. x @+ z) = RepFun\ z\ (\lambda z. x @+ z)$
 $\longleftrightarrow y = z$

<proof>

lemma *hadd-hmem-cancel [simp]*: $x @+ y \in x @+ z \longleftrightarrow y \in z$

<proof>

lemma *ord-of-add*: $ord\text{-of}\ (i+j) = ord\text{-of}\ i @+ ord\text{-of}\ j$

<proof>

lemma *Ord-hadd*: $Ord\ x \implies Ord\ y \implies Ord\ (x @+ y)$

<proof>

lemma *hmem-self-hadd [simp]*: $k1 \in k1 @+ k2 \longleftrightarrow 0 \in k2$

<proof>

lemma *hadd-commute*: $Ord\ x \implies Ord\ y \implies x @+ y = y @+ x$

<proof>

lemma *hadd-cancel-left [simp]*: $Ord\ x \implies y @+ x = z @+ x \longleftrightarrow y = z$

<proof>

5.1.2 The predecessor function

definition *pred* :: $hf \Rightarrow hf$

where $\text{pred } x \equiv (\text{THE } y. \text{succ } y = x \vee x=0 \wedge y=0)$

lemma *pred-succ* [*simp*]: $\text{pred } (\text{succ } x) = x$
<proof>

lemma *pred-0* [*simp*]: $\text{pred } 0 = 0$
<proof>

lemma *succ-pred* [*simp*]: $\text{Ord } x \implies x \neq 0 \implies \text{succ } (\text{pred } x) = x$
<proof>

lemma *pred-mem* [*simp*]: $\text{Ord } x \implies x \neq 0 \implies \text{pred } x \in x$
<proof>

lemma *Ord-pred* [*simp*]: $\text{Ord } x \implies \text{Ord } (\text{pred } x)$
<proof>

lemma *hadd-pred-right*: $\text{Ord } y \implies y \neq 0 \implies x @+ \text{pred } y = \text{pred } (x @+ y)$
<proof>

lemma *Ord-pred-HUnion*: $\text{Ord}(k) \implies \text{pred } k = \bigsqcup k$
<proof>

5.2 A Concatentation Operation for Sequences

definition *shift* :: $hf \Rightarrow hf \Rightarrow hf$
where $\text{shift } f \text{ delta} = \{v . u \in f, \exists n y. u = \langle n, y \rangle \wedge v = \langle \text{delta } @+ n, y \rangle\}$

lemma *shiftD*: $x \in \text{shift } f \text{ delta} \implies \exists u. u \in f \wedge x = \langle \text{delta } @+ \text{hfst } u, \text{hsnd } u \rangle$
<proof>

lemma *hmem-shift-iff*: $\langle m, y \rangle \in \text{shift } f \text{ delta} \longleftrightarrow (\exists n. m = \text{delta } @+ n \wedge \langle n, y \rangle \in f)$
<proof>

lemma *hmem-shift-add-iff* [*simp*]: $\langle \text{delta } @+ n, y \rangle \in \text{shift } f \text{ delta} \longleftrightarrow \langle n, y \rangle \in f$
<proof>

lemma *hrelation-shift* [*simp*]: $\text{hrelation } (\text{shift } f \text{ delta})$
<proof>

lemma *app-shift* [*simp*]: $\text{app } (\text{shift } f \text{ delta}) (k @+ j) = \text{app } f j$
<proof>

lemma *hfunction-shift-iff* [*simp*]: $\text{hfunction } (\text{shift } f \text{ delta}) = \text{hfunction } f$
<proof>

lemma *hdomain-shift-add*: $\text{hdomain } (\text{shift } f \text{ delta}) = \{\text{delta } @+ n . n \in \text{hdomain } f\}$

<proof>

lemma *hdomain-shift-disjoint*: $\text{delta} \sqcap \text{hdomain} (\text{shift } f \text{ delta}) = 0$
<proof>

definition *seq-append* :: $hf \Rightarrow hf \Rightarrow hf \Rightarrow hf$
where *seq-append* $k f g \equiv \text{hrestrict } f k \sqcup \text{shift } g k$

lemma *hrelation-seq-append* [*simp*]: *hrelation* (*seq-append* $k f g$)
<proof>

lemma *Seq-append*:
assumes *Seq* $s1 k1$ *Seq* $s2 k2$
shows *Seq* (*seq-append* $k1 s1 s2$) ($k1 @+ k2$)
<proof>

lemma *app-hunion1*: $x \notin \text{hdomain } g \Longrightarrow \text{app } (f \sqcup g) x = \text{app } f x$
<proof>

lemma *app-hunion2*: $x \notin \text{hdomain } f \Longrightarrow \text{app } (f \sqcup g) x = \text{app } g x$
<proof>

lemma *Seq-append-app1*: *Seq* $s k \Longrightarrow l \in k \Longrightarrow \text{app } (\text{seq-append } k s s') l = \text{app } s l$
<proof>

lemma *Seq-append-app2*: *Seq* $s1 k1 \Longrightarrow \text{Seq } s2 k2 \Longrightarrow l = k1 @+ j \Longrightarrow \text{app } (\text{seq-append } k1 s1 s2) l = \text{app } s2 j$
<proof>

5.3 Nonempty sequences indexed by ordinals

definition *OrdDom* **where**
OrdDom $r \equiv \forall x y. \langle x, y \rangle \in r \longrightarrow \text{Ord } x$

lemma *OrdDom-insf*: $\llbracket \text{OrdDom } s; \text{Ord } k \rrbracket \Longrightarrow \text{OrdDom } (\text{insf } s (\text{succ } k) y)$
<proof>

lemma *OrdDom-hunion* [*simp*]: $\text{OrdDom } (s1 \sqcup s2) \longleftrightarrow \text{OrdDom } s1 \wedge \text{OrdDom } s2$
<proof>

lemma *OrdDom-hrestrict*: $\text{OrdDom } s \Longrightarrow \text{OrdDom } (\text{hrestrict } s A)$
<proof>

lemma *OrdDom-shift*: $\llbracket \text{OrdDom } s; \text{Ord } k \rrbracket \Longrightarrow \text{OrdDom } (\text{shift } s k)$
<proof>

A sequence of positive length ending with y

definition $LstSeq :: hf \Rightarrow hf \Rightarrow hf \Rightarrow bool$

where $LstSeq\ s\ k\ y \equiv Seq\ s\ (succ\ k) \wedge Ord\ k \wedge \langle k, y \rangle \in s \wedge OrdDom\ s$

lemma $LstSeq\ imp\ Seq\ succ: LstSeq\ s\ k\ y \Longrightarrow Seq\ s\ (succ\ k)$

$\langle proof \rangle$

lemma $LstSeq\ imp\ Seq\ same: LstSeq\ s\ k\ y \Longrightarrow Seq\ s\ k$

$\langle proof \rangle$

lemma $LstSeq\ imp\ Ord: LstSeq\ s\ k\ y \Longrightarrow Ord\ k$

$\langle proof \rangle$

lemma $LstSeq\ trunc: LstSeq\ s\ k\ y \Longrightarrow l \in k \Longrightarrow LstSeq\ s\ l\ (app\ s\ l)$

$\langle proof \rangle$

lemma $LstSeq\ insf: LstSeq\ s\ k\ z \Longrightarrow LstSeq\ (insf\ s\ (succ\ k)\ y)\ (succ\ k)\ y$

$\langle proof \rangle$

lemma $app\ insf\ LstSeq: LstSeq\ s\ k\ z \Longrightarrow app\ (insf\ s\ (succ\ k)\ y)\ (succ\ k) = y$

$\langle proof \rangle$

lemma $app\ insf2\ LstSeq: LstSeq\ s\ k\ z \Longrightarrow k' \neq succ\ k \Longrightarrow app\ (insf\ s\ (succ\ k)\ y)\ k' = app\ s\ k'$

$\langle proof \rangle$

lemma $app\ insf\ LstSeq\ if: LstSeq\ s\ k\ z \Longrightarrow app\ (insf\ s\ (succ\ k)\ y)\ k' = (if\ k' = succ\ k\ then\ y\ else\ app\ s\ k')$

$\langle proof \rangle$

lemma $LstSeq\ append\ app1:$

$LstSeq\ s\ k\ y \Longrightarrow l \in succ\ k \Longrightarrow app\ (seq\ append\ (succ\ k)\ s\ s')\ l = app\ s\ l$

$\langle proof \rangle$

lemma $LstSeq\ append\ app2:$

$\llbracket LstSeq\ s1\ k1\ y1; LstSeq\ s2\ k2\ y2; l = succ\ k1\ @+ j \rrbracket$

$\Longrightarrow app\ (seq\ append\ (succ\ k1)\ s1\ s2)\ l = app\ s2\ j$

$\langle proof \rangle$

lemma $Seq\ append\ pair:$

$\llbracket Seq\ s1\ k1; Seq\ s2\ (succ\ n); \langle n, y \rangle \in s2; Ord\ n \rrbracket \Longrightarrow \langle k1\ @+ n, y \rangle \in (seq\ append\ k1\ s1\ s2)$

$\langle proof \rangle$

lemma $Seq\ append\ OrdDom: \llbracket Ord\ k; OrdDom\ s1; OrdDom\ s2 \rrbracket \Longrightarrow OrdDom\ (seq\ append\ k\ s1\ s2)$

$\langle proof \rangle$

lemma $LstSeq\ append:$

$\llbracket LstSeq\ s1\ k1\ y1; LstSeq\ s2\ k2\ y2 \rrbracket \Longrightarrow LstSeq\ (seq\ append\ (succ\ k1)\ s1\ s2)\ (succ$

$(k1 \text{ @+ } k2)) \ y2$
 ⟨proof⟩

lemma *LstSeq-app [simp]*: $LstSeq \ s \ k \ y \implies app \ s \ k = y$
 ⟨proof⟩

5.3.1 Sequence-building operators

definition *Builds* :: $(hf \Rightarrow bool) \Rightarrow (hf \Rightarrow hf \Rightarrow hf \Rightarrow bool) \Rightarrow hf \Rightarrow hf \Rightarrow bool$
where $Builds \ B \ C \ s \ l \equiv B \ (app \ s \ l) \vee (\exists m \in l. \exists n \in l. C \ (app \ s \ l) \ (app \ s \ m) \ (app \ s \ n))$

definition *BuildSeq* :: $(hf \Rightarrow bool) \Rightarrow (hf \Rightarrow hf \Rightarrow hf \Rightarrow bool) \Rightarrow hf \Rightarrow hf \Rightarrow hf \Rightarrow bool$
where $BuildSeq \ B \ C \ s \ k \ y \equiv LstSeq \ s \ k \ y \wedge (\forall l \in succ \ k. Builds \ B \ C \ s \ l)$

lemma *BuildSeqI*: $LstSeq \ s \ k \ y \implies (\bigwedge l. l \in succ \ k \implies Builds \ B \ C \ s \ l) \implies BuildSeq \ B \ C \ s \ k \ y$
 ⟨proof⟩

lemma *BuildSeq-imp-LstSeq*: $BuildSeq \ B \ C \ s \ k \ y \implies LstSeq \ s \ k \ y$
 ⟨proof⟩

lemma *BuildSeq-imp-Seq*: $BuildSeq \ B \ C \ s \ k \ y \implies Seq \ s \ (succ \ k)$
 ⟨proof⟩

lemma *BuildSeq-conj-distrib*:
 $BuildSeq \ (\lambda x. B \ x \wedge P \ x) \ (\lambda x \ y \ z. C \ x \ y \ z \wedge P \ x) \ s \ k \ y \longleftrightarrow BuildSeq \ B \ C \ s \ k \ y \wedge (\forall l \in succ \ k. P \ (app \ s \ l))$
 ⟨proof⟩

lemma *BuildSeq-mono*:
assumes $y: BuildSeq \ B \ C \ s \ k \ y$
and $B: \bigwedge x. B \ x \implies B' \ x$ **and** $C: \bigwedge x \ y \ z. C \ x \ y \ z \implies C' \ x \ y \ z$
shows $BuildSeq \ B' \ C' \ s \ k \ y$
 ⟨proof⟩

lemma *BuildSeq-trunc*:
assumes $b: BuildSeq \ B \ C \ s \ k \ y$
and $l: l \in k$
shows $BuildSeq \ B \ C \ s \ l \ (app \ s \ l)$
 ⟨proof⟩

5.3.2 Showing that Sequences can be Constructed

lemma *Builds-insf*: $Builds \ B \ C \ s \ l \implies LstSeq \ s \ k \ z \implies l \in succ \ k \implies Builds \ B \ C \ (insf \ s \ (succ \ k) \ y) \ l$
 ⟨proof⟩

lemma *BuildSeq-insf*:

assumes $b: \text{BuildSeq } B \ C \ s \ k \ z$
and $m: m \in \text{succ } k$
and $n: n \in \text{succ } k$
and $y: B \ y \ \vee \ C \ y \ (\text{app } s \ m) \ (\text{app } s \ n)$
shows $\text{BuildSeq } B \ C \ (\text{insf } s \ (\text{succ } k) \ y) \ (\text{succ } k) \ y$
 $\langle \text{proof} \rangle$

lemma *BuildSeq-insf1*:
assumes $b: \text{BuildSeq } B \ C \ s \ k \ z$
and $y: B \ y$
shows $\text{BuildSeq } B \ C \ (\text{insf } s \ (\text{succ } k) \ y) \ (\text{succ } k) \ y$
 $\langle \text{proof} \rangle$

lemma *BuildSeq-insf2*:
assumes $b: \text{BuildSeq } B \ C \ s \ k \ z$
and $m: m \in k$
and $n: n \in k$
and $y: C \ y \ (\text{app } s \ m) \ (\text{app } s \ n)$
shows $\text{BuildSeq } B \ C \ (\text{insf } s \ (\text{succ } k) \ y) \ (\text{succ } k) \ y$
 $\langle \text{proof} \rangle$

lemma *BuildSeq-append*:
assumes $s1: \text{BuildSeq } B \ C \ s1 \ k1 \ y1$ **and** $s2: \text{BuildSeq } B \ C \ s2 \ k2 \ y2$
shows $\text{BuildSeq } B \ C \ (\text{seq-append } (\text{succ } k1) \ s1 \ s2) \ (\text{succ } (k1 \ @+ \ k2)) \ y2$
 $\langle \text{proof} \rangle$

lemma *BuildSeq-combine*:
assumes $b1: \text{BuildSeq } B \ C \ s1 \ k1 \ y1$ **and** $b2: \text{BuildSeq } B \ C \ s2 \ k2 \ y2$
and $y: C \ y \ y1 \ y2$
shows $\text{BuildSeq } B \ C \ (\text{insf } (\text{seq-append } (\text{succ } k1) \ s1 \ s2) \ (\text{succ } (\text{succ } (k1 \ @+ \ k2))))$
 $y \ (\text{succ } (\text{succ } (k1 \ @+ \ k2))) \ y$
 $\langle \text{proof} \rangle$

lemma *LstSeq-1*: $\text{LstSeq } \{\langle 0, y \rangle\} \ 0 \ y$
 $\langle \text{proof} \rangle$

lemma *BuildSeq-1*: $B \ y \ \Longrightarrow \ \text{BuildSeq } B \ C \ \{\langle 0, y \rangle\} \ 0 \ y$
 $\langle \text{proof} \rangle$

lemma *BuildSeq-exI*: $B \ t \ \Longrightarrow \ \exists \ s \ k. \ \text{BuildSeq } B \ C \ s \ k \ t$
 $\langle \text{proof} \rangle$

5.3.3 Proving Properties of Given Sequences

lemma *BuildSeq-succ-E*:
assumes $s: \text{BuildSeq } B \ C \ s \ k \ y$
obtains $B \ y \ | \ m \ n$ **where** $m \in k \ n \in k \ C \ y \ (\text{app } s \ m) \ (\text{app } s \ n)$
 $\langle \text{proof} \rangle$

lemma *BuildSeq-induct* [consumes 1, case-names B C]:

assumes *major*: *BuildSeq* B C s k a

and B: $\bigwedge x. B x \implies P x$

and C: $\bigwedge x y z. C x y z \implies P y \implies P z \implies P x$

shows P a

<proof>

definition *BuildSeq2* :: $[[hf, hf] \Rightarrow bool, [hf, hf, hf, hf, hf, hf] \Rightarrow bool, hf, hf, hf, hf] \Rightarrow bool$

$\Rightarrow bool$

where *BuildSeq2* B C s k y y' \equiv

BuildSeq ($\lambda p. \exists x x'. p = \langle x, x' \rangle \wedge B x x'$)

$(\lambda p q r. \exists x x' y y' z z'. p = \langle x, x' \rangle \wedge q = \langle y, y' \rangle \wedge r = \langle z, z' \rangle \wedge C x x' y y' z z')$

s k $\langle y, y' \rangle$

lemma *BuildSeq2-combine*:

assumes b1: *BuildSeq2* B C s1 k1 y1 y1' **and** b2: *BuildSeq2* B C s2 k2 y2 y2'

and y: C y y' y1 y1' y2 y2'

shows *BuildSeq2* B C (*insf* (*seq-append* (*succ* k1) s1 s2) (*succ* (*succ* (k1 @+ k2)))) $\langle y, y' \rangle$

(*succ* (*succ* (k1 @+ k2))) y y'

<proof>

lemma *BuildSeq2-1*: B y y' \implies *BuildSeq2* B C $\{\langle 0, y, y' \rangle\}$ 0 y y'

<proof>

lemma *BuildSeq2-exI*: B t t' \implies $\exists s k. \text{BuildSeq2 } B C s k t t'$

<proof>

lemma *BuildSeq2-induct* [consumes 1, case-names B C]:

assumes *BuildSeq2* B C s k a a'

and B: $\bigwedge x x'. B x x' \implies P x x'$

and C: $\bigwedge x x' y y' z z'. C x x' y y' z z' \implies P y y' \implies P z z' \implies P x x'$

shows P a a'

<proof>

definition *BuildSeq3*

:: $[[hf, hf, hf] \Rightarrow bool, [hf, hf, hf, hf, hf, hf, hf, hf, hf, hf] \Rightarrow bool, hf, hf, hf, hf, hf] \Rightarrow bool$

where *BuildSeq3* B C s k y y' y'' \equiv

BuildSeq ($\lambda p. \exists x x' x''. p = \langle x, x', x'' \rangle \wedge B x x' x''$)

$(\lambda p q r. \exists x x' x'' y y' y'' z z' z''.$

$p = \langle x, x', x'' \rangle \wedge q = \langle y, y', y'' \rangle \wedge r = \langle z, z', z'' \rangle \wedge$

$C x x' x'' y y' y'' z z' z''$)

s k $\langle y, y', y'' \rangle$

lemma *BuildSeq3-combine*:

assumes b1: *BuildSeq3* B C s1 k1 y1 y1' y1'' **and** b2: *BuildSeq3* B C s2 k2 y2 y2' y2''

and $y: C\ y\ y'\ y''\ y1\ y1'\ y1''\ y2\ y2'\ y2''$
shows $BuildSeq3\ B\ C\ (insf\ (seq-append\ (succ\ k1)\ s1\ s2)\ (succ\ (succ\ (k1\ @+\ k2))))\ \langle y,\ y',\ y'' \rangle$
 $(succ\ (succ\ (k1\ @+\ k2)))\ y\ y'\ y''$
 $\langle proof \rangle$

lemma $BuildSeq3-1: B\ y\ y'\ y'' \implies BuildSeq3\ B\ C\ \{\{0,\ y,\ y',\ y''\}\}\ 0\ y\ y'\ y''$
 $\langle proof \rangle$

lemma $BuildSeq3-exI: B\ t\ t'\ t'' \implies \exists\ s\ k.\ BuildSeq3\ B\ C\ s\ k\ t\ t'\ t''$
 $\langle proof \rangle$

lemma $BuildSeq3-induct$ [*consumes 1, case-names B C*]:
assumes $BuildSeq3\ B\ C\ s\ k\ a\ a''$
and $B: \bigwedge x\ x'\ x''. B\ x\ x'\ x'' \implies P\ x\ x'\ x''$
and $C: \bigwedge x\ x'\ x''\ y\ y'\ y''\ z\ z'\ z''. C\ x\ x'\ x''\ y\ y'\ y''\ z\ z'\ z'' \implies P\ y\ y'\ y'' \implies P\ z\ z'\ z'' \implies P\ x\ x'\ x''$
shows $P\ a\ a'\ a''$
 $\langle proof \rangle$

5.4 A Unique Predecessor for every non-empty set

lemma $Rep-hf-0$ [*simp*]: $Rep-hf\ 0 = 0$
 $\langle proof \rangle$

lemma $hmem-imp-less: x \in y \implies Rep-hf\ x < Rep-hf\ y$
 $\langle proof \rangle$

lemma $hsubset-imp-le$:
assumes $x \leq y$ **shows** $Rep-hf\ x \leq Rep-hf\ y$
 $\langle proof \rangle$

lemma $diff-hmem-imp-less: \text{assumes } x \in y \text{ shows } Rep-hf\ (y - \{x\}) < Rep-hf\ y$
 $\langle proof \rangle$

definition $least :: hf \Rightarrow hf$
where $least\ a \equiv (THE\ x.\ x \in a \wedge (\forall y.\ y \in a \longrightarrow Rep-hf\ x \leq Rep-hf\ y))$

lemma $least-equality$:
assumes $x \in a$ **and** $\bigwedge y.\ y \in a \implies Rep-hf\ x \leq Rep-hf\ y$
shows $least\ a = x$
 $\langle proof \rangle$

lemma $leastI2-order$:
assumes $x \in a$
and $\bigwedge y.\ y \in a \implies Rep-hf\ x \leq Rep-hf\ y$
and $\bigwedge z.\ z \in a \implies \forall y.\ y \in a \longrightarrow Rep-hf\ z \leq Rep-hf\ y \implies Q\ z$
shows $Q\ (least\ a)$
 $\langle proof \rangle$

lemma *nonempty-imp-ex-least*: $a \neq 0 \implies \exists x. x \in a \wedge (\forall y. y \in a \longrightarrow \text{Rep-hf } x \leq \text{Rep-hf } y)$
<proof>

lemma *least-hmem*: $a \neq 0 \implies \text{least } a \in a$
<proof>

end

Bibliography

- [1] L. Kirby. Addition and multiplication of sets. *Mathematical Logic Quarterly*, 53(1):52–65, 2007.
- [2] S. Świerczkowski. Finite sets and Gödel’s incompleteness theorems. *Dissertationes Mathematicae*, 422:1–58, 2003. <http://journals.impan.gov.pl/dm/Inf/422-0-1.html>.