

ZF

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December 3, 2009

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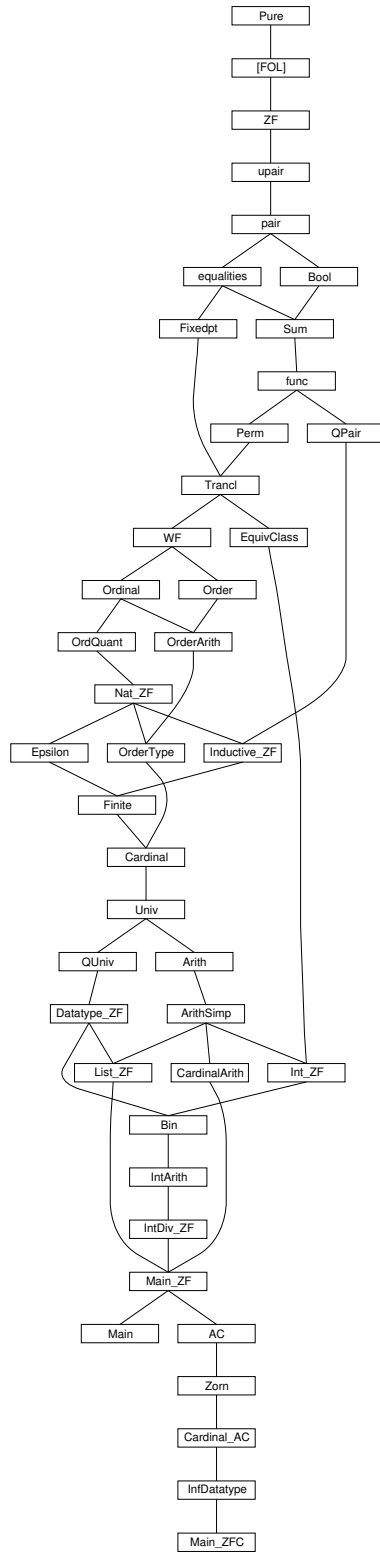
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1 ZF: Zermelo-Fraenkel Set Theory

theory *ZF* **imports** *FOL* **begin**

$\langle ML \rangle$

global

typedecl *i*

arities *i* :: *term*

consts

0 :: *i* (0) — the empty set
Pow :: *i* => *i* — power sets
Inf :: *i* — infinite set

Bounded Quantifiers

consts

Ball :: [*i*, *i* => *o*] => *o*
Bex :: [*i*, *i* => *o*] => *o*

General Union and Intersection

consts

Union :: *i* => *i*
Inter :: *i* => *i*

Variations on Replacement

consts

PrimReplace :: [*i*, [*i*, *i*] => *o*] => *i*
Replace :: [*i*, [*i*, *i*] => *o*] => *i*
RepFun :: [*i*, *i* => *i*] => *i*
Collect :: [*i*, *i* => *o*] => *i*

Definite descriptions – via Replace over the set "1"

consts

The :: (*i* => *o*) => *i* (**binder** *THE* 10)
If :: [*o*, *i*, *i*] => *i* ((*if* (-)/ *then* (-)/ *else* (-)) [10] 10)

abbreviation (*input*)

old-if :: [*o*, *i*, *i*] => *i* (*if* '(-,-,-')) **where**
if(*P*,*a*,*b*) == *If*(*P*,*a*,*b*)

Finite Sets

consts

Upair :: [*i*, *i*] => *i*
cons :: [*i*, *i*] => *i*
succ :: *i* => *i*

Ordered Pairing

consts

Pair :: $[i, i] \Rightarrow i$
fst :: $i \Rightarrow i$
snd :: $i \Rightarrow i$
split :: $[[i, i] \Rightarrow 'a, i] \Rightarrow 'a::\{\}$ — for pattern-matching

Sigma and Pi Operators

consts

Sigma :: $[i, i \Rightarrow i] \Rightarrow i$
Pi :: $[i, i \Rightarrow i] \Rightarrow i$

Relations and Functions

consts

domain :: $i \Rightarrow i$
range :: $i \Rightarrow i$
field :: $i \Rightarrow i$
converse :: $i \Rightarrow i$
relation :: $i \Rightarrow o$ — recognizes sets of pairs
function :: $i \Rightarrow o$ — recognizes functions; can have non-pairs
Lambda :: $[i, i \Rightarrow i] \Rightarrow i$
restrict :: $[i, i] \Rightarrow i$

Infixes in order of decreasing precedence

consts

Image :: $[i, i] \Rightarrow i$ (**infixl** “ 90) — image
vimage :: $[i, i] \Rightarrow i$ (**infixl** -“ 90) — inverse image
apply :: $[i, i] \Rightarrow i$ (**infixl** ‘ 90) — function application
Int :: $[i, i] \Rightarrow i$ (**infixl** *Int* 70) — binary intersection
Un :: $[i, i] \Rightarrow i$ (**infixl** *Un* 65) — binary union
Diff :: $[i, i] \Rightarrow i$ (**infixl** - 65) — set difference
Subset :: $[i, i] \Rightarrow o$ (**infixl** <= 50) — subset relation
mem :: $[i, i] \Rightarrow o$ (**infixl** : 50) — membership relation

abbreviation

not-mem :: $[i, i] \Rightarrow o$ (**infixl** ~: 50) — negated membership relation
where $x \sim: y == \sim (x : y)$

abbreviation

cart-prod :: $[i, i] \Rightarrow i$ (**infixr** * 80) — Cartesian product
where $A * B == \text{Sigma}(A, \%-. B)$

abbreviation

function-space :: $[i, i] \Rightarrow i$ (**infixr** -> 60) — function space
where $A -> B == \text{Pi}(A, \%-. B)$

nonterminals *is patterns*

syntax

```

:: i => is          (-)
@Enum    :: [i, is] => is      (-, / -)

@Finset  :: is => i           ({(-)})
@Tuple   :: [i, is] => i       (<(-, / -)>)
@Collect :: [pttrn, i, o] => i  ((1{- . / -}) )
@Replace :: [pttrn, pttrn, i, o] => i ((1{- . / - : -, -}) )
@RepFun  :: [i, pttrn, i] => i  ((1{- . / - : -}) [51,0,51])
@INTER   :: [pttrn, i, i] => i  ((3INT -:- / -) 10)
@UNION   :: [pttrn, i, i] => i  ((3UN -:- / -) 10)
@PROD    :: [pttrn, i, i] => i  ((3PROD -:- / -) 10)
@SUM     :: [pttrn, i, i] => i  ((3SUM -:- / -) 10)
@lam     :: [pttrn, i, i] => i  ((3lam -:- / -) 10)
@Ball    :: [pttrn, i, o] => o  ((3ALL -:- / -) 10)
@Bex     :: [pttrn, i, o] => o  ((3EX -:- / -) 10)

```

```

@pattern :: patterns => pttrn      (<->)
          :: pttrn => patterns      (-)
@patterns :: [pttrn, patterns] => patterns (-, / -)

```

translations

```

{x, xs} == cons(x, {xs})
{x}      == cons(x, 0)
{x:A. P} == Collect(A, %x. P)
{y. x:A. Q} == Replace(A, %x y. Q)
{b. x:A} == RepFun(A, %x. b)
INT x:A. B == Inter({B. x:A})
UN x:A. B == Union({B. x:A})
PROD x:A. B == Pi(A, %x. B)
SUM x:A. B == Sigma(A, %x. B)
lam x:A. f == Lambda(A, %x. f)
ALL x:A. P == Ball(A, %x. P)
EX x:A. P == Bex(A, %x. P)

<x, y, z> == <x, <y, z>>
<x, y>    == Pair(x, y)
%<x,y,zs>.b == split(%x <y,zs>.b)
%<x,y>.b   == split(%x y. b)

```

notation (*xsymbols*)

```

cart-prod (infixr × 80) and
Int       (infixl ∩ 70) and
Un        (infixl ∪ 65) and

```

function-space (**infixr** \rightarrow 60) and
Subset (**infixl** \subseteq 50) and
mem (**infixl** \in 50) and
not-mem (**infixl** \notin 50) and
Union (\bigcup - [90] 90) and
Inter (\bigcap - [90] 90)

syntax (*xsymbols*)

@Collect :: [pttrn, i, o] => i ((1{- ∈ - ./ -}))
 @Replace :: [pttrn, pttrn, i, o] => i ((1{- ./ - ∈ -, -}))
 @RepFun :: [i, pttrn, i] => i ((1{- ./ - ∈ -}) [51,0,51])
 @UNION :: [pttrn, i, i] => i ((3 \bigcup -∈-./ -) 10)
 @INTER :: [pttrn, i, i] => i ((3 \bigcap -∈-./ -) 10)
 @PROD :: [pttrn, i, i] => i ((3 Π -∈-./ -) 10)
 @SUM :: [pttrn, i, i] => i ((3 Σ -∈-./ -) 10)
 @lam :: [pttrn, i, i] => i ((3 λ -∈-./ -) 10)
 @Ball :: [pttrn, i, o] => o ((3 \forall -∈-./ -) 10)
 @Bex :: [pttrn, i, o] => o ((3 \exists -∈-./ -) 10)
 @Tuple :: [i, is] => i (({-./ -}))
 @pattern :: patterns => pttrn ((-))

notation (*HTML output*)

cart-prod (**infixr** \times 80) and
Int (**infixl** \cap 70) and
Un (**infixl** \cup 65) and
Subset (**infixl** \subseteq 50) and
mem (**infixl** \in 50) and
not-mem (**infixl** \notin 50) and
Union (\bigcup - [90] 90) and
Inter (\bigcap - [90] 90)

syntax (*HTML output*)

@Collect :: [pttrn, i, o] => i ((1{- ∈ - ./ -}))
 @Replace :: [pttrn, pttrn, i, o] => i ((1{- ./ - ∈ -, -}))
 @RepFun :: [i, pttrn, i] => i ((1{- ./ - ∈ -}) [51,0,51])
 @UNION :: [pttrn, i, i] => i ((3 \bigcup -∈-./ -) 10)
 @INTER :: [pttrn, i, i] => i ((3 \bigcap -∈-./ -) 10)
 @PROD :: [pttrn, i, i] => i ((3 Π -∈-./ -) 10)
 @SUM :: [pttrn, i, i] => i ((3 Σ -∈-./ -) 10)
 @lam :: [pttrn, i, i] => i ((3 λ -∈-./ -) 10)
 @Ball :: [pttrn, i, o] => o ((3 \forall -∈-./ -) 10)
 @Bex :: [pttrn, i, o] => o ((3 \exists -∈-./ -) 10)
 @Tuple :: [i, is] => i (({-./ -}))
 @pattern :: patterns => pttrn ((-))

finalconsts

0 Pow Inf Union PrimReplace mem

defs

Ball-def: $Ball(A, P) == \forall x. x \in A \rightarrow P(x)$

Bex-def: $Bex(A, P) == \exists x. x \in A \ \& \ P(x)$

subset-def: $A \leq B == \forall x \in A. x \in B$

local

axioms

extension: $A = B \leftrightarrow A \leq B \ \& \ B \leq A$

Union-iff: $A \in Union(C) \leftrightarrow (\exists B \in C. A \in B)$

Pow-iff: $A \in Pow(B) \leftrightarrow A \leq B$

infinity: $0 \in Inf \ \& \ (\forall y \in Inf. succ(y) \in Inf)$

foundation: $A = 0 \mid (\exists x \in A. \forall y \in x. y \sim A)$

replacement: $(\forall x \in A. \forall y \ z. P(x, y) \ \& \ P(x, z) \rightarrow y = z) \implies$
 $b \in PrimReplace(A, P) \leftrightarrow (\exists x \in A. P(x, b))$

defs

Replace-def: $Replace(A, P) == PrimReplace(A, \lambda x y. (EX!z. P(x, z)) \ \& \ P(x, y))$

RepFun-def: $RepFun(A, f) == \{y \mid x \in A, y = f(x)\}$

Collect-def: $Collect(A, P) == \{y \mid x \in A, x = y \ \& \ P(x)\}$

Upair-def: $Upair(a, b) == \{y. x \in Pow(Pow(0)), (x = 0 \ \& \ y = a) \mid (x = Pow(0) \ \& \ y = b)\}$

cons-def: $\text{cons}(a,A) == \text{Upair}(a,a) \text{ Un } A$
succ-def: $\text{succ}(i) == \text{cons}(i, i)$

Diff-def: $A - B == \{ x \in A . \sim(x \in B) \}$
Inter-def: $\text{Inter}(A) == \{ x \in \text{Union}(A) . \forall y \in A. x \in y \}$
Un-def: $A \text{ Un } B == \text{Union}(\text{Upair}(A,B))$
Int-def: $A \text{ Int } B == \text{Inter}(\text{Upair}(A,B))$

the-def: $\text{The}(P) == \text{Union}(\{y . x \in \{0\}, P(y)\})$
if-def: $\text{if}(P,a,b) == \text{THE } z. P \ \& \ z=a \mid \sim P \ \& \ z=b$

Pair-def: $\langle a,b \rangle == \{\{a,a\}, \{a,b\}\}$
fst-def: $\text{fst}(p) == \text{THE } a. \exists b. p = \langle a,b \rangle$
snd-def: $\text{snd}(p) == \text{THE } b. \exists a. p = \langle a,b \rangle$
split-def: $\text{split}(c) == \%p. c(\text{fst}(p), \text{snd}(p))$
Sigma-def: $\text{Sigma}(A,B) == \bigcup x \in A. \bigcup y \in B(x). \{ \langle x,y \rangle \}$

converse-def: $\text{converse}(r) == \{z. w \in r, \exists x y. w = \langle x,y \rangle \ \& \ z = \langle y,x \rangle\}$

domain-def: $\text{domain}(r) == \{x. w \in r, \exists y. w = \langle x,y \rangle\}$
range-def: $\text{range}(r) == \text{domain}(\text{converse}(r))$
field-def: $\text{field}(r) == \text{domain}(r) \text{ Un } \text{range}(r)$
relation-def: $\text{relation}(r) == \forall z \in r. \exists x y. z = \langle x,y \rangle$
function-def: $\text{function}(r) ==$
 $\quad \forall x y. \langle x,y \rangle : r \dashrightarrow (\forall y'. \langle x,y' \rangle : r \dashrightarrow y=y')$
image-def: $r \text{ `` } A == \{y : \text{range}(r) . \exists x \in A. \langle x,y \rangle : r\}$
vimage-def: $r \text{ -`` } A == \text{converse}(r) \text{ `` } A$

lam-def: $\text{Lambda}(A,b) == \{ \langle x,b(x) \rangle . x \in A \}$
apply-def: $f'a == \text{Union}(f'\{a\})$
Pi-def: $\text{Pi}(A,B) == \{f \in \text{Pow}(\text{Sigma}(A,B)). A \leq \text{domain}(f) \ \& \ \text{function}(f)\}$

restrict-def: $\text{restrict}(r,A) == \{z : r. \exists x \in A. \exists y. z = \langle x,y \rangle\}$

1.1 Substitution

lemma *subst-elem:* $[| \ b \in A; \ a=b \ |] ==> a \in A$
<proof>

1.2 Bounded universal quantifier

lemma *ballI* [*intro!*]: $[\![\! \! x. x \in A \implies P(x) \! \!]\!] \implies \forall x \in A. P(x)$
 $\langle proof \rangle$

lemmas *strip* = *impI allI ballI*

lemma *bspec* [*dest?*]: $[\![\forall x \in A. P(x); x: A \!]\!] \implies P(x)$
 $\langle proof \rangle$

lemma *rev-ballE* [*elim*]:
 $[\![\forall x \in A. P(x); x \sim : A \implies Q; P(x) \implies Q \!]\!] \implies Q$
 $\langle proof \rangle$

lemma *ballE*: $[\![\forall x \in A. P(x); P(x) \implies Q; x \sim : A \implies Q \!]\!] \implies Q$
 $\langle proof \rangle$

lemma *rev-bspec*: $[\![x: A; \forall x \in A. P(x) \!]\!] \implies P(x)$
 $\langle proof \rangle$

lemma *ball-triv* [*simp*]: $(\forall x \in A. P) <-> ((\exists x. x \in A) \dashv\dashv P)$
 $\langle proof \rangle$

lemma *ball-cong* [*cong*]:
 $[\![A=A'; \! \! x. x \in A' \implies P(x) <-> P'(x) \!]\!] \implies (\forall x \in A. P(x)) <-> (\forall x \in A'. P'(x))$
 $\langle proof \rangle$

lemma *atomize-ball*:
 $(\! \! x. x \in A \implies P(x)) == \text{Trueprop } (\forall x \in A. P(x))$
 $\langle proof \rangle$

lemmas [*symmetric, rulify*] = *atomize-ball*
and [*symmetric, defn*] = *atomize-ball*

1.3 Bounded existential quantifier

lemma *bexI* [*intro*]: $[\![P(x); x: A \!]\!] \implies \exists x \in A. P(x)$
 $\langle proof \rangle$

lemma *rev-bexI*: $[\![x \in A; P(x) \!]\!] \implies \exists x \in A. P(x)$
 $\langle proof \rangle$

lemma *bexCI*: $[\![\forall x \in A. \sim P(x) \implies P(a); a: A \!]\!] \implies \exists x \in A. P(x)$

$\langle proof \rangle$

lemma *bexE* [*elim!*]: $[\exists x \in A. P(x); !!x. [x \in A; P(x)] ==> Q] ==> Q$
 $\langle proof \rangle$

lemma *bex-triv* [*simp*]: $(\exists x \in A. P) <-> ((\exists x. x \in A) \& P)$
 $\langle proof \rangle$

lemma *bex-cong* [*cong*]:
 $[A=A'; !!x. x \in A' ==> P(x) <-> P'(x)]$
 $==> (\exists x \in A. P(x)) <-> (\exists x \in A'. P'(x))$
 $\langle proof \rangle$

1.4 Rules for subsets

lemma *subsetI* [*intro!*]:
 $(!!x. x \in A ==> x \in B) ==> A <= B$
 $\langle proof \rangle$

lemma *subsetD* [*elim*]: $[A <= B; c \in A] ==> c \in B$
 $\langle proof \rangle$

lemma *subsetCE* [*elim*]:
 $[A <= B; c \sim A ==> P; c \in B ==> P] ==> P$
 $\langle proof \rangle$

lemma *rev-subsetD*: $[c \in A; A <= B] ==> c \in B$
 $\langle proof \rangle$

lemma *contra-subsetD*: $[A <= B; c \sim B] ==> c \sim A$
 $\langle proof \rangle$

lemma *rev-contra-subsetD*: $[c \sim B; A <= B] ==> c \sim A$
 $\langle proof \rangle$

lemma *subset-refl* [*simp*]: $A <= A$
 $\langle proof \rangle$

lemma *subset-trans*: $[A <= B; B <= C] ==> A <= C$
 $\langle proof \rangle$

lemma *subset-iff*:
 $A <= B <-> (\forall x. x \in A \longrightarrow x \in B)$
 $\langle proof \rangle$

1.5 Rules for equality

lemma *equalityI* [*intro*]: $\llbracket A \leq B; B \leq A \rrbracket \implies A = B$
 $\langle \text{proof} \rangle$

lemma *equality-iffI*: $(!!x. x \in A \leftrightarrow x \in B) \implies A = B$
 $\langle \text{proof} \rangle$

lemmas *equalityD1* = *extension* [*THEN iffD1, THEN conjunct1, standard*]
lemmas *equalityD2* = *extension* [*THEN iffD1, THEN conjunct2, standard*]

lemma *equalityE*: $\llbracket A = B; \llbracket A \leq B; B \leq A \rrbracket \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *equalityCE*:
 $\llbracket A = B; \llbracket c \in A; c \in B \rrbracket \implies P; \llbracket c \sim A; c \sim B \rrbracket \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *equality-iffD*:
 $A = B \implies (!!x. x : A \leftrightarrow x : B)$
 $\langle \text{proof} \rangle$

1.6 Rules for Replace – the derived form of replacement

lemma *Replace-iff*:
 $b : \{y. x \in A, P(x, y)\} \leftrightarrow (\exists x \in A. P(x, b) \ \& \ (\forall y. P(x, y) \longrightarrow y = b))$
 $\langle \text{proof} \rangle$

lemma *ReplaceI* [*intro*]:
 $\llbracket P(x, b); x : A; !!y. P(x, y) \implies y = b \rrbracket \implies$
 $b : \{y. x \in A, P(x, y)\}$
 $\langle \text{proof} \rangle$

lemma *ReplaceE*:
 $\llbracket b : \{y. x \in A, P(x, y)\};$
 $!!x. \llbracket x : A; P(x, b); \forall y. P(x, y) \longrightarrow y = b \rrbracket \implies R$
 $\rrbracket \implies R$
 $\langle \text{proof} \rangle$

lemma *ReplaceE2* [*elim!*]:
 $\llbracket b : \{y. x \in A, P(x, y)\};$
 $!!x. \llbracket x : A; P(x, b) \rrbracket \implies R$
 $\rrbracket \implies R$
 $\langle \text{proof} \rangle$

lemma *Replace-cong* [*cong*]:

$$\llbracket A=B; \text{!!}x\ y.\ x\in B \implies P(x,y) \text{ <-> } Q(x,y) \rrbracket \implies$$

$$\text{Replace}(A,P) = \text{Replace}(B,Q)$$

$$\langle \text{proof} \rangle$$

1.7 Rules for RepFun

lemma *RepFunI*: $a \in A \implies f(a) : \{f(x). x \in A\}$
 $\langle \text{proof} \rangle$

lemma *RepFun-eqI* [*intro*]: $\llbracket b=f(a); a \in A \rrbracket \implies b : \{f(x). x \in A\}$
 $\langle \text{proof} \rangle$

lemma *RepFunE* [*elim!*]:

$$\llbracket b : \{f(x). x \in A\};$$

$$\text{!!}x. \llbracket x \in A; b=f(x) \rrbracket \implies P \rrbracket \implies$$

$$P$$

$$\langle \text{proof} \rangle$$

lemma *RepFun-cong* [*cong*]:

$$\llbracket A=B; \text{!!}x. x \in B \implies f(x)=g(x) \rrbracket \implies \text{RepFun}(A,f) = \text{RepFun}(B,g)$$

$$\langle \text{proof} \rangle$$

lemma *RepFun-iff* [*simp*]: $b : \{f(x). x \in A\} \text{ <-> } (\exists x \in A. b=f(x))$
 $\langle \text{proof} \rangle$

lemma *triv-RepFun* [*simp*]: $\{x. x \in A\} = A$
 $\langle \text{proof} \rangle$

1.8 Rules for Collect – forming a subset by separation

lemma *separation* [*simp*]: $a : \{x \in A. P(x)\} \text{ <-> } a \in A \ \& \ P(a)$
 $\langle \text{proof} \rangle$

lemma *CollectI* [*intro!*]: $\llbracket a \in A; P(a) \rrbracket \implies a : \{x \in A. P(x)\}$
 $\langle \text{proof} \rangle$

lemma *CollectE* [*elim!*]: $\llbracket a : \{x \in A. P(x)\}; \llbracket a \in A; P(a) \rrbracket \implies R \rrbracket \implies R$
 $\langle \text{proof} \rangle$

lemma *CollectD1*: $a : \{x \in A. P(x)\} \implies a \in A$
 $\langle \text{proof} \rangle$

lemma *CollectD2*: $a : \{x \in A. P(x)\} \implies P(a)$
 $\langle \text{proof} \rangle$

lemma *Collect-cong* [*cong*]:

$$\llbracket A=B; \text{!!}x. x \in B \implies P(x) \text{ <-> } Q(x) \rrbracket$$

$$\implies \text{Collect}(A, \%x. P(x)) = \text{Collect}(B, \%x. Q(x))$$

$$\langle \text{proof} \rangle$$

1.9 Rules for Unions

declare *Union-iff* [*simp*]

lemma *UnionI* [*intro*]: $[\mid B: C; A: B \mid] \implies A: \text{Union}(C)$
 $\langle \text{proof} \rangle$

lemma *UnionE* [*elim!*]: $[\mid A \in \text{Union}(C); !!B. [\mid A: B; B: C \mid] \implies R \mid] \implies R$
 $\langle \text{proof} \rangle$

1.10 Rules for Unions of families

lemma *UN-iff* [*simp*]: $b: (\bigcup_{x \in A}. B(x)) <-> (\exists x \in A. b \in B(x))$
 $\langle \text{proof} \rangle$

lemma *UN-I*: $[\mid a: A; b: B(a) \mid] \implies b: (\bigcup_{x \in A}. B(x))$
 $\langle \text{proof} \rangle$

lemma *UN-E* [*elim!*]:
 $[\mid b: (\bigcup_{x \in A}. B(x)); !!x. [\mid x: A; b: B(x) \mid] \implies R \mid] \implies R$
 $\langle \text{proof} \rangle$

lemma *UN-cong*:
 $[\mid A=B; !!x. x \in B \implies C(x)=D(x) \mid] \implies (\bigcup_{x \in A}. C(x)) = (\bigcup_{x \in B}. D(x))$
 $\langle \text{proof} \rangle$

1.11 Rules for the empty set

lemma *not-mem-empty* [*simp*]: $a \sim: 0$
 $\langle \text{proof} \rangle$

lemmas *emptyE* [*elim!*] = *not-mem-empty* [*THEN notE, standard*]

lemma *empty-subsetI* [*simp*]: $0 \leq A$
 $\langle \text{proof} \rangle$

lemma *equals0I*: $[\mid !!y. y \in A \implies \text{False} \mid] \implies A=0$
 $\langle \text{proof} \rangle$

lemma *equals0D* [*dest*]: $A=0 \implies a \sim: A$
 $\langle \text{proof} \rangle$

declare *sym* [*THEN equals0D, dest*]

lemma *not-emptyI*: $a \in A \implies A \sim = 0$

$\langle proof \rangle$

lemma *not-emptyE*: $[| A \sim 0; !!x. x \in A ==> R |] ==> R$
 $\langle proof \rangle$

1.12 Rules for Inter

lemma *Inter-iff*: $A \in \text{Inter}(C) <-> (\forall x \in C. A: x) \ \& \ C \neq 0$
 $\langle proof \rangle$

lemma *InterI* [*intro!*]:
 $[| !!x. x: C ==> A: x; C \neq 0 |] ==> A \in \text{Inter}(C)$
 $\langle proof \rangle$

lemma *InterD* [*elim*]: $[| A \in \text{Inter}(C); B \in C |] ==> A \in B$
 $\langle proof \rangle$

lemma *InterE* [*elim*]:
 $[| A \in \text{Inter}(C); B \sim C ==> R; A \in B ==> R |] ==> R$
 $\langle proof \rangle$

1.13 Rules for Intersections of families

lemma *INT-iff*: $b : (\bigcap x \in A. B(x)) <-> (\forall x \in A. b \in B(x)) \ \& \ A \neq 0$
 $\langle proof \rangle$

lemma *INT-I*: $[| !!x. x: A ==> b: B(x); A \neq 0 |] ==> b: (\bigcap x \in A. B(x))$
 $\langle proof \rangle$

lemma *INT-E*: $[| b : (\bigcap x \in A. B(x)); a: A |] ==> b \in B(a)$
 $\langle proof \rangle$

lemma *INT-cong*:
 $[| A=B; !!x. x \in B ==> C(x)=D(x) |] ==> (\bigcap x \in A. C(x)) = (\bigcap x \in B. D(x))$
 $\langle proof \rangle$

1.14 Rules for Powersets

lemma *PowI*: $A \leq B ==> A \in \text{Pow}(B)$
 $\langle proof \rangle$

lemma *PowD*: $A \in \text{Pow}(B) ==> A \leq B$
 $\langle proof \rangle$

declare *Pow-iff* [*iff*]

lemmas *Pow-bottom* = *empty-subsetI* [*THEN PowI*]

lemmas *Pow-top* = *subset-refl* [*THEN PowI*]

1.15 Cantor's Theorem: There is no surjection from a set to its powerset.

lemma *cantor*: $\exists S \in \text{Pow}(A). \forall x \in A. b(x) \sim S$
 $\langle \text{proof} \rangle$

$\langle \text{ML} \rangle$

end

2 upair: Unordered Pairs

theory *upair* **imports** *ZF*
uses *Tools/typechk.ML* **begin**

$\langle \text{ML} \rangle$

lemma *atomize-ball* [*symmetric, rulify*]:
 $(!!x. x:A ==> P(x)) == \text{Trueprop } (\text{ALL } x:A. P(x))$
 $\langle \text{proof} \rangle$

2.1 Unordered Pairs: constant *Upair*

lemma *Upair-iff* [*simp*]: $c : \text{Upair}(a,b) <-> (c=a \mid c=b)$
 $\langle \text{proof} \rangle$

lemma *UpairI1*: $a : \text{Upair}(a,b)$
 $\langle \text{proof} \rangle$

lemma *UpairI2*: $b : \text{Upair}(a,b)$
 $\langle \text{proof} \rangle$

lemma *UpairE*: $[| a : \text{Upair}(b,c); a=b ==> P; a=c ==> P |] ==> P$
 $\langle \text{proof} \rangle$

2.2 Rules for Binary Union, Defined via *Upair*

lemma *Un-iff* [*simp*]: $c : A \text{ Un } B <-> (c:A \mid c:B)$
 $\langle \text{proof} \rangle$

lemma *UnI1*: $c : A ==> c : A \text{ Un } B$
 $\langle \text{proof} \rangle$

lemma *UnI2*: $c : B ==> c : A \text{ Un } B$

$\langle proof \rangle$

declare $UnI1$ [elim?] $UnI2$ [elim?]

lemma UnE [elim!]: $[[c : A \text{ Un } B; c:A ==> P; c:B ==> P]] ==> P$
 $\langle proof \rangle$

lemma UnE' : $[[c : A \text{ Un } B; c:A ==> P; [c:B; c\sim:A]] ==> P]] ==> P$
 $\langle proof \rangle$

lemma $UnCI$ [intro!]: $(c \sim: B ==> c : A) ==> c : A \text{ Un } B$
 $\langle proof \rangle$

2.3 Rules for Binary Intersection, Defined via $Upair$

lemma $Int\text{-}iff$ [simp]: $c : A \text{ Int } B <-> (c:A \& c:B)$
 $\langle proof \rangle$

lemma $IntI$ [intro!]: $[[c : A; c : B]] ==> c : A \text{ Int } B$
 $\langle proof \rangle$

lemma $IntD1$: $c : A \text{ Int } B ==> c : A$
 $\langle proof \rangle$

lemma $IntD2$: $c : A \text{ Int } B ==> c : B$
 $\langle proof \rangle$

lemma $IntE$ [elim!]: $[[c : A \text{ Int } B; [c:A; c:B]] ==> P]] ==> P$
 $\langle proof \rangle$

2.4 Rules for Set Difference, Defined via $Upair$

lemma $Diff\text{-}iff$ [simp]: $c : A - B <-> (c:A \& c\sim:B)$
 $\langle proof \rangle$

lemma $DiffI$ [intro!]: $[[c : A; c \sim: B]] ==> c : A - B$
 $\langle proof \rangle$

lemma $DiffD1$: $c : A - B ==> c : A$
 $\langle proof \rangle$

lemma $DiffD2$: $c : A - B ==> c \sim: B$
 $\langle proof \rangle$

lemma $DiffE$ [elim!]: $[[c : A - B; [c:A; c\sim:B]] ==> P]] ==> P$
 $\langle proof \rangle$

2.5 Rules for *cons*

lemma *cons-iff* [*simp*]: $a : \text{cons}(b, A) <-> (a=b \mid a:A)$
 $\langle \text{proof} \rangle$

lemma *consI1* [*simp, TC*]: $a : \text{cons}(a, B)$
 $\langle \text{proof} \rangle$

lemma *consI2*: $a : B ==> a : \text{cons}(b, B)$
 $\langle \text{proof} \rangle$

lemma *consE* [*elim!*]: $[\mid a : \text{cons}(b, A); a=b ==> P; a:A ==> P \mid] ==> P$
 $\langle \text{proof} \rangle$

lemma *consE'*:
 $[\mid a : \text{cons}(b, A); a=b ==> P; \mid a:A; a \sim b \mid] ==> P \mid] ==> P$
 $\langle \text{proof} \rangle$

lemma *consCI* [*intro!*]: $(a \sim b ==> a=b) ==> a : \text{cons}(b, B)$
 $\langle \text{proof} \rangle$

lemma *cons-not-0* [*simp*]: $\text{cons}(a, B) \sim 0$
 $\langle \text{proof} \rangle$

lemmas *cons-neq-0* = *cons-not-0* [*THEN notE, standard*]

declare *cons-not-0* [*THEN not-sym, simp*]

2.6 Singletons

lemma *singleton-iff*: $a : \{b\} <-> a=b$
 $\langle \text{proof} \rangle$

lemma *singletonI* [*intro!*]: $a : \{a\}$
 $\langle \text{proof} \rangle$

lemmas *singletonE* = *singleton-iff* [*THEN iffD1, elim-format, standard, elim!*]

2.7 Descriptions

lemma *the-equality* [*intro*]:
 $[\mid P(a); \text{!!}x. P(x) ==> x=a \mid] ==> (\text{THE } x. P(x)) = a$
 $\langle \text{proof} \rangle$

lemma *the-equality2*: $[\mid \text{EX! } x. P(x); P(a) \mid] ==> (\text{THE } x. P(x)) = a$

$\langle \text{proof} \rangle$

lemma *theI*: $EX! x. P(x) \implies P(\text{THE } x. P(x))$
 $\langle \text{proof} \rangle$

lemma *the-0*: $\sim (EX! x. P(x)) \implies (\text{THE } x. P(x)) = 0$
 $\langle \text{proof} \rangle$

lemma *theI2*:
 assumes *p1*: $\sim Q(0) \implies EX! x. P(x)$
 and *p2*: $!!x. P(x) \implies Q(x)$
 shows $Q(\text{THE } x. P(x))$
 $\langle \text{proof} \rangle$

lemma *the-eq-trivial* [*simp*]: $(\text{THE } x. x = a) = a$
 $\langle \text{proof} \rangle$

lemma *the-eq-trivial2* [*simp*]: $(\text{THE } x. a = x) = a$
 $\langle \text{proof} \rangle$

2.8 Conditional Terms: *if-then-else*

lemma *if-true* [*simp*]: $(\text{if True then } a \text{ else } b) = a$
 $\langle \text{proof} \rangle$

lemma *if-false* [*simp*]: $(\text{if False then } a \text{ else } b) = b$
 $\langle \text{proof} \rangle$

lemma *if-cong*:
 $[[P <-> Q; Q \implies a=c; \sim Q \implies b=d]]$
 $\implies (\text{if } P \text{ then } a \text{ else } b) = (\text{if } Q \text{ then } c \text{ else } d)$
 $\langle \text{proof} \rangle$

lemma *if-weak-cong*: $P <-> Q \implies (\text{if } P \text{ then } x \text{ else } y) = (\text{if } Q \text{ then } x \text{ else } y)$
 $\langle \text{proof} \rangle$

lemma *if-P*: $P \implies (\text{if } P \text{ then } a \text{ else } b) = a$
 $\langle \text{proof} \rangle$

lemma *if-not-P*: $\sim P \implies (\text{if } P \text{ then } a \text{ else } b) = b$
 $\langle \text{proof} \rangle$

lemma *split-if* [*split*]:

$P(\text{if } Q \text{ then } x \text{ else } y) <-> ((Q \dashrightarrow P(x)) \ \& \ (\sim Q \dashrightarrow P(y)))$
 $\langle \text{proof} \rangle$

lemmas *split-if-eq1* = *split-if* [*of* %*x*. *x* = *b*, *standard*]

lemmas *split-if-eq2* = *split-if* [*of* %*x*. *a* = *x*, *standard*]

lemmas *split-if-mem1* = *split-if* [*of* %*x*. *x* : *b*, *standard*]

lemmas *split-if-mem2* = *split-if* [*of* %*x*. *a* : *x*, *standard*]

lemmas *split-ifs* = *split-if-eq1* *split-if-eq2* *split-if-mem1* *split-if-mem2*

lemma *if-iff*: $a: (\text{if } P \text{ then } x \text{ else } y) <-> P \ \& \ a:x \mid \sim P \ \& \ a:y$

$\langle \text{proof} \rangle$

lemma *if-type* [*TC*]:

$[\mid P \implies a: A; \ \sim P \implies b: A \mid] \implies (\text{if } P \text{ then } a \text{ else } b): A$
 $\langle \text{proof} \rangle$

lemma *split-if-asm*: $P(\text{if } Q \text{ then } x \text{ else } y) <-> (\sim((Q \ \& \ \sim P(x)) \mid (\sim Q \ \& \ \sim P(y))))$

$\langle \text{proof} \rangle$

lemmas *if-splits* = *split-if* *split-if-asm*

2.9 Consequences of Foundation

lemma *mem-asym*: $[\mid a:b; \ \sim P \implies b:a \mid] \implies P$

$\langle \text{proof} \rangle$

lemma *mem-irrefl*: $a:a \implies P$

$\langle \text{proof} \rangle$

lemma *mem-not-refl*: $a \sim: a$

$\langle \text{proof} \rangle$

lemma *mem-imp-not-eq*: $a:A \implies a \sim = A$

$\langle \text{proof} \rangle$

lemma *eq-imp-not-mem*: $a=A \implies a \sim: A$

$\langle proof \rangle$

2.10 Rules for Successor

lemma *succ-iff*: $i : succ(j) \leftrightarrow i=j \mid i:j$
 $\langle proof \rangle$

lemma *succI1* [*simp*]: $i : succ(i)$
 $\langle proof \rangle$

lemma *succI2*: $i : j \implies i : succ(j)$
 $\langle proof \rangle$

lemma *succE* [*elim!*]:
 $[[i : succ(j); i=j \implies P; i:j \implies P]] \implies P$
 $\langle proof \rangle$

lemma *succCI* [*intro!*]: $(i \sim j \implies i=j) \implies i : succ(j)$
 $\langle proof \rangle$

lemma *succ-not-0* [*simp*]: $succ(n) \sim 0$
 $\langle proof \rangle$

lemmas *succ-neq-0* = *succ-not-0* [*THEN notE, standard, elim!*]

declare *succ-not-0* [*THEN not-sym, simp*]
declare *sym* [*THEN succ-neq-0, elim!*]

lemmas *succ-subsetD* = *succI1* [*THEN* [2] *subsetD*]

lemmas *succ-neq-self* = *succI1* [*THEN mem-imp-not-eq, THEN not-sym, standard*]

lemma *succ-inject-iff* [*simp*]: $succ(m) = succ(n) \leftrightarrow m=n$
 $\langle proof \rangle$

lemmas *succ-inject* = *succ-inject-iff* [*THEN iffD1, standard, dest!*]

2.11 Miniscoping of the Bounded Universal Quantifier

lemma *ball-simps1*:
 $(ALL x:A. P(x) \ \& \ Q) \leftrightarrow (ALL x:A. P(x)) \ \& \ (A=0 \mid Q)$
 $(ALL x:A. P(x) \mid Q) \leftrightarrow ((ALL x:A. P(x)) \mid Q)$
 $(ALL x:A. P(x) \dashv\vdash Q) \leftrightarrow ((EX x:A. P(x)) \dashv\vdash Q)$
 $(\sim(ALL x:A. P(x))) \leftrightarrow (EX x:A. \sim P(x))$
 $(ALL x:0.P(x)) \leftrightarrow True$
 $(ALL x:succ(i).P(x)) \leftrightarrow P(i) \ \& \ (ALL x:i. P(x))$

$(ALL\ x:cons(a,B).P(x)) <-> P(a) \ \& \ (ALL\ x:B. P(x))$
 $(ALL\ x:RepFun(A,f). P(x)) <-> (ALL\ y:A. P(f(y)))$
 $(ALL\ x:Union(A).P(x)) <-> (ALL\ y:A. ALL\ x:y. P(x))$
 $\langle proof \rangle$

lemma *ball-simps2*:

$(ALL\ x:A. P \ \& \ Q(x)) <-> (A=0 \mid P) \ \& \ (ALL\ x:A. Q(x))$
 $(ALL\ x:A. P \mid Q(x)) <-> (P \mid (ALL\ x:A. Q(x)))$
 $(ALL\ x:A. P \dashv\vdash Q(x)) <-> (P \dashv\vdash (ALL\ x:A. Q(x)))$
 $\langle proof \rangle$

lemma *ball-simps3*:

$(ALL\ x:Collect(A,Q).P(x)) <-> (ALL\ x:A. Q(x) \dashv\vdash P(x))$
 $\langle proof \rangle$

lemmas *ball-simps* [simp] = *ball-simps1 ball-simps2 ball-simps3*

lemma *ball-conj-distrib*:

$(ALL\ x:A. P(x) \ \& \ Q(x)) <-> ((ALL\ x:A. P(x)) \ \& \ (ALL\ x:A. Q(x)))$
 $\langle proof \rangle$

2.12 Miniscoping of the Bounded Existential Quantifier

lemma *bex-simps1*:

$(EX\ x:A. P(x) \ \& \ Q) <-> ((EX\ x:A. P(x)) \ \& \ Q)$
 $(EX\ x:A. P(x) \mid Q) <-> (EX\ x:A. P(x)) \mid (A^{\sim}=0 \ \& \ Q)$
 $(EX\ x:A. P(x) \dashv\vdash Q) <-> ((ALL\ x:A. P(x)) \dashv\vdash (A^{\sim}=0 \ \& \ Q))$
 $(EX\ x:0.P(x)) <-> False$
 $(EX\ x:succ(i).P(x)) <-> P(i) \mid (EX\ x:i. P(x))$
 $(EX\ x:cons(a,B).P(x)) <-> P(a) \mid (EX\ x:B. P(x))$
 $(EX\ x:RepFun(A,f). P(x)) <-> (EX\ y:A. P(f(y)))$
 $(EX\ x:Union(A).P(x)) <-> (EX\ y:A. EX\ x:y. P(x))$
 $(\sim(EX\ x:A. P(x))) <-> (ALL\ x:A. \sim P(x))$
 $\langle proof \rangle$

lemma *bex-simps2*:

$(EX\ x:A. P \ \& \ Q(x)) <-> (P \ \& \ (EX\ x:A. Q(x)))$
 $(EX\ x:A. P \mid Q(x)) <-> (A^{\sim}=0 \ \& \ P) \mid (EX\ x:A. Q(x))$
 $(EX\ x:A. P \dashv\vdash Q(x)) <-> ((A=0 \mid P) \dashv\vdash (EX\ x:A. Q(x)))$
 $\langle proof \rangle$

lemma *bex-simps3*:

$(EX\ x:Collect(A,Q).P(x)) <-> (EX\ x:A. Q(x) \ \& \ P(x))$
 $\langle proof \rangle$

lemmas *bex-simps* [simp] = *bex-simps1 bex-simps2 bex-simps3*

lemma *bex-disj-distrib*:

$(EX\ x:A. P(x) \mid Q(x)) <-> ((EX\ x:A. P(x)) \mid (EX\ x:A. Q(x)))$

$\langle proof \rangle$

lemma *bex-triv-one-point1* [simp]: $(\exists x:A. x=a) <-> (a:A)$
 $\langle proof \rangle$

lemma *bex-triv-one-point2* [simp]: $(\exists x:A. a=x) <-> (a:A)$
 $\langle proof \rangle$

lemma *bex-one-point1* [simp]: $(\exists x:A. x=a \ \& \ P(x)) <-> (a:A \ \& \ P(a))$
 $\langle proof \rangle$

lemma *bex-one-point2* [simp]: $(\exists x:A. a=x \ \& \ P(x)) <-> (a:A \ \& \ P(a))$
 $\langle proof \rangle$

lemma *ball-one-point1* [simp]: $(\forall x:A. x=a \ \rightarrow \ P(x)) <-> (a:A \ \rightarrow \ P(a))$
 $\langle proof \rangle$

lemma *ball-one-point2* [simp]: $(\forall x:A. a=x \ \rightarrow \ P(x)) <-> (a:A \ \rightarrow \ P(a))$
 $\langle proof \rangle$

2.13 Miniscoping of the Replacement Operator

These cover both *Replace* and *Collect*

lemma *Rep-simps* [simp]:
 $\{x. y:0, R(x,y)\} = 0$
 $\{x:0. P(x)\} = 0$
 $\{x:A. Q\} = (\text{if } Q \text{ then } A \text{ else } 0)$
 $\text{RepFun}(0,f) = 0$
 $\text{RepFun}(\text{succ}(i),f) = \text{cons}(f(i), \text{RepFun}(i,f))$
 $\text{RepFun}(\text{cons}(a,B),f) = \text{cons}(f(a), \text{RepFun}(B,f))$
 $\langle proof \rangle$

2.14 Miniscoping of Unions

lemma *UN-simps1*:
 $(\text{UN } x:C. \text{cons}(a, B(x))) = (\text{if } C=0 \text{ then } 0 \text{ else } \text{cons}(a, \text{UN } x:C. B(x)))$
 $(\text{UN } x:C. A(x) \ \text{Un } B') = (\text{if } C=0 \text{ then } 0 \text{ else } (\text{UN } x:C. A(x)) \ \text{Un } B')$
 $(\text{UN } x:C. A' \ \text{Un } B(x)) = (\text{if } C=0 \text{ then } 0 \text{ else } A' \ \text{Un } (\text{UN } x:C. B(x)))$
 $(\text{UN } x:C. A(x) \ \text{Int } B') = ((\text{UN } x:C. A(x)) \ \text{Int } B')$
 $(\text{UN } x:C. A' \ \text{Int } B(x)) = (A' \ \text{Int } (\text{UN } x:C. B(x)))$
 $(\text{UN } x:C. A(x) - B') = ((\text{UN } x:C. A(x)) - B')$
 $(\text{UN } x:C. A' - B(x)) = (\text{if } C=0 \text{ then } 0 \text{ else } A' - (\text{INT } x:C. B(x)))$
 $\langle proof \rangle$

lemma *UN-simps2*:
 $(\text{UN } x: \text{Union}(A). B(x)) = (\text{UN } y:A. \text{UN } x:y. B(x))$

$$\begin{aligned} (UN\ z: (UN\ x:A. B(x)). C(z)) &= (UN\ x:A. UN\ z: B(x). C(z)) \\ (UN\ x: RepFun(A,f). B(x)) &= (UN\ a:A. B(f(a))) \end{aligned}$$
 $\langle proof \rangle$

lemmas $UN-simps\ [simp] = UN-simps1\ UN-simps2$

Opposite of miniscoping: pull the operator out

lemma $UN-extend-simps1$:

$$\begin{aligned} (UN\ x:C. A(x))\ Un\ B &= (if\ C=0\ then\ B\ else\ (UN\ x:C. A(x)\ Un\ B)) \\ ((UN\ x:C. A(x))\ Int\ B) &= (UN\ x:C. A(x)\ Int\ B) \\ ((UN\ x:C. A(x)) - B) &= (UN\ x:C. A(x) - B) \end{aligned}$$

$\langle proof \rangle$

lemma $UN-extend-simps2$:

$$\begin{aligned} cons(a, UN\ x:C. B(x)) &= (if\ C=0\ then\ \{a\}\ else\ (UN\ x:C. cons(a, B(x)))) \\ A\ Un\ (UN\ x:C. B(x)) &= (if\ C=0\ then\ A\ else\ (UN\ x:C. A\ Un\ B(x))) \\ (A\ Int\ (UN\ x:C. B(x))) &= (UN\ x:C. A\ Int\ B(x)) \\ A - (INT\ x:C. B(x)) &= (if\ C=0\ then\ A\ else\ (UN\ x:C. A - B(x))) \\ (UN\ y:A. UN\ x:y. B(x)) &= (UN\ x: Union(A). B(x)) \\ (UN\ a:A. B(f(a))) &= (UN\ x: RepFun(A,f). B(x)) \end{aligned}$$

$\langle proof \rangle$

lemma $UN-UN-extend$:

$$(UN\ x:A. UN\ z: B(x). C(z)) = (UN\ z: (UN\ x:A. B(x)). C(z))$$

$\langle proof \rangle$

lemmas $UN-extend-simps = UN-extend-simps1\ UN-extend-simps2\ UN-UN-extend$

2.15 Miniscoping of Intersections

lemma $INT-simps1$:

$$\begin{aligned} (INT\ x:C. A(x)\ Int\ B) &= (INT\ x:C. A(x))\ Int\ B \\ (INT\ x:C. A(x) - B) &= (INT\ x:C. A(x)) - B \\ (INT\ x:C. A(x)\ Un\ B) &= (if\ C=0\ then\ 0\ else\ (INT\ x:C. A(x))\ Un\ B) \end{aligned}$$

$\langle proof \rangle$

lemma $INT-simps2$:

$$\begin{aligned} (INT\ x:C. A\ Int\ B(x)) &= A\ Int\ (INT\ x:C. B(x)) \\ (INT\ x:C. A - B(x)) &= (if\ C=0\ then\ 0\ else\ A - (UN\ x:C. B(x))) \\ (INT\ x:C. cons(a, B(x))) &= (if\ C=0\ then\ 0\ else\ cons(a, INT\ x:C. B(x))) \\ (INT\ x:C. A\ Un\ B(x)) &= (if\ C=0\ then\ 0\ else\ A\ Un\ (INT\ x:C. B(x))) \end{aligned}$$

$\langle proof \rangle$

lemmas $INT-simps\ [simp] = INT-simps1\ INT-simps2$

Opposite of miniscoping: pull the operator out

lemma $INT-extend-simps1$:

$$\begin{aligned} (INT\ x:C. A(x))\ Int\ B &= (INT\ x:C. A(x)\ Int\ B) \\ (INT\ x:C. A(x) - B) &= (INT\ x:C. A(x) - B) \end{aligned}$$

$(INT\ x:C. A(x))\ Un\ B = (if\ C=0\ then\ B\ else\ (INT\ x:C. A(x)\ Un\ B))$
 $\langle proof \rangle$

lemma *INT-extend-simps2*:

$A\ Int\ (INT\ x:C. B(x)) = (INT\ x:C. A\ Int\ B(x))$
 $A - (UN\ x:C. B(x)) = (if\ C=0\ then\ A\ else\ (INT\ x:C. A - B(x)))$
 $cons(a, INT\ x:C. B(x)) = (if\ C=0\ then\ \{a\}\ else\ (INT\ x:C. cons(a, B(x))))$
 $A\ Un\ (INT\ x:C. B(x)) = (if\ C=0\ then\ A\ else\ (INT\ x:C. A\ Un\ B(x)))$
 $\langle proof \rangle$

lemmas *INT-extend-simps* = *INT-extend-simps1* *INT-extend-simps2*

2.16 Other simprules

lemma *misc-simps* [*simp*]:

$0\ Un\ A = A$
 $A\ Un\ 0 = A$
 $0\ Int\ A = 0$
 $A\ Int\ 0 = 0$
 $0 - A = 0$
 $A - 0 = A$
 $Union(0) = 0$
 $Union(cons(b,A)) = b\ Un\ Union(A)$
 $Inter(\{b\}) = b$
 $\langle proof \rangle$

end

3 pair: Ordered Pairs

theory *pair* **imports** *upair*

uses *simpdata.ML* **begin**

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

$\langle proof \rangle$

lemma *doubleton-eq-iff*: $\{a,b\} = \{c,d\} \iff (a=c \ \& \ b=d) \mid (a=d \ \& \ b=c)$

$\langle proof \rangle$

lemma *Pair-iff* [*simp*]: $\langle a,b \rangle = \langle c,d \rangle \iff a=c \ \& \ b=d$

$\langle proof \rangle$

lemmas *Pair-inject* = *Pair-iff* [*THEN* *iffD1*, *THEN* *conjE*, *standard*, *elim!*]

lemmas *Pair-inject1* = *Pair-iff* [*THEN* *iffD1*, *THEN* *conjunct1*, *standard*]

lemmas *Pair-inject2* = *Pair-iff* [*THEN* *iffD1*, *THEN* *conjunct2*, *standard*]

lemma *Pair-not-0*: $\langle a, b \rangle \sim = 0$

$\langle proof \rangle$

lemmas *Pair-neq-0* = *Pair-not-0* [*THEN notE, standard, elim!*]

declare *sym* [*THEN Pair-neq-0, elim!*]

lemma *Pair-neq-fst*: $\langle a, b \rangle = a \implies P$

$\langle proof \rangle$

lemma *Pair-neq-snd*: $\langle a, b \rangle = b \implies P$

$\langle proof \rangle$

3.1 Sigma: Disjoint Union of a Family of Sets

Generalizes Cartesian product

lemma *Sigma-iff* [*simp*]: $\langle a, b \rangle : \text{Sigma}(A, B) \iff a:A \ \& \ b:B(a)$

$\langle proof \rangle$

lemma *SigmaI* [*TC, intro!*]: $\llbracket a:A; \ b:B(a) \rrbracket \implies \langle a, b \rangle : \text{Sigma}(A, B)$

$\langle proof \rangle$

lemmas *SigmaD1* = *Sigma-iff* [*THEN iffD1, THEN conjunct1, standard*]

lemmas *SigmaD2* = *Sigma-iff* [*THEN iffD1, THEN conjunct2, standard*]

lemma *SigmaE* [*elim!*]:

$\llbracket c : \text{Sigma}(A, B);$
 $\quad !!x \ y. \llbracket x:A; \ y:B(x); \ c=\langle x, y \rangle \rrbracket \implies P$

$\rrbracket \implies P$

$\langle proof \rangle$

lemma *SigmaE2* [*elim!*]:

$\llbracket \langle a, b \rangle : \text{Sigma}(A, B);$
 $\quad \llbracket a:A; \ b:B(a) \rrbracket \implies P$

$\rrbracket \implies P$

$\langle proof \rangle$

lemma *Sigma-cong*:

$\llbracket A=A'; \quad !!x. \ x:A' \implies B(x)=B'(x) \rrbracket \implies$
 $\quad \text{Sigma}(A, B) = \text{Sigma}(A', B')$

$\langle proof \rangle$

lemma *Sigma-empty1* [*simp*]: $\text{Sigma}(0, B) = 0$

$\langle proof \rangle$

lemma *Sigma-empty2* [simp]: $A * 0 = 0$
 $\langle \text{proof} \rangle$

lemma *Sigma-empty-iff*: $A * B = 0 \iff A = 0 \mid B = 0$
 $\langle \text{proof} \rangle$

3.2 Projections *fst* and *snd*

lemma *fst-conv* [simp]: $\text{fst}(\langle a, b \rangle) = a$
 $\langle \text{proof} \rangle$

lemma *snd-conv* [simp]: $\text{snd}(\langle a, b \rangle) = b$
 $\langle \text{proof} \rangle$

lemma *fst-type* [TC]: $p : \text{Sigma}(A, B) \implies \text{fst}(p) : A$
 $\langle \text{proof} \rangle$

lemma *snd-type* [TC]: $p : \text{Sigma}(A, B) \implies \text{snd}(p) : B(\text{fst}(p))$
 $\langle \text{proof} \rangle$

lemma *Pair-fst-snd-eq*: $a : \text{Sigma}(A, B) \implies \langle \text{fst}(a), \text{snd}(a) \rangle = a$
 $\langle \text{proof} \rangle$

3.3 The Eliminator, *split*

lemma *split* [simp]: $\text{split}(\%x y. c(x, y), \langle a, b \rangle) == c(a, b)$
 $\langle \text{proof} \rangle$

lemma *split-type* [TC]:

$$\begin{aligned} & [\mid p : \text{Sigma}(A, B); \\ & \quad !!x y. [\mid x : A; y : B(x)] \implies c(x, y) : C(\langle x, y \rangle) \\ &] \implies \text{split}(\%x y. c(x, y), p) : C(p) \end{aligned}$$

 $\langle \text{proof} \rangle$

lemma *expand-split*:

$$u : A * B \implies R(\text{split}(c, u)) \iff (ALL x : A. ALL y : B. u = \langle x, y \rangle \iff R(c(x, y)))$$

 $\langle \text{proof} \rangle$

3.4 A version of *split* for Formulae: Result Type *o*

lemma *splitI*: $R(a, b) \implies \text{split}(R, \langle a, b \rangle)$
 $\langle \text{proof} \rangle$

lemma *splitE*:

$$\begin{aligned} & [\mid \text{split}(R, z); z : \text{Sigma}(A, B); \\ & \quad !!x y. [\mid z = \langle x, y \rangle; R(x, y)] \implies P \\ &] \implies P \end{aligned}$$

 $\langle \text{proof} \rangle$

lemma *splitD*: $\text{split}(R, \langle a, b \rangle) \implies R(a, b)$
 $\langle \text{proof} \rangle$

Complex rules for Sigma.

lemma *split-paired-Bex-Sigma* [simp]:
 $(\exists z \in \text{Sigma}(A, B). P(z)) \iff (\exists x \in A. \exists y \in B(x). P(\langle x, y \rangle))$
 $\langle \text{proof} \rangle$

lemma *split-paired-Ball-Sigma* [simp]:
 $(\forall z \in \text{Sigma}(A, B). P(z)) \iff (\forall x \in A. \forall y \in B(x). P(\langle x, y \rangle))$
 $\langle \text{proof} \rangle$

end

4 equalities: Basic Equalities and Inclusions

theory *equalities* **imports** *pair* **begin**

These cover union, intersection, converse, domain, range, etc. Philippe de Groote proved many of the inclusions.

lemma *in-mono*: $A \subseteq B \implies x \in A \implies x \in B$
 $\langle \text{proof} \rangle$

lemma *the-eq-0* [simp]: $(\text{THE } x. \text{False}) = 0$
 $\langle \text{proof} \rangle$

4.1 Bounded Quantifiers

The following are not added to the default simpset because (a) they duplicate the body and (b) there are no similar rules for *Int*.

lemma *ball-Un*: $(\forall x \in A \cup B. P(x)) \iff (\forall x \in A. P(x)) \ \& \ (\forall x \in B. P(x))$
 $\langle \text{proof} \rangle$

lemma *bex-Un*: $(\exists x \in A \cup B. P(x)) \iff (\exists x \in A. P(x)) \ \vee \ (\exists x \in B. P(x))$
 $\langle \text{proof} \rangle$

lemma *ball-UN*: $(\forall z \in (\bigcup x \in A. B(x)). P(z)) \iff (\forall x \in A. \forall z \in B(x). P(z))$
 $\langle \text{proof} \rangle$

lemma *bex-UN*: $(\exists z \in (\bigcup x \in A. B(x)). P(z)) \iff (\exists x \in A. \exists z \in B(x). P(z))$
 $\langle \text{proof} \rangle$

4.2 Converse of a Relation

lemma *converse-iff* [simp]: $\langle a, b \rangle \in \text{converse}(r) \iff \langle b, a \rangle \in r$
 <proof>

lemma *converseI* [intro!]: $\langle a, b \rangle \in r \implies \langle b, a \rangle \in \text{converse}(r)$
 <proof>

lemma *converseD*: $\langle a, b \rangle \in \text{converse}(r) \implies \langle b, a \rangle \in r$
 <proof>

lemma *converseE* [elim!]:

$$\begin{aligned} & [| \text{ } yx \in \text{converse}(r); \\ & \quad !!x \ y. [| \text{ } yx = \langle y, x \rangle; \langle x, y \rangle \in r \text{ } |] \implies P \text{ } |] \\ & \implies P \end{aligned}$$

 <proof>

lemma *converse-converse*: $r \subseteq \text{Sigma}(A, B) \implies \text{converse}(\text{converse}(r)) = r$
 <proof>

lemma *converse-type*: $r \subseteq A * B \implies \text{converse}(r) \subseteq B * A$
 <proof>

lemma *converse-prod* [simp]: $\text{converse}(A * B) = B * A$
 <proof>

lemma *converse-empty* [simp]: $\text{converse}(0) = 0$
 <proof>

lemma *converse-subset-iff*:

$$A \subseteq \text{Sigma}(X, Y) \implies \text{converse}(A) \subseteq \text{converse}(B) \iff A \subseteq B$$

 <proof>

4.3 Finite Set Constructions Using cons

lemma *cons-subsetI*: $[| \text{ } a \in C; B \subseteq C \text{ } |] \implies \text{cons}(a, B) \subseteq C$
 <proof>

lemma *subset-consI*: $B \subseteq \text{cons}(a, B)$
 <proof>

lemma *cons-subset-iff* [iff]: $\text{cons}(a, B) \subseteq C \iff a \in C \ \& \ B \subseteq C$
 <proof>

lemmas *cons-subsetE* = *cons-subset-iff* [THEN iffD1, THEN conjE, standard]

lemma *subset-empty-iff*: $A \subseteq 0 \iff A = 0$
 <proof>

lemma *subset-cons-iff*: $C \subseteq \text{cons}(a, B) \leftrightarrow C \subseteq B \mid (a \in C \ \& \ C - \{a\} \subseteq B)$
 $\langle \text{proof} \rangle$

lemma *cons-eq*: $\{a\} \cup B = \text{cons}(a, B)$
 $\langle \text{proof} \rangle$

lemma *cons-commute*: $\text{cons}(a, \text{cons}(b, C)) = \text{cons}(b, \text{cons}(a, C))$
 $\langle \text{proof} \rangle$

lemma *cons-absorb*: $a: B \implies \text{cons}(a, B) = B$
 $\langle \text{proof} \rangle$

lemma *cons-Diff*: $a: B \implies \text{cons}(a, B - \{a\}) = B$
 $\langle \text{proof} \rangle$

lemma *Diff-cons-eq*: $\text{cons}(a, B) - C = (\text{if } a \in C \text{ then } B - C \text{ else } \text{cons}(a, B - C))$
 $\langle \text{proof} \rangle$

lemma *equal-singleton* [rule-format]: $[\mid a: C; \ \forall y \in C. y = b \mid] \implies C = \{b\}$
 $\langle \text{proof} \rangle$

lemma [simp]: $\text{cons}(a, \text{cons}(a, B)) = \text{cons}(a, B)$
 $\langle \text{proof} \rangle$

lemma *singleton-subsetI*: $a \in C \implies \{a\} \subseteq C$
 $\langle \text{proof} \rangle$

lemma *singleton-subsetD*: $\{a\} \subseteq C \implies a \in C$
 $\langle \text{proof} \rangle$

lemma *subset-succI*: $i \subseteq \text{succ}(i)$
 $\langle \text{proof} \rangle$

lemma *succ-subsetI*: $[\mid i \in j; \ i \subseteq j \mid] \implies \text{succ}(i) \subseteq j$
 $\langle \text{proof} \rangle$

lemma *succ-subsetE*:
 $[\mid \text{succ}(i) \subseteq j; \ [\mid i \in j; \ i \subseteq j \mid] \implies P \mid] \implies P$
 $\langle \text{proof} \rangle$

lemma *succ-subset-iff*: $\text{succ}(a) \subseteq B \leftrightarrow (a \subseteq B \ \& \ a \in B)$
 $\langle \text{proof} \rangle$

4.4 Binary Intersection

lemma *Int-subset-iff*: $C \subseteq A \text{ Int } B \leftrightarrow C \subseteq A \ \& \ C \subseteq B$
<proof>

lemma *Int-lower1*: $A \text{ Int } B \subseteq A$
<proof>

lemma *Int-lower2*: $A \text{ Int } B \subseteq B$
<proof>

lemma *Int-greatest*: $[| C \subseteq A; C \subseteq B |] ==> C \subseteq A \text{ Int } B$
<proof>

lemma *Int-cons*: $\text{cons}(a, B) \text{ Int } C \subseteq \text{cons}(a, B \text{ Int } C)$
<proof>

lemma *Int-absorb [simp]*: $A \text{ Int } A = A$
<proof>

lemma *Int-left-absorb*: $A \text{ Int } (A \text{ Int } B) = A \text{ Int } B$
<proof>

lemma *Int-commute*: $A \text{ Int } B = B \text{ Int } A$
<proof>

lemma *Int-left-commute*: $A \text{ Int } (B \text{ Int } C) = B \text{ Int } (A \text{ Int } C)$
<proof>

lemma *Int-assoc*: $(A \text{ Int } B) \text{ Int } C = A \text{ Int } (B \text{ Int } C)$
<proof>

lemmas *Int-ac= Int-assoc Int-left-absorb Int-commute Int-left-commute*

lemma *Int-absorb1*: $B \subseteq A ==> A \cap B = B$
<proof>

lemma *Int-absorb2*: $A \subseteq B ==> A \cap B = A$
<proof>

lemma *Int-Un-distrib*: $A \text{ Int } (B \text{ Un } C) = (A \text{ Int } B) \text{ Un } (A \text{ Int } C)$
<proof>

lemma *Int-Un-distrib2*: $(B \text{ Un } C) \text{ Int } A = (B \text{ Int } A) \text{ Un } (C \text{ Int } A)$
<proof>

lemma *subset-Int-iff*: $A \subseteq B \leftrightarrow A \text{ Int } B = A$
<proof>

lemma *subset-Int-iff2*: $A \subseteq B \iff B \text{ Int } A = A$
 $\langle \text{proof} \rangle$

lemma *Int-Diff-eq*: $C \subseteq A \implies (A - B) \text{ Int } C = C - B$
 $\langle \text{proof} \rangle$

lemma *Int-cons-left*:
 $\text{cons}(a, A) \text{ Int } B = (\text{if } a \in B \text{ then } \text{cons}(a, A \text{ Int } B) \text{ else } A \text{ Int } B)$
 $\langle \text{proof} \rangle$

lemma *Int-cons-right*:
 $A \text{ Int } \text{cons}(a, B) = (\text{if } a \in A \text{ then } \text{cons}(a, A \text{ Int } B) \text{ else } A \text{ Int } B)$
 $\langle \text{proof} \rangle$

lemma *cons-Int-distrib*: $\text{cons}(x, A \cap B) = \text{cons}(x, A) \cap \text{cons}(x, B)$
 $\langle \text{proof} \rangle$

4.5 Binary Union

lemma *Un-subset-iff*: $A \cup B \subseteq C \iff A \subseteq C \ \& \ B \subseteq C$
 $\langle \text{proof} \rangle$

lemma *Un-upper1*: $A \subseteq A \cup B$
 $\langle \text{proof} \rangle$

lemma *Un-upper2*: $B \subseteq A \cup B$
 $\langle \text{proof} \rangle$

lemma *Un-least*: $[\mid A \subseteq C; \ B \subseteq C \mid] \implies A \cup B \subseteq C$
 $\langle \text{proof} \rangle$

lemma *Un-cons*: $\text{cons}(a, B) \cup C = \text{cons}(a, B \cup C)$
 $\langle \text{proof} \rangle$

lemma *Un-absorb [simp]*: $A \cup A = A$
 $\langle \text{proof} \rangle$

lemma *Un-left-absorb*: $A \cup (A \cup B) = A \cup B$
 $\langle \text{proof} \rangle$

lemma *Un-commute*: $A \cup B = B \cup A$
 $\langle \text{proof} \rangle$

lemma *Un-left-commute*: $A \cup (B \cup C) = B \cup (A \cup C)$
 $\langle \text{proof} \rangle$

lemma *Un-assoc*: $(A \cup B) \cup C = A \cup (B \cup C)$
 $\langle \text{proof} \rangle$

lemmas $Un-ac = Un-assoc \ Un-left-absorb \ Un-commute \ Un-left-commute$

lemma $Un-absorb1: A \subseteq B ==> A \cup B = B$
 $\langle proof \rangle$

lemma $Un-absorb2: B \subseteq A ==> A \cup B = A$
 $\langle proof \rangle$

lemma $Un-Int-distrib: (A \ Int \ B) \ Un \ C = (A \ Un \ C) \ Int \ (B \ Un \ C)$
 $\langle proof \rangle$

lemma $subset-Un-iff: A \subseteq B <-> A \ Un \ B = B$
 $\langle proof \rangle$

lemma $subset-Un-iff2: A \subseteq B <-> B \ Un \ A = B$
 $\langle proof \rangle$

lemma $Un-empty \ [iff]: (A \ Un \ B = 0) <-> (A = 0 \ \& \ B = 0)$
 $\langle proof \rangle$

lemma $Un-eq-Union: A \ Un \ B = Union(\{A, B\})$
 $\langle proof \rangle$

4.6 Set Difference

lemma $Diff-subset: A - B \subseteq A$
 $\langle proof \rangle$

lemma $Diff-contains: [| \ C \subseteq A; \ C \ Int \ B = 0 \ |] ==> C \subseteq A - B$
 $\langle proof \rangle$

lemma $subset-Diff-cons-iff: B \subseteq A - cons(c, C) <-> B \subseteq A - C \ \& \ c \sim: B$
 $\langle proof \rangle$

lemma $Diff-cancel: A - A = 0$
 $\langle proof \rangle$

lemma $Diff-triv: A \ Int \ B = 0 ==> A - B = A$
 $\langle proof \rangle$

lemma $empty-Diff \ [simp]: 0 - A = 0$
 $\langle proof \rangle$

lemma $Diff-0 \ [simp]: A - 0 = A$
 $\langle proof \rangle$

lemma $Diff-eq-0-iff: A - B = 0 <-> A \subseteq B$
 $\langle proof \rangle$

lemma *Diff-cons*: $A - \text{cons}(a, B) = A - B - \{a\}$
 $\langle \text{proof} \rangle$

lemma *Diff-cons2*: $A - \text{cons}(a, B) = A - \{a\} - B$
 $\langle \text{proof} \rangle$

lemma *Diff-disjoint*: $A \text{ Int } (B - A) = 0$
 $\langle \text{proof} \rangle$

lemma *Diff-partition*: $A \subseteq B \implies A \text{ Un } (B - A) = B$
 $\langle \text{proof} \rangle$

lemma *subset-Un-Diff*: $A \subseteq B \text{ Un } (A - B)$
 $\langle \text{proof} \rangle$

lemma *double-complement*: $[A \subseteq B; B \subseteq C] \implies B - (C - A) = A$
 $\langle \text{proof} \rangle$

lemma *double-complement-Un*: $(A \text{ Un } B) - (B - A) = A$
 $\langle \text{proof} \rangle$

lemma *Un-Int-crazy*:
 $(A \text{ Int } B) \text{ Un } (B \text{ Int } C) \text{ Un } (C \text{ Int } A) = (A \text{ Un } B) \text{ Int } (B \text{ Un } C) \text{ Int } (C \text{ Un } A)$
 $\langle \text{proof} \rangle$

lemma *Diff-Un*: $A - (B \text{ Un } C) = (A - B) \text{ Int } (A - C)$
 $\langle \text{proof} \rangle$

lemma *Diff-Int*: $A - (B \text{ Int } C) = (A - B) \text{ Un } (A - C)$
 $\langle \text{proof} \rangle$

lemma *Un-Diff*: $(A \text{ Un } B) - C = (A - C) \text{ Un } (B - C)$
 $\langle \text{proof} \rangle$

lemma *Int-Diff*: $(A \text{ Int } B) - C = A \text{ Int } (B - C)$
 $\langle \text{proof} \rangle$

lemma *Diff-Int-distrib*: $C \text{ Int } (A - B) = (C \text{ Int } A) - (C \text{ Int } B)$
 $\langle \text{proof} \rangle$

lemma *Diff-Int-distrib2*: $(A - B) \text{ Int } C = (A \text{ Int } C) - (B \text{ Int } C)$
 $\langle \text{proof} \rangle$

lemma *Un-Int-assoc-iff*: $(A \text{ Int } B) \text{ Un } C = A \text{ Int } (B \text{ Un } C) \iff C \subseteq A$
 $\langle \text{proof} \rangle$

4.7 Big Union and Intersection

lemma *Union-subset-iff*: $Union(A) \subseteq C \leftrightarrow (\forall x \in A. x \subseteq C)$
 $\langle proof \rangle$

lemma *Union-upper*: $B \in A \implies B \subseteq Union(A)$
 $\langle proof \rangle$

lemma *Union-least*: $[\mid \forall x. x \in A \implies x \subseteq C \mid] \implies Union(A) \subseteq C$
 $\langle proof \rangle$

lemma *Union-cons* [simp]: $Union(cons(a, B)) = a \cup Union(B)$
 $\langle proof \rangle$

lemma *Union-Un-distrib*: $Union(A \cup B) = Union(A) \cup Union(B)$
 $\langle proof \rangle$

lemma *Union-Int-subset*: $Union(A \cap B) \subseteq Union(A) \cap Union(B)$
 $\langle proof \rangle$

lemma *Union-disjoint*: $Union(C) \cap A = 0 \leftrightarrow (\forall B \in C. B \cap A = 0)$
 $\langle proof \rangle$

lemma *Union-empty-iff*: $Union(A) = 0 \leftrightarrow (\forall B \in A. B = 0)$
 $\langle proof \rangle$

lemma *Int-Union2*: $Union(B) \cap A = (\bigcup C \in B. C \cap A)$
 $\langle proof \rangle$

lemma *Inter-subset-iff*: $A \neq 0 \implies C \subseteq Inter(A) \leftrightarrow (\forall x \in A. C \subseteq x)$
 $\langle proof \rangle$

lemma *Inter-lower*: $B \in A \implies Inter(A) \subseteq B$
 $\langle proof \rangle$

lemma *Inter-greatest*: $[\mid A \neq 0; \forall x. x \in A \implies C \subseteq x \mid] \implies C \subseteq Inter(A)$
 $\langle proof \rangle$

lemma *INT-lower*: $x \in A \implies (\bigcap x \in A. B(x)) \subseteq B(x)$
 $\langle proof \rangle$

lemma *INT-greatest*: $[\mid A \neq 0; \forall x. x \in A \implies C \subseteq B(x) \mid] \implies C \subseteq (\bigcap x \in A. B(x))$
 $\langle proof \rangle$

lemma *Inter-0* [simp]: $Inter(0) = 0$

$\langle proof \rangle$

lemma *Inter-Un-subset*:

$\llbracket z \in A; z \in B \rrbracket \implies Inter(A) \cup Inter(B) \subseteq Inter(A \text{ Int } B)$
 $\langle proof \rangle$

lemma *Inter-Un-distrib*:

$\llbracket A \neq 0; B \neq 0 \rrbracket \implies Inter(A \cup B) = Inter(A) \text{ Int } Inter(B)$
 $\langle proof \rangle$

lemma *Union-singleton*: $Union(\{b\}) = b$

$\langle proof \rangle$

lemma *Inter-singleton*: $Inter(\{b\}) = b$

$\langle proof \rangle$

lemma *Inter-cons* [simp]:

$Inter(cons(a, B)) = (\text{if } B=0 \text{ then } a \text{ else } a \text{ Int } Inter(B))$
 $\langle proof \rangle$

4.8 Unions and Intersections of Families

lemma *subset-UN-iff-eq*: $A \subseteq (\bigcup i \in I. B(i)) \iff A = (\bigcup i \in I. A \text{ Int } B(i))$

$\langle proof \rangle$

lemma *UN-subset-iff*: $(\bigcup x \in A. B(x)) \subseteq C \iff (\forall x \in A. B(x) \subseteq C)$

$\langle proof \rangle$

lemma *UN-upper*: $x \in A \implies B(x) \subseteq (\bigcup x \in A. B(x))$

$\langle proof \rangle$

lemma *UN-least*: $\llbracket \exists x. x \in A \implies B(x) \subseteq C \rrbracket \implies (\bigcup x \in A. B(x)) \subseteq C$

$\langle proof \rangle$

lemma *Union-eq-UN*: $Union(A) = (\bigcup x \in A. x)$

$\langle proof \rangle$

lemma *Inter-eq-INT*: $Inter(A) = (\bigcap x \in A. x)$

$\langle proof \rangle$

lemma *UN-0* [simp]: $(\bigcup i \in 0. A(i)) = 0$

$\langle proof \rangle$

lemma *UN-singleton*: $(\bigcup x \in A. \{x\}) = A$

$\langle proof \rangle$

lemma *UN-Un*: $(\bigcup i \in A \cup B. C(i)) = (\bigcup i \in A. C(i)) \cup (\bigcup i \in B. C(i))$

$\langle proof \rangle$

lemma *INT-Un*: $(\bigcap_{i \in I} \text{Un } J. A(i)) =$
 (if $I=0$ *then* $\bigcap_{j \in J. A(j)}$
 else if $J=0$ *then* $\bigcap_{i \in I. A(i)}$
 else $((\bigcap_{i \in I. A(i)) \text{Int } (\bigcap_{j \in J. A(j)))}$
 $\langle \text{proof} \rangle$

lemma *UN-UN-flatten*: $(\bigcup x \in (\bigcup_{y \in A. B(y)). C(x)) = (\bigcup_{y \in A. \bigcup_{x \in B(y). C(x)})$
 $\langle \text{proof} \rangle$

lemma *Int-UN-distrib*: $B \text{Int } (\bigcup_{i \in I. A(i)) = (\bigcup_{i \in I. B \text{Int } A(i)}$
 $\langle \text{proof} \rangle$

lemma *Un-INT-distrib*: $I \neq 0 \implies B \text{Un } (\bigcap_{i \in I. A(i)) = (\bigcap_{i \in I. B \text{Un } A(i)}$
 $\langle \text{proof} \rangle$

lemma *Int-UN-distrib2*:
 $(\bigcup_{i \in I. A(i)) \text{Int } (\bigcup_{j \in J. B(j)) = (\bigcup_{i \in I. \bigcup_{j \in J. A(i) \text{Int } B(j)}$
 $\langle \text{proof} \rangle$

lemma *Un-INT-distrib2*: $[I \neq 0; J \neq 0] \implies$
 $(\bigcap_{i \in I. A(i)) \text{Un } (\bigcap_{j \in J. B(j)) = (\bigcap_{i \in I. \bigcap_{j \in J. A(i) \text{Un } B(j)}$
 $\langle \text{proof} \rangle$

lemma *UN-constant [simp]*: $(\bigcup_{y \in A. c) = (\text{if } A=0 \text{ then } 0 \text{ else } c)$
 $\langle \text{proof} \rangle$

lemma *INT-constant [simp]*: $(\bigcap_{y \in A. c) = (\text{if } A=0 \text{ then } 0 \text{ else } c)$
 $\langle \text{proof} \rangle$

lemma *UN-RepFun [simp]*: $(\bigcup_{y \in \text{RepFun}(A, f). B(y)) = (\bigcup_{x \in A. B(f(x)))$
 $\langle \text{proof} \rangle$

lemma *INT-RepFun [simp]*: $(\bigcap_{x \in \text{RepFun}(A, f). B(x)) = (\bigcap_{a \in A. B(f(a)))$
 $\langle \text{proof} \rangle$

lemma *INT-Union-eq*:
 $0 \sim: A \implies (\bigcap_{x \in \text{Union}(A). B(x)) = (\bigcap_{y \in A. \bigcap_{x \in y. B(x)})$
 $\langle \text{proof} \rangle$

lemma *INT-UN-eq*:
 $(\forall x \in A. B(x) \sim 0)$
 $\implies (\bigcap_{z \in (\bigcup_{x \in A. B(x)). C(z)) = (\bigcap_{x \in A. \bigcap_{z \in B(x). C(z)}$
 $\langle \text{proof} \rangle$

lemma *UN-Un-distrib*:

$$(\bigcup_{i \in I}. A(i) \text{ Un } B(i)) = (\bigcup_{i \in I}. A(i)) \text{ Un } (\bigcup_{i \in I}. B(i))$$

<proof>

lemma *INT-Int-distrib*:

$$I \neq 0 \implies (\bigcap_{i \in I}. A(i) \text{ Int } B(i)) = (\bigcap_{i \in I}. A(i)) \text{ Int } (\bigcap_{i \in I}. B(i))$$

<proof>

lemma *UN-Int-subset*:

$$(\bigcup_{z \in I \text{ Int } J}. A(z)) \subseteq (\bigcup_{z \in I}. A(z)) \text{ Int } (\bigcup_{z \in J}. A(z))$$

<proof>

lemma *Diff-UN*: $I \neq 0 \implies B - (\bigcup_{i \in I}. A(i)) = (\bigcap_{i \in I}. B - A(i))$

<proof>

lemma *Diff-INT*: $I \neq 0 \implies B - (\bigcap_{i \in I}. A(i)) = (\bigcup_{i \in I}. B - A(i))$

<proof>

lemma *Sigma-cons1*: $\text{Sigma}(\text{cons}(a, B), C) = (\{a\} * C(a)) \text{ Un } \text{Sigma}(B, C)$

<proof>

lemma *Sigma-cons2*: $A * \text{cons}(b, B) = A * \{b\} \text{ Un } A * B$

<proof>

lemma *Sigma-succ1*: $\text{Sigma}(\text{succ}(A), B) = (\{A\} * B(A)) \text{ Un } \text{Sigma}(A, B)$

<proof>

lemma *Sigma-succ2*: $A * \text{succ}(B) = A * \{B\} \text{ Un } A * B$

<proof>

lemma *SUM-UN-distrib1*:

$$(\sum x \in (\bigcup_{y \in A}. C(y)). B(x)) = (\bigcup_{y \in A}. \sum x \in C(y). B(x))$$

<proof>

lemma *SUM-UN-distrib2*:

$$(\sum i \in I. \bigcup_{j \in J}. C(i, j)) = (\bigcup_{j \in J}. \sum i \in I. C(i, j))$$

<proof>

lemma *SUM-Un-distrib1*:

$$(\sum i \in I \text{ Un } J. C(i)) = (\sum i \in I. C(i)) \text{ Un } (\sum j \in J. C(j))$$

<proof>

lemma *SUM-Un-distrib2*:

$$(\Sigma i \in I. A(i) \text{ Un } B(i)) = (\Sigma i \in I. A(i)) \text{ Un } (\Sigma i \in I. B(i))$$

<proof>

lemma *prod-Un-distrib2*: $I * (A \text{ Un } B) = I * A \text{ Un } I * B$

<proof>

lemma *SUM-Int-distrib1*:

$$(\Sigma i \in I \text{ Int } J. C(i)) = (\Sigma i \in I. C(i)) \text{ Int } (\Sigma j \in J. C(j))$$

<proof>

lemma *SUM-Int-distrib2*:

$$(\Sigma i \in I. A(i) \text{ Int } B(i)) = (\Sigma i \in I. A(i)) \text{ Int } (\Sigma i \in I. B(i))$$

<proof>

lemma *prod-Int-distrib2*: $I * (A \text{ Int } B) = I * A \text{ Int } I * B$

<proof>

lemma *SUM-eq-UN*: $(\Sigma i \in I. A(i)) = (\bigcup i \in I. \{i\} * A(i))$

<proof>

lemma *times-subset-iff*:

$$(A' * B' \subseteq A * B) \leftrightarrow (A' = 0 \mid B' = 0 \mid (A' \subseteq A) \ \& \ (B' \subseteq B))$$

<proof>

lemma *Int-Sigma-eq*:

$$(\Sigma x \in A'. B'(x)) \text{ Int } (\Sigma x \in A. B(x)) = (\Sigma x \in A' \text{ Int } A. B'(x)) \text{ Int } B(x)$$

<proof>

lemma *domain-iff*: $a: \text{domain}(r) \leftrightarrow (EX y. \langle a, y \rangle \in r)$

<proof>

lemma *domainI* [intro]: $\langle a, b \rangle \in r \implies a: \text{domain}(r)$

<proof>

lemma *domainE* [elim!]:

$$[\mid a \in \text{domain}(r); \ !y. \langle a, y \rangle \in r \implies P \mid] \implies P$$

<proof>

lemma *domain-subset*: $\text{domain}(\text{Sigma}(A, B)) \subseteq A$

<proof>

lemma *domain-of-prod*: $b \in B \implies \text{domain}(A * B) = A$

$\langle \text{proof} \rangle$

lemma *domain-0* [simp]: $\text{domain}(0) = 0$
 $\langle \text{proof} \rangle$

lemma *domain-cons* [simp]: $\text{domain}(\text{cons}(\langle a, b \rangle, r)) = \text{cons}(a, \text{domain}(r))$
 $\langle \text{proof} \rangle$

lemma *domain-Un-eq* [simp]: $\text{domain}(A \text{ Un } B) = \text{domain}(A) \text{ Un } \text{domain}(B)$
 $\langle \text{proof} \rangle$

lemma *domain-Int-subset*: $\text{domain}(A \text{ Int } B) \subseteq \text{domain}(A) \text{ Int } \text{domain}(B)$
 $\langle \text{proof} \rangle$

lemma *domain-Diff-subset*: $\text{domain}(A) - \text{domain}(B) \subseteq \text{domain}(A - B)$
 $\langle \text{proof} \rangle$

lemma *domain-UN*: $\text{domain}(\bigcup x \in A. B(x)) = (\bigcup x \in A. \text{domain}(B(x)))$
 $\langle \text{proof} \rangle$

lemma *domain-Union*: $\text{domain}(\text{Union}(A)) = (\bigcup x \in A. \text{domain}(x))$
 $\langle \text{proof} \rangle$

lemma *rangeI* [intro]: $\langle a, b \rangle \in r \implies b \in \text{range}(r)$
 $\langle \text{proof} \rangle$

lemma *rangeE* [elim!]: $[\![\ b \in \text{range}(r); \ \exists x. \langle x, b \rangle \in r \implies P \]\!] \implies P$
 $\langle \text{proof} \rangle$

lemma *range-subset*: $\text{range}(A * B) \subseteq B$
 $\langle \text{proof} \rangle$

lemma *range-of-prod*: $a \in A \implies \text{range}(A * B) = B$
 $\langle \text{proof} \rangle$

lemma *range-0* [simp]: $\text{range}(0) = 0$
 $\langle \text{proof} \rangle$

lemma *range-cons* [simp]: $\text{range}(\text{cons}(\langle a, b \rangle, r)) = \text{cons}(b, \text{range}(r))$
 $\langle \text{proof} \rangle$

lemma *range-Un-eq* [simp]: $\text{range}(A \text{ Un } B) = \text{range}(A) \text{ Un } \text{range}(B)$
 $\langle \text{proof} \rangle$

lemma *range-Int-subset*: $\text{range}(A \text{ Int } B) \subseteq \text{range}(A) \text{ Int } \text{range}(B)$
 $\langle \text{proof} \rangle$

lemma *range-Diff-subset*: $\text{range}(A) - \text{range}(B) \subseteq \text{range}(A - B)$
 $\langle \text{proof} \rangle$

lemma *domain-converse* [simp]: $\text{domain}(\text{converse}(r)) = \text{range}(r)$
 $\langle \text{proof} \rangle$

lemma *range-converse* [simp]: $\text{range}(\text{converse}(r)) = \text{domain}(r)$
 $\langle \text{proof} \rangle$

lemma *fieldI1*: $\langle a, b \rangle \in r \implies a \in \text{field}(r)$
 $\langle \text{proof} \rangle$

lemma *fieldI2*: $\langle a, b \rangle \in r \implies b \in \text{field}(r)$
 $\langle \text{proof} \rangle$

lemma *fieldCI* [intro]:
 $(\sim \langle c, a \rangle \in r \implies \langle a, b \rangle \in r) \implies a \in \text{field}(r)$
 $\langle \text{proof} \rangle$

lemma *fieldE* [elim!]:
 $\begin{array}{l} \llbracket a \in \text{field}(r); \\ \quad \llbracket x. \langle a, x \rangle \in r \implies P; \\ \quad \llbracket x. \langle x, a \rangle \in r \implies P \quad \quad \quad \rrbracket \implies P \end{array}$
 $\langle \text{proof} \rangle$

lemma *field-subset*: $\text{field}(A * B) \subseteq A \cup B$
 $\langle \text{proof} \rangle$

lemma *domain-subset-field*: $\text{domain}(r) \subseteq \text{field}(r)$
 $\langle \text{proof} \rangle$

lemma *range-subset-field*: $\text{range}(r) \subseteq \text{field}(r)$
 $\langle \text{proof} \rangle$

lemma *domain-times-range*: $r \subseteq \text{Sigma}(A, B) \implies r \subseteq \text{domain}(r) * \text{range}(r)$
 $\langle \text{proof} \rangle$

lemma *field-times-field*: $r \subseteq \text{Sigma}(A, B) \implies r \subseteq \text{field}(r) * \text{field}(r)$
 $\langle \text{proof} \rangle$

lemma *relation-field-times-field*: $\text{relation}(r) \implies r \subseteq \text{field}(r) * \text{field}(r)$
 $\langle \text{proof} \rangle$

lemma *field-of-prod*: $\text{field}(A * A) = A$
 $\langle \text{proof} \rangle$

lemma *field-0* [*simp*]: $\text{field}(0) = 0$

<proof>

lemma *field-cons* [*simp*]: $\text{field}(\text{cons}(\langle a, b \rangle, r)) = \text{cons}(a, \text{cons}(b, \text{field}(r)))$

<proof>

lemma *field-Un-eq* [*simp*]: $\text{field}(A \text{ Un } B) = \text{field}(A) \text{ Un } \text{field}(B)$

<proof>

lemma *field-Int-subset*: $\text{field}(A \text{ Int } B) \subseteq \text{field}(A) \text{ Int } \text{field}(B)$

<proof>

lemma *field-Diff-subset*: $\text{field}(A) - \text{field}(B) \subseteq \text{field}(A - B)$

<proof>

lemma *field-converse* [*simp*]: $\text{field}(\text{converse}(r)) = \text{field}(r)$

<proof>

lemma *rel-Union*: $(\forall x \in S. \exists X A B. x \subseteq A * B) ==>$

$\text{Union}(S) \subseteq \text{domain}(\text{Union}(S)) * \text{range}(\text{Union}(S))$

<proof>

lemma *rel-Un*: $[\mid r \subseteq A * B; s \subseteq C * D \mid] ==> (r \text{ Un } s) \subseteq (A \text{ Un } C) * (B \text{ Un } D)$

<proof>

lemma *domain-Diff-eq*: $[\mid \langle a, c \rangle \in r; c \sim b \mid] ==> \text{domain}(r - \{\langle a, b \rangle\}) = \text{domain}(r)$

<proof>

lemma *range-Diff-eq*: $[\mid \langle c, b \rangle \in r; c \sim a \mid] ==> \text{range}(r - \{\langle a, b \rangle\}) = \text{range}(r)$

<proof>

4.9 Image of a Set under a Function or Relation

lemma *image-iff*: $b \in r''A \iff (\exists x \in A. \langle x, b \rangle \in r)$

<proof>

lemma *image-singleton-iff*: $b \in r''\{a\} \iff \langle a, b \rangle \in r$

<proof>

lemma *imageI* [*intro*]: $[\mid \langle a, b \rangle \in r; a \in A \mid] ==> b \in r''A$

<proof>

lemma *imageE* [*elim!*]:

$[\mid b \in r''A; !!x. [\mid \langle x, b \rangle \in r; x \in A \mid] ==> P \mid] ==> P$

<proof>

lemma *image-subset*: $r \subseteq A*B \implies r''C \subseteq B$

<proof>

lemma *image-0 [simp]*: $r''0 = 0$

<proof>

lemma *image-Un [simp]*: $r''(A \text{ Un } B) = (r''A) \text{ Un } (r''B)$

<proof>

lemma *image-UN*: $r''(\bigcup_{x \in A}. B(x)) = (\bigcup_{x \in A}. r''B(x))$

<proof>

lemma *Collect-image-eq*:

$\{z \in \text{Sigma}(A,B). P(z)\}''C = (\bigcup_{x \in A}. \{y \in B(x). x \in C \ \& \ P(\langle x,y \rangle)\})$

<proof>

lemma *image-Int-subset*: $r''(A \text{ Int } B) \subseteq (r''A) \text{ Int } (r''B)$

<proof>

lemma *image-Int-square-subset*: $(r \text{ Int } A*A)''B \subseteq (r''B) \text{ Int } A$

<proof>

lemma *image-Int-square*: $B \subseteq A \implies (r \text{ Int } A*A)''B = (r''B) \text{ Int } A$

<proof>

lemma *image-0-left [simp]*: $0''A = 0$

<proof>

lemma *image-Un-left*: $(r \text{ Un } s)''A = (r''A) \text{ Un } (s''A)$

<proof>

lemma *image-Int-subset-left*: $(r \text{ Int } s)''A \subseteq (r''A) \text{ Int } (s''A)$

<proof>

4.10 Inverse Image of a Set under a Function or Relation

lemma *vimage-iff*:

$a \in r-''B \iff (\exists y \in B. \langle a,y \rangle \in r)$

<proof>

lemma *vimage-singleton-iff*: $a \in r-''\{b\} \iff \langle a,b \rangle \in r$

<proof>

lemma *vimageI [intro]*: $[\langle a,b \rangle \in r; b \in B] \implies a \in r-''B$

<proof>

lemma *vimageE* [*elim!*]:

$\llbracket a: r - \text{``}B; !!x. \llbracket \langle a, x \rangle \in r; x \in B \rrbracket \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *vimage-subset*: $r \subseteq A * B \implies r - \text{``}C \subseteq A$

$\langle \text{proof} \rangle$

lemma *vimage-0* [*simp*]: $r - \text{``}0 = 0$

$\langle \text{proof} \rangle$

lemma *vimage-Un* [*simp*]: $r - \text{``}(A \text{ Un } B) = (r - \text{``}A) \text{ Un } (r - \text{``}B)$

$\langle \text{proof} \rangle$

lemma *vimage-Int-subset*: $r - \text{``}(A \text{ Int } B) \subseteq (r - \text{``}A) \text{ Int } (r - \text{``}B)$

$\langle \text{proof} \rangle$

lemma *vimage-eq-UN*: $f - \text{``}B = (\bigcup_{y \in B}. f - \text{``}\{y\})$

$\langle \text{proof} \rangle$

lemma *function-vimage-Int*:

$\text{function}(f) \implies f - \text{``}(A \text{ Int } B) = (f - \text{``}A) \text{ Int } (f - \text{``}B)$
 $\langle \text{proof} \rangle$

lemma *function-vimage-Diff*: $\text{function}(f) \implies f - \text{``}(A - B) = (f - \text{``}A) - (f - \text{``}B)$

$\langle \text{proof} \rangle$

lemma *function-image-vimage*: $\text{function}(f) \implies f - \text{``}(f - \text{``}A) \subseteq A$

$\langle \text{proof} \rangle$

lemma *vimage-Int-square-subset*: $(r \text{ Int } A * A) - \text{``}B \subseteq (r - \text{``}B) \text{ Int } A$

$\langle \text{proof} \rangle$

lemma *vimage-Int-square*: $B \subseteq A \implies (r \text{ Int } A * A) - \text{``}B = (r - \text{``}B) \text{ Int } A$

$\langle \text{proof} \rangle$

lemma *vimage-0-left* [*simp*]: $0 - \text{``}A = 0$

$\langle \text{proof} \rangle$

lemma *vimage-Un-left*: $(r \text{ Un } s) - \text{``}A = (r - \text{``}A) \text{ Un } (s - \text{``}A)$

$\langle \text{proof} \rangle$

lemma *vimage-Int-subset-left*: $(r \text{ Int } s) - \text{``}A \subseteq (r - \text{``}A) \text{ Int } (s - \text{``}A)$

$\langle \text{proof} \rangle$

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

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

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

lemma *converse-UN* [simp]: $\text{converse}(\bigcup x \in A. B(x)) = (\bigcup x \in A. \text{converse}(B(x)))$
 $\langle \text{proof} \rangle$

lemma *converse-INT* [simp]:
 $\text{converse}(\bigcap x \in A. B(x)) = (\bigcap x \in A. \text{converse}(B(x)))$
 $\langle \text{proof} \rangle$

4.11 Powerset Operator

lemma *Pow-0* [simp]: $\text{Pow}(0) = \{0\}$
 $\langle \text{proof} \rangle$

lemma *Pow-insert*: $\text{Pow}(\text{cons}(a, A)) = \text{Pow}(A) \text{ Un } \{\text{cons}(a, X) \mid X \in \text{Pow}(A)\}$
 $\langle \text{proof} \rangle$

lemma *Un-Pow-subset*: $\text{Pow}(A) \text{ Un } \text{Pow}(B) \subseteq \text{Pow}(A \text{ Un } B)$
 $\langle \text{proof} \rangle$

lemma *UN-Pow-subset*: $(\bigcup x \in A. \text{Pow}(B(x))) \subseteq \text{Pow}(\bigcup x \in A. B(x))$
 $\langle \text{proof} \rangle$

lemma *subset-Pow-Union*: $A \subseteq \text{Pow}(\text{Union}(A))$
 $\langle \text{proof} \rangle$

lemma *Union-Pow-eq* [simp]: $\text{Union}(\text{Pow}(A)) = A$
 $\langle \text{proof} \rangle$

lemma *Union-Pow-iff*: $\text{Union}(A) \in \text{Pow}(B) \iff A \in \text{Pow}(\text{Pow}(B))$
 $\langle \text{proof} \rangle$

lemma *Pow-Int-eq* [simp]: $\text{Pow}(A \text{ Int } B) = \text{Pow}(A) \text{ Int } \text{Pow}(B)$
 $\langle \text{proof} \rangle$

lemma *Pow-INT-eq*: $A \neq 0 \implies \text{Pow}(\bigcap x \in A. B(x)) = (\bigcap x \in A. \text{Pow}(B(x)))$
 $\langle \text{proof} \rangle$

4.12 RepFun

lemma *RepFun-subset*: $[\![\!| x. x \in A \implies f(x) \in B \!| \implies \{f(x). x \in A\} \subseteq B$
 $\langle proof \rangle$

lemma *RepFun-eq-0-iff* [simp]: $\{f(x). x \in A\} = 0 \iff A = 0$
 $\langle proof \rangle$

lemma *RepFun-constant* [simp]: $\{c. x \in A\} = (\text{if } A = 0 \text{ then } 0 \text{ else } \{c\})$
 $\langle proof \rangle$

4.13 Collect

lemma *Collect-subset*: $\text{Collect}(A, P) \subseteq A$
 $\langle proof \rangle$

lemma *Collect-Un*: $\text{Collect}(A \text{ Un } B, P) = \text{Collect}(A, P) \text{ Un } \text{Collect}(B, P)$
 $\langle proof \rangle$

lemma *Collect-Int*: $\text{Collect}(A \text{ Int } B, P) = \text{Collect}(A, P) \text{ Int } \text{Collect}(B, P)$
 $\langle proof \rangle$

lemma *Collect-Diff*: $\text{Collect}(A - B, P) = \text{Collect}(A, P) - \text{Collect}(B, P)$
 $\langle proof \rangle$

lemma *Collect-cons*: $\{x \in \text{cons}(a, B). P(x)\} =$
 $(\text{if } P(a) \text{ then } \text{cons}(a, \{x \in B. P(x)\}) \text{ else } \{x \in B. P(x)\})$
 $\langle proof \rangle$

lemma *Int-Collect-self-eq*: $A \text{ Int } \text{Collect}(A, P) = \text{Collect}(A, P)$
 $\langle proof \rangle$

lemma *Collect-Collect-eq* [simp]:
 $\text{Collect}(\text{Collect}(A, P), Q) = \text{Collect}(A, \%x. P(x) \ \& \ Q(x))$
 $\langle proof \rangle$

lemma *Collect-Int-Collect-eq*:
 $\text{Collect}(A, P) \text{ Int } \text{Collect}(A, Q) = \text{Collect}(A, \%x. P(x) \ \& \ Q(x))$
 $\langle proof \rangle$

lemma *Collect-Union-eq* [simp]:
 $\text{Collect}(\bigcup x \in A. B(x), P) = (\bigcup x \in A. \text{Collect}(B(x), P))$
 $\langle proof \rangle$

lemma *Collect-Int-left*: $\{x \in A. P(x)\} \text{ Int } B = \{x \in A \text{ Int } B. P(x)\}$
 $\langle proof \rangle$

lemma *Collect-Int-right*: $A \text{ Int } \{x \in B. P(x)\} = \{x \in A \text{ Int } B. P(x)\}$
 $\langle proof \rangle$

lemma *Collect-disj-eq*: $\{x \in A. P(x) \mid Q(x)\} = \text{Collect}(A, P) \text{ Un } \text{Collect}(A, Q)$
 $\langle \text{proof} \rangle$

lemma *Collect-conj-eq*: $\{x \in A. P(x) \ \& \ Q(x)\} = \text{Collect}(A, P) \text{ Int } \text{Collect}(A, Q)$
 $\langle \text{proof} \rangle$

lemmas *subset-SIs* = *subset-refl cons-subsetI subset-consI*
Union-least UN-least Un-least
Inter-greatest Int-greatest RepFun-subset
Un-upper1 Un-upper2 Int-lower1 Int-lower2

$\langle ML \rangle$

end

5 Fixedpt: Least and Greatest Fixed Points; the Knaster-Tarski Theorem

theory *Fixedpt* **imports** *equalities* **begin**

definition

bnd-mono :: $[i, i \Rightarrow i] \Rightarrow o$ **where**
 $\text{bnd-mono}(D, h) == h(D) \leq D \ \& \ (\text{ALL } W \ X. W \leq X \longrightarrow X \leq D \longrightarrow h(W) \leq h(X))$

definition

lfp :: $[i, i \Rightarrow i] \Rightarrow i$ **where**
 $\text{lfp}(D, h) == \text{Inter}(\{X: \text{Pow}(D). h(X) \leq X\})$

definition

gfp :: $[i, i \Rightarrow i] \Rightarrow i$ **where**
 $\text{gfp}(D, h) == \text{Union}(\{X: \text{Pow}(D). X \leq h(X)\})$

The theorem is proved in the lattice of subsets of D , namely $\text{Pow}(D)$, with Inter as the greatest lower bound.

5.1 Monotone Operators

lemma *bnd-monoI*:

$[\mid h(D) \leq D;$
 $\quad \text{!! } W \ X. [\mid W \leq D; X \leq D; W \leq X] \implies h(W) \leq h(X)$
 $\quad \mid] \implies \text{bnd-mono}(D, h)$
 $\langle \text{proof} \rangle$

lemma *bnd-monoD1*: $\text{bnd-mono}(D, h) \implies h(D) \leq D$

$\langle proof \rangle$

lemma *bnd-monoD2*: $\llbracket \text{bnd-mono}(D, h); W \leq X; X \leq D \rrbracket \implies h(W) \leq h(X)$
 $\langle proof \rangle$

lemma *bnd-mono-subset*:
 $\llbracket \text{bnd-mono}(D, h); X \leq D \rrbracket \implies h(X) \leq D$
 $\langle proof \rangle$

lemma *bnd-mono-Un*:
 $\llbracket \text{bnd-mono}(D, h); A \leq D; B \leq D \rrbracket \implies h(A) \text{ Un } h(B) \leq h(A \text{ Un } B)$
 $\langle proof \rangle$

lemma *bnd-mono-UN*:
 $\llbracket \text{bnd-mono}(D, h); \forall i \in I. A(i) \leq D \rrbracket \implies h(\bigcup_{i \in I} A(i)) \leq h(\bigcup_{i \in I} A(i))$
 $\langle proof \rangle$

lemma *bnd-mono-Int*:
 $\llbracket \text{bnd-mono}(D, h); A \leq D; B \leq D \rrbracket \implies h(A \text{ Int } B) \leq h(A) \text{ Int } h(B)$
 $\langle proof \rangle$

5.2 Proof of Knaster-Tarski Theorem using *lfp*

lemma *lfp-lowerbound*:
 $\llbracket h(A) \leq A; A \leq D \rrbracket \implies \text{lfp}(D, h) \leq A$
 $\langle proof \rangle$

lemma *lfp-subset*: $\text{lfp}(D, h) \leq D$
 $\langle proof \rangle$

lemma *def-lfp-subset*: $A == \text{lfp}(D, h) \implies A \leq D$
 $\langle proof \rangle$

lemma *lfp-greatest*:
 $\llbracket h(D) \leq D; \forall X. \llbracket h(X) \leq X; X \leq D \rrbracket \implies A \leq X \rrbracket \implies A \leq \text{lfp}(D, h)$
 $\langle proof \rangle$

lemma *lfp-lemma1*:
 $\llbracket \text{bnd-mono}(D, h); h(A) \leq A; A \leq D \rrbracket \implies h(\text{lfp}(D, h)) \leq A$
 $\langle proof \rangle$

lemma *lfp-lemma2*: $\text{bnd-mono}(D, h) \implies h(\text{lfp}(D, h)) \leq \text{lfp}(D, h)$

$\langle proof \rangle$

lemma *lfp-lemma3*:

$bnd\text{-}mono(D, h) ==> lfp(D, h) \leq h(lfp(D, h))$

$\langle proof \rangle$

lemma *lfp-unfold*: $bnd\text{-}mono(D, h) ==> lfp(D, h) = h(lfp(D, h))$

$\langle proof \rangle$

lemma *def-lfp-unfold*:

$[| A == lfp(D, h); \ bnd\text{-}mono(D, h) |] ==> A = h(A)$

$\langle proof \rangle$

5.3 General Induction Rule for Least Fixedpoints

lemma *Collect-is-pre-fixedpt*:

$[| \ bnd\text{-}mono(D, h); \ !!x. x : h(Collect(lfp(D, h), P)) ==> P(x) \ |]$
 $==> h(Collect(lfp(D, h), P)) \leq Collect(lfp(D, h), P)$

$\langle proof \rangle$

lemma *induct*:

$[| \ bnd\text{-}mono(D, h); \ a : lfp(D, h);$
 $\quad !!x. x : h(Collect(lfp(D, h), P)) ==> P(x)$
 $\quad |] ==> P(a)$

$\langle proof \rangle$

lemma *def-induct*:

$[| \ A == lfp(D, h); \ bnd\text{-}mono(D, h); \ a:A;$
 $\quad !!x. x : h(Collect(A, P)) ==> P(x)$
 $\quad |] ==> P(a)$

$\langle proof \rangle$

lemma *lfp-Int-lowerbound*:

$[| \ h(D \text{ Int } A) \leq A; \ bnd\text{-}mono(D, h) \ |] ==> lfp(D, h) \leq A$

$\langle proof \rangle$

lemma *lfp-mono*:

assumes *hmono*: $bnd\text{-}mono(D, h)$

and *imono*: $bnd\text{-}mono(E, i)$

and *subhi*: $!!X. X \leq D ==> h(X) \leq i(X)$

shows $lfp(D, h) \leq lfp(E, i)$

$\langle proof \rangle$

lemma *lfp-mono2*:

$\llbracket i(D) \leq D; \forall X. X \leq D \implies h(X) \leq i(X) \rrbracket \implies \text{lfp}(D, h) \leq \text{lfp}(D, i)$
 $\langle \text{proof} \rangle$

lemma *lfp-cong*:

$\llbracket D = D'; \forall X. X \leq D' \implies h(X) = h'(X) \rrbracket \implies \text{lfp}(D, h) = \text{lfp}(D', h')$
 $\langle \text{proof} \rangle$

5.4 Proof of Knaster-Tarski Theorem using *gfp*

lemma *gfp-upperbound*: $\llbracket A \leq h(A); A \leq D \rrbracket \implies A \leq \text{gfp}(D, h)$
 $\langle \text{proof} \rangle$

lemma *gfp-subset*: $\text{gfp}(D, h) \leq D$
 $\langle \text{proof} \rangle$

lemma *def-gfp-subset*: $A = \text{gfp}(D, h) \implies A \leq D$
 $\langle \text{proof} \rangle$

lemma *gfp-least*:

$\llbracket \text{bnd-mono}(D, h); \forall X. \llbracket X \leq h(X); X \leq D \rrbracket \implies X \leq A \rrbracket \implies$
 $\text{gfp}(D, h) \leq A$
 $\langle \text{proof} \rangle$

lemma *gfp-lemma1*:

$\llbracket \text{bnd-mono}(D, h); A \leq h(A); A \leq D \rrbracket \implies A \leq h(\text{gfp}(D, h))$
 $\langle \text{proof} \rangle$

lemma *gfp-lemma2*: $\text{bnd-mono}(D, h) \implies \text{gfp}(D, h) \leq h(\text{gfp}(D, h))$
 $\langle \text{proof} \rangle$

lemma *gfp-lemma3*:

$\text{bnd-mono}(D, h) \implies h(\text{gfp}(D, h)) \leq \text{gfp}(D, h)$
 $\langle \text{proof} \rangle$

lemma *gfp-unfold*: $\text{bnd-mono}(D, h) \implies \text{gfp}(D, h) = h(\text{gfp}(D, h))$
 $\langle \text{proof} \rangle$

lemma *def-gfp-unfold*:

$\llbracket A = \text{gfp}(D, h); \text{bnd-mono}(D, h) \rrbracket \implies A = h(A)$
 $\langle \text{proof} \rangle$

5.5 Coinduction Rules for Greatest Fixed Points

lemma *weak-coinduct*: $\llbracket a : X; X \leq h(X); X \leq D \rrbracket \implies a : \text{gfp}(D, h)$
 $\langle \text{proof} \rangle$

lemma *coinduct-lemma*:

$$[[X \leq h(X \text{ Un } \text{gfp}(D, h)); X \leq D; \text{ bnd-mono}(D, h)]] \implies$$

$$X \text{ Un } \text{gfp}(D, h) \leq h(X \text{ Un } \text{gfp}(D, h))$$

$$\langle \text{proof} \rangle$$

lemma *coinduct*:

$$[[\text{ bnd-mono}(D, h); a : X; X \leq h(X \text{ Un } \text{gfp}(D, h)); X \leq D]]$$

$$\implies a : \text{gfp}(D, h)$$

$$\langle \text{proof} \rangle$$

lemma *def-coinduct*:

$$[[A == \text{gfp}(D, h); \text{ bnd-mono}(D, h); a : X; X \leq h(X \text{ Un } A); X \leq D]]$$

$$\implies$$

$$a : A$$

$$\langle \text{proof} \rangle$$

lemma *def-Collect-coinduct*:

$$[[A == \text{gfp}(D, \%w. \text{Collect}(D, P(w))); \text{ bnd-mono}(D, \%w. \text{Collect}(D, P(w)));$$

$$a : X; X \leq D; !!z. z : X \implies P(X \text{ Un } A, z)]] \implies$$

$$a : A$$

$$\langle \text{proof} \rangle$$

lemma *gfp-mono*:

$$[[\text{ bnd-mono}(D, h); D \leq E;$$

$$!!X. X \leq D \implies h(X) \leq i(X)]] \implies \text{gfp}(D, h) \leq \text{gfp}(E, i)$$

$$\langle \text{proof} \rangle$$

end

6 Bool: Booleans in Zermelo-Fraenkel Set Theory

theory *Bool* **imports** *pair* **begin**

abbreviation

$$\text{one} \ (1) \ \mathbf{where}$$

$$1 == \text{succ}(0)$$

abbreviation

$$\text{two} \ (2) \ \mathbf{where}$$

$$2 == \text{succ}(1)$$

2 is equal to bool, but is used as a number rather than a type.

definition *bool* == $\{0, 1\}$

definition $\text{cond}(b,c,d) == \text{if}(b=1,c,d)$

definition $\text{not}(b) == \text{cond}(b,0,1)$

definition

$\text{and} \quad :: [i,i] ==> i \quad (\text{infixl and } 70) \quad \text{where}$
 $a \text{ and } b == \text{cond}(a,b,0)$

definition

$\text{or} \quad :: [i,i] ==> i \quad (\text{infixl or } 65) \quad \text{where}$
 $a \text{ or } b == \text{cond}(a,1,b)$

definition

$\text{xor} \quad :: [i,i] ==> i \quad (\text{infixl xor } 65) \quad \text{where}$
 $a \text{ xor } b == \text{cond}(a,\text{not}(b),b)$

lemmas $\text{bool-defs} = \text{bool-def cond-def}$

lemma $\text{singleton-0}: \{0\} = 1$
 $\langle \text{proof} \rangle$

lemma $\text{bool-1I} \text{ [simp,TC]}: 1 : \text{bool}$
 $\langle \text{proof} \rangle$

lemma $\text{bool-0I} \text{ [simp,TC]}: 0 : \text{bool}$
 $\langle \text{proof} \rangle$

lemma $\text{one-not-0}: 1 \sim 0$
 $\langle \text{proof} \rangle$

lemmas $\text{one-neq-0} = \text{one-not-0} \text{ [THEN notE, standard]}$

lemma boolE :
 $\llbracket c : \text{bool}; \quad c=1 ==> P; \quad c=0 ==> P \rrbracket ==> P$
 $\langle \text{proof} \rangle$

lemma $\text{cond-1} \text{ [simp]}: \text{cond}(1,c,d) = c$
 $\langle \text{proof} \rangle$

lemma $\text{cond-0} \text{ [simp]}: \text{cond}(0,c,d) = d$
 $\langle \text{proof} \rangle$

lemma *cond-type* [TC]: [| *b*: bool; *c*: A(1); *d*: A(0) |] ==> *cond*(*b*,*c*,*d*): A(*b*)
 <proof>

lemma *cond-simple-type*: [| *b*: bool; *c*: A; *d*: A |] ==> *cond*(*b*,*c*,*d*): A
 <proof>

lemma *def-cond-1*: [| !!*b*. *j*(*b*)==cond(*b*,*c*,*d*) |] ==> *j*(1) = *c*
 <proof>

lemma *def-cond-0*: [| !!*b*. *j*(*b*)==cond(*b*,*c*,*d*) |] ==> *j*(0) = *d*
 <proof>

lemmas *not-1* = *not-def* [THEN *def-cond-1*, *standard*, *simp*]
lemmas *not-0* = *not-def* [THEN *def-cond-0*, *standard*, *simp*]

lemmas *and-1* = *and-def* [THEN *def-cond-1*, *standard*, *simp*]
lemmas *and-0* = *and-def* [THEN *def-cond-0*, *standard*, *simp*]

lemmas *or-1* = *or-def* [THEN *def-cond-1*, *standard*, *simp*]
lemmas *or-0* = *or-def* [THEN *def-cond-0*, *standard*, *simp*]

lemmas *xor-1* = *xor-def* [THEN *def-cond-1*, *standard*, *simp*]
lemmas *xor-0* = *xor-def* [THEN *def-cond-0*, *standard*, *simp*]

lemma *not-type* [TC]: *a*:bool ==> *not*(*a*) : bool
 <proof>

lemma *and-type* [TC]: [| *a*:bool; *b*:bool |] ==> *a and b* : bool
 <proof>

lemma *or-type* [TC]: [| *a*:bool; *b*:bool |] ==> *a or b* : bool
 <proof>

lemma *xor-type* [TC]: [| *a*:bool; *b*:bool |] ==> *a xor b* : bool
 <proof>

lemmas *bool-typechecks* = *bool-1I bool-0I cond-type not-type and-type*
or-type xor-type

6.1 Laws About 'not'

lemma *not-not* [*simp*]: *a*:bool ==> *not*(*not*(*a*)) = *a*
 <proof>

lemma *not-and* [*simp*]: *a*:bool ==> *not*(*a and b*) = *not*(*a*) *or not*(*b*)
 <proof>

lemma *not-or* [simp]: $a:\text{bool} \implies \text{not}(a \text{ or } b) = \text{not}(a) \text{ and } \text{not}(b)$
 $\langle \text{proof} \rangle$

6.2 Laws About 'and'

lemma *and-absorb* [simp]: $a:\text{bool} \implies a \text{ and } a = a$
 $\langle \text{proof} \rangle$

lemma *and-commute*: $[| a:\text{bool}; b:\text{bool} |] \implies a \text{ and } b = b \text{ and } a$
 $\langle \text{proof} \rangle$

lemma *and-assoc*: $a:\text{bool} \implies (a \text{ and } b) \text{ and } c = a \text{ and } (b \text{ and } c)$
 $\langle \text{proof} \rangle$

lemma *and-or-distrib*: $[| a:\text{bool}; b:\text{bool}; c:\text{bool} |] \implies$
 $(a \text{ or } b) \text{ and } c = (a \text{ and } c) \text{ or } (b \text{ and } c)$
 $\langle \text{proof} \rangle$

6.3 Laws About 'or'

lemma *or-absorb* [simp]: $a:\text{bool} \implies a \text{ or } a = a$
 $\langle \text{proof} \rangle$

lemma *or-commute*: $[| a:\text{bool}; b:\text{bool} |] \implies a \text{ or } b = b \text{ or } a$
 $\langle \text{proof} \rangle$

lemma *or-assoc*: $a:\text{bool} \implies (a \text{ or } b) \text{ or } c = a \text{ or } (b \text{ or } c)$
 $\langle \text{proof} \rangle$

lemma *or-and-distrib*: $[| a:\text{bool}; b:\text{bool}; c:\text{bool} |] \implies$
 $(a \text{ and } b) \text{ or } c = (a \text{ or } c) \text{ and } (b \text{ or } c)$
 $\langle \text{proof} \rangle$

definition

$\text{bool-of-o} :: o \Rightarrow i$ **where**
 $\text{bool-of-o}(P) == (\text{if } P \text{ then } 1 \text{ else } 0)$

lemma [simp]: $\text{bool-of-o}(\text{True}) = 1$
 $\langle \text{proof} \rangle$

lemma [simp]: $\text{bool-of-o}(\text{False}) = 0$
 $\langle \text{proof} \rangle$

lemma [simp,TC]: $\text{bool-of-o}(P) \in \text{bool}$
 $\langle \text{proof} \rangle$

lemma [simp]: $(\text{bool-of-o}(P) = 1) <-> P$
 $\langle \text{proof} \rangle$

lemma *[simp]*: $(\text{bool-of-o}(P) = 0) <-> \sim P$
 $\langle \text{proof} \rangle$

$\langle ML \rangle$

end

7 Sum: Disjoint Sums

theory *Sum* **imports** *Bool equalities* **begin**

And the "Part" primitive for simultaneous recursive type definitions

global

constdefs

sum :: $[i, i] => i$ (infixr + 65)
 $A + B == \{0\} * A \text{ Un } \{1\} * B$

Inl :: $i => i$
 $\text{Inl}(a) == <0, a>$

Inr :: $i => i$
 $\text{Inr}(b) == <1, b>$

case :: $[i => i, i => i, i] => i$
 $\text{case}(c, d) == (\%<y, z>. \text{cond}(y, d(z), c(z)))$

Part :: $[i, i => i] => i$
 $\text{Part}(A, h) == \{x: A. \text{EX } z. x = h(z)\}$

local

7.1 Rules for the *Part* Primitive

lemma *Part-iff*:

$a : \text{Part}(A, h) <-> a : A \ \& \ (\text{EX } y. a = h(y))$
 $\langle \text{proof} \rangle$

lemma *Part-eqI* [*intro*]:

$[[a : A; a = h(b)]] ==> a : \text{Part}(A, h)$
 $\langle \text{proof} \rangle$

lemmas *PartI* = *refl* [*THEN* [2] *Part-eqI*]

lemma *PartE* [*elim!*]:

$[[a : \text{Part}(A, h); !!z. [[a : A; a = h(z)]] ==> P]]$
 $==> P$

$\langle proof \rangle$

lemma *Part-subset*: $Part(A, h) \leq A$
 $\langle proof \rangle$

7.2 Rules for Disjoint Sums

lemmas *sum-defs* = *sum-def Inl-def Inr-def case-def*

lemma *Sigma-bool*: $Sigma(bool, C) = C(0) + C(1)$
 $\langle proof \rangle$

lemma *InlI* [*intro!*, *simp*, *TC*]: $a : A \implies Inl(a) : A+B$
 $\langle proof \rangle$

lemma *InrI* [*intro!*, *simp*, *TC*]: $b : B \implies Inr(b) : A+B$
 $\langle proof \rangle$

lemma *sumE* [*elim!*]:
 $[| u : A+B;$
 $!!x. [| x:A; u=Inl(x) |] \implies P;$
 $!!y. [| y:B; u=Inr(y) |] \implies P$
 $|] \implies P$
 $\langle proof \rangle$

lemma *Inl-iff* [*iff*]: $Inl(a)=Inl(b) \iff a=b$
 $\langle proof \rangle$

lemma *Inr-iff* [*iff*]: $Inr(a)=Inr(b) \iff a=b$
 $\langle proof \rangle$

lemma *Inl-Inr-iff* [*simp*]: $Inl(a)=Inr(b) \iff False$
 $\langle proof \rangle$

lemma *Inr-Inl-iff* [*simp*]: $Inr(b)=Inl(a) \iff False$
 $\langle proof \rangle$

lemma *sum-empty* [*simp*]: $0+0 = 0$
 $\langle proof \rangle$

lemmas *Inl-inject* = *Inl-iff [THEN iffD1, standard]*

lemmas $Inr-inject = Inr-iff$ [*THEN* $iffD1$, *standard*]
lemmas $Inl-neq-Inr = Inl-Inr-iff$ [*THEN* $iffD1$, *THEN* $FalseE$, *elim!*]
lemmas $Inr-neq-Inl = Inr-Inl-iff$ [*THEN* $iffD1$, *THEN* $FalseE$, *elim!*]

lemma $InlD$: $Inl(a): A+B ==> a: A$
 $\langle proof \rangle$

lemma $InrD$: $Inr(b): A+B ==> b: B$
 $\langle proof \rangle$

lemma $sum-iff$: $u: A+B <-> (EX\ x.\ x:A \ \&\ u=Inl(x)) \mid (EX\ y.\ y:B \ \&\ u=Inr(y))$
 $\langle proof \rangle$

lemma $Inl-in-sum-iff$ [*simp*]: $(Inl(x) \in A+B) <-> (x \in A)$
 $\langle proof \rangle$

lemma $Inr-in-sum-iff$ [*simp*]: $(Inr(y) \in A+B) <-> (y \in B)$
 $\langle proof \rangle$

lemma $sum-subset-iff$: $A+B <= C+D <-> A<=C \ \&\ B<=D$
 $\langle proof \rangle$

lemma $sum-equal-iff$: $A+B = C+D <-> A=C \ \&\ B=D$
 $\langle proof \rangle$

lemma $sum-eq-2-times$: $A+A = 2*A$
 $\langle proof \rangle$

7.3 The Eliminator: *case*

lemma $case-Inl$ [*simp*]: $case(c, d, Inl(a)) = c(a)$
 $\langle proof \rangle$

lemma $case-Inr$ [*simp*]: $case(c, d, Inr(b)) = d(b)$
 $\langle proof \rangle$

lemma $case-type$ [*TC*]:

$$\begin{aligned} &[[\ u: A+B; \\ &\quad !!x.\ x: A ==> c(x): C(Inl(x)); \\ &\quad !!y.\ y: B ==> d(y): C(Inr(y)) \\ &]] ==> case(c,d,u) : C(u) \end{aligned}$$
 $\langle proof \rangle$

lemma $expand-case$: $u: A+B ==>$

$$\begin{aligned} &R(case(c,d,u)) <-> \\ &((ALL\ x:A.\ u = Inl(x) --> R(c(x))) \ \&\ \\ &(ALL\ y:B.\ u = Inr(y) --> R(d(y)))) \end{aligned}$$
 $\langle proof \rangle$

lemma *case-cong*:

```

  [| z: A+B;
    !!x. x:A ==> c(x)=c'(x);
    !!y. y:B ==> d(y)=d'(y)
  |] ==> case(c,d,z) = case(c',d',z)
<proof>

```

lemma *case-case*: $z: A+B \implies$

```

  case(c, d, case(%x. Inl(c'(x)), %y. Inr(d'(y)), z)) =
  case(%x. c(c'(x)), %y. d(d'(y)), z)
<proof>

```

7.4 More Rules for $Part(A, h)$

lemma *Part-mono*: $A \leq B \implies Part(A, h) \leq Part(B, h)$
 <proof>

lemma *Part-Collect*: $Part(Collect(A, P), h) = Collect(Part(A, h), P)$
 <proof>

lemmas *Part-CollectE* =

Part-Collect [*THEN equalityD1*, *THEN subsetD*, *THEN CollectE*, *standard*]

lemma *Part-Inl*: $Part(A+B, Inl) = \{Inl(x). x: A\}$
 <proof>

lemma *Part-Inr*: $Part(A+B, Inr) = \{Inr(y). y: B\}$
 <proof>

lemma *PartD1*: $a : Part(A, h) \implies a : A$
 <proof>

lemma *Part-id*: $Part(A, \%x. x) = A$
 <proof>

lemma *Part-Inr2*: $Part(A+B, \%x. Inr(h(x))) = \{Inr(y). y: Part(B, h)\}$
 <proof>

lemma *Part-sum-equality*: $C \leq A+B \implies Part(C, Inl) \cup Part(C, Inr) = C$
 <proof>

end

8 func: Functions, Function Spaces, Lambda-Abstraction

theory *func* **imports** *equalities Sum* **begin**

8.1 The Pi Operator: Dependent Function Space

lemma *subset-Sigma-imp-relation*: $r \leq \text{Sigma}(A,B) \implies \text{relation}(r)$
 $\langle \text{proof} \rangle$

lemma *relation-converse-converse* [simp]:
 $\text{relation}(r) \implies \text{converse}(\text{converse}(r)) = r$
 $\langle \text{proof} \rangle$

lemma *relation-restrict* [simp]: $\text{relation}(\text{restrict}(r,A))$
 $\langle \text{proof} \rangle$

lemma *Pi-iff*:
 $f: \text{Pi}(A,B) \iff \text{function}(f) \ \& \ f \leq \text{Sigma}(A,B) \ \& \ A \leq \text{domain}(f)$
 $\langle \text{proof} \rangle$

lemma *Pi-iff-old*:
 $f: \text{Pi}(A,B) \iff f \leq \text{Sigma}(A,B) \ \& \ (\text{ALL } x:A. \text{EX! } y. \langle x,y \rangle : f)$
 $\langle \text{proof} \rangle$

lemma *fun-is-function*: $f: \text{Pi}(A,B) \implies \text{function}(f)$
 $\langle \text{proof} \rangle$

lemma *function-imp-Pi*:
 $[\text{function}(f); \text{relation}(f)] \implies f \in \text{domain}(f) \multimap \text{range}(f)$
 $\langle \text{proof} \rangle$

lemma *functionI*:
 $[\text{!!}x \ y \ y'. [\langle x,y \rangle : r; \langle x,y' \rangle : r] \implies y=y'] \implies \text{function}(r)$
 $\langle \text{proof} \rangle$

lemma *fun-is-rel*: $f: \text{Pi}(A,B) \implies f \leq \text{Sigma}(A,B)$
 $\langle \text{proof} \rangle$

lemma *Pi-cong*:
 $[\text{A}=\text{A}'; \text{!!}x. x:\text{A}' \implies B(x)=B'(x)] \implies \text{Pi}(A,B) = \text{Pi}(A',B')$
 $\langle \text{proof} \rangle$

lemma *fun-weaken-type*: $[\text{f}: \text{A} \multimap \text{B}; \text{B} \leq \text{D}] \implies \text{f}: \text{A} \multimap \text{D}$
 $\langle \text{proof} \rangle$

8.2 Function Application

lemma *apply-equality2*: $[\langle a,b \rangle : f; \langle a,c \rangle : f; f: \text{Pi}(A,B)] \implies b=c$
 $\langle \text{proof} \rangle$

lemma *function-apply-equality*: $[[\langle a, b \rangle : f; \text{function}(f)]] \implies f'a = b$
 $\langle \text{proof} \rangle$

lemma *apply-equality*: $[[\langle a, b \rangle : f; f : \text{Pi}(A, B)]] \implies f'a = b$
 $\langle \text{proof} \rangle$

lemma *apply-0*: $a \sim : \text{domain}(f) \implies f'a = 0$
 $\langle \text{proof} \rangle$

lemma *Pi-memberD*: $[[f : \text{Pi}(A, B); c : f]] \implies \text{EX } x : A. c = \langle x, f'x \rangle$
 $\langle \text{proof} \rangle$

lemma *function-apply-Pair*: $[[\text{function}(f); a : \text{domain}(f)]] \implies \langle a, f'a \rangle : f$
 $\langle \text{proof} \rangle$

lemma *apply-Pair*: $[[f : \text{Pi}(A, B); a : A]] \implies \langle a, f'a \rangle : f$
 $\langle \text{proof} \rangle$

lemma *apply-type* [TC]: $[[f : \text{Pi}(A, B); a : A]] \implies f'a : B(a)$
 $\langle \text{proof} \rangle$

lemma *apply-funtype*: $[[f : A \multimap B; a : A]] \implies f'a : B$
 $\langle \text{proof} \rangle$

lemma *apply-iff*: $f : \text{Pi}(A, B) \implies \langle a, b \rangle : f \iff a : A \ \& \ f'a = b$
 $\langle \text{proof} \rangle$

lemma *Pi-type*: $[[f : \text{Pi}(A, C); !!x. x : A \implies f'x : B(x)]] \implies f : \text{Pi}(A, B)$
 $\langle \text{proof} \rangle$

lemma *Pi-Collect-iff*:
 $(f : \text{Pi}(A, \%x. \{y : B(x). P(x, y)\}))$
 $\iff f : \text{Pi}(A, B) \ \& \ (\text{ALL } x : A. P(x, f'x))$
 $\langle \text{proof} \rangle$

lemma *Pi-weaken-type*:
 $[[f : \text{Pi}(A, B); !!x. x : A \implies B(x) \leq C(x)]] \implies f : \text{Pi}(A, C)$
 $\langle \text{proof} \rangle$

lemma *domain-type*: $[[\langle a, b \rangle : f; f : \text{Pi}(A, B)]] \implies a : A$

$\langle proof \rangle$

lemma *range-type*: $[| <a,b> : f; f : Pi(A,B) |] ==> b : B(a)$
 $\langle proof \rangle$

lemma *Pair-mem-PiD*: $[| <a,b> : f; f : Pi(A,B) |] ==> a:A \& b:B(a) \& f'a = b$
 $\langle proof \rangle$

8.3 Lambda Abstraction

lemma *lamI*: $a:A ==> <a,b(a)> : (lam\ x:A. b(x))$
 $\langle proof \rangle$

lemma *lamE*:
 $[| p : (lam\ x:A. b(x)); !!x. [x:A; p=<x,b(x)>] |] ==> P$
 $\langle proof \rangle$

lemma *lamD*: $[| <a,c> : (lam\ x:A. b(x)) |] ==> c = b(a)$
 $\langle proof \rangle$

lemma *lam-type* [TC]:
 $[| !!x. x:A ==> b(x) : B(x) |] ==> (lam\ x:A. b(x)) : Pi(A,B)$
 $\langle proof \rangle$

lemma *lam-funtype*: $(lam\ x:A. b(x)) : A -> \{b(x). x:A\}$
 $\langle proof \rangle$

lemma *function-lam*: *function* $(lam\ x:A. b(x))$
 $\langle proof \rangle$

lemma *relation-lam*: *relation* $(lam\ x:A. b(x))$
 $\langle proof \rangle$

lemma *beta-if* [simp]: $(lam\ x:A. b(x))\ 'a = (if\ a : A\ then\ b(a)\ else\ 0)$
 $\langle proof \rangle$

lemma *beta*: $a : A ==> (lam\ x:A. b(x))\ 'a = b(a)$
 $\langle proof \rangle$

lemma *lam-empty* [simp]: $(lam\ x:0. b(x)) = 0$
 $\langle proof \rangle$

lemma *domain-lam* [simp]: $domain(Lambda(A,b)) = A$
 $\langle proof \rangle$

lemma *lam-cong* [cong]:
 $[| A=A'; !!x. x:A' ==> b(x)=b'(x) |] ==> Lambda(A,b) = Lambda(A',b')$

$\langle proof \rangle$

lemma *lam-theI*:

$(!!x. x:A ==> EX! y. Q(x,y)) ==> EX f. ALL x:A. Q(x, f'x)$

$\langle proof \rangle$

lemma *lam-eqE*: $[(lam x:A. f(x)) = (lam x:A. g(x)); a:A] ==> f(a)=g(a)$

$\langle proof \rangle$

lemma *Pi-empty1* [simp]: $Pi(0,A) = \{0\}$

$\langle proof \rangle$

lemma *singleton-fun* [simp]: $\{<a,b>\} : \{a\} -> \{b\}$

$\langle proof \rangle$

lemma *Pi-empty2* [simp]: $(A->0) = (if A=0 then \{0\} else 0)$

$\langle proof \rangle$

lemma *fun-space-empty-iff* [iff]: $(A->X)=0 \longleftrightarrow X=0 \ \& \ (A \neq 0)$

$\langle proof \rangle$

8.4 Extensionality

lemma *fun-subset*:

$[[f : Pi(A,B); g : Pi(C,D); A<=C;$
 $!!x. x:A ==> f'x = g'x]] ==> f<=g$

$\langle proof \rangle$

lemma *fun-extension*:

$[[f : Pi(A,B); g : Pi(A,D);$
 $!!x. x:A ==> f'x = g'x]] ==> f=g$

$\langle proof \rangle$

lemma *eta* [simp]: $f : Pi(A,B) ==> (lam x:A. f'x) = f$

$\langle proof \rangle$

lemma *fun-extension-iff*:

$[[f:Pi(A,B); g:Pi(A,C)]] ==> (ALL a:A. f'a = g'a) <-> f=g$

$\langle proof \rangle$

lemma *fun-subset-eq*: $[[f:Pi(A,B); g:Pi(A,C)]] ==> f <= g <-> (f = g)$

$\langle proof \rangle$

lemma *Pi-lamE*:
 assumes *major*: $f: Pi(A,B)$
 and *minor*: $!!b. [| ALL x:A. b(x):B(x); f = (lam x:A. b(x)) |] ==> P$
 shows P
 $\langle proof \rangle$

8.5 Images of Functions

lemma *image-lam*: $C \leq A ==> (lam x:A. b(x)) \text{ `` } C = \{b(x). x:C\}$
 $\langle proof \rangle$

lemma *Repfun-function-if*:
 $function(f)$
 $==> \{f'x. x:C\} = (if C \leq domain(f) then f''C else cons(0,f''C))$
 $\langle proof \rangle$

lemma *image-function*:
 $[| function(f); C \leq domain(f) |] ==> f''C = \{f'x. x:C\}$
 $\langle proof \rangle$

lemma *image-fun*: $[| f : Pi(A,B); C \leq A |] ==> f''C = \{f'x. x:C\}$
 $\langle proof \rangle$

lemma *image-eq-UN*:
 assumes $f: f \in Pi(A,B)$ $C \subseteq A$ shows $f''C = (\bigcup x \in C. \{f'x\})$
 $\langle proof \rangle$

lemma *Pi-image-cons*:
 $[| f: Pi(A,B); x: A |] ==> f \text{ `` } cons(x,y) = cons(f'x, f''y)$
 $\langle proof \rangle$

8.6 Properties of $restrict(f, A)$

lemma *restrict-subset*: $restrict(f,A) \leq f$
 $\langle proof \rangle$

lemma *function-restrictI*:
 $function(f) ==> function(restrict(f,A))$
 $\langle proof \rangle$

lemma *restrict-type2*: $[| f: Pi(C,B); A \leq C |] ==> restrict(f,A) : Pi(A,B)$
 $\langle proof \rangle$

lemma *restrict*: $restrict(f,A) \text{ `` } a = (if a : A then f'a else 0)$
 $\langle proof \rangle$

lemma *restrict-empty [simp]*: $restrict(f,0) = 0$
 $\langle proof \rangle$

lemma *restrict-iff*: $z \in \text{restrict}(r, A) \longleftrightarrow z \in r \ \& \ (\exists x \in A. \exists y. z = \langle x, y \rangle)$
 $\langle \text{proof} \rangle$

lemma *restrict-restrict* [simp]:
 $\text{restrict}(\text{restrict}(r, A), B) = \text{restrict}(r, A \text{ Int } B)$
 $\langle \text{proof} \rangle$

lemma *domain-restrict* [simp]: $\text{domain}(\text{restrict}(f, C)) = \text{domain}(f) \text{ Int } C$
 $\langle \text{proof} \rangle$

lemma *restrict-idem*: $f \leq \text{Sigma}(A, B) \implies \text{restrict}(f, A) = f$
 $\langle \text{proof} \rangle$

lemma *domain-restrict-idem*:
 $[\text{domain}(r) \leq A; \text{relation}(r)] \implies \text{restrict}(r, A) = r$
 $\langle \text{proof} \rangle$

lemma *domain-restrict-lam* [simp]: $\text{domain}(\text{restrict}(\text{Lambda}(A, f), C)) = A \text{ Int } C$
 $\langle \text{proof} \rangle$

lemma *restrict-if* [simp]: $\text{restrict}(f, A) \text{ ` } a = (\text{if } a : A \text{ then } f \text{` } a \text{ else } 0)$
 $\langle \text{proof} \rangle$

lemma *restrict-lam-eq*:
 $A \leq C \implies \text{restrict}(\text{lam } x:C. b(x), A) = (\text{lam } x:A. b(x))$
 $\langle \text{proof} \rangle$

lemma *fun-cons-restrict-eq*:
 $f : \text{cons}(a, b) \rightarrow B \implies f = \text{cons}(\text{` } a \text{, } \text{restrict}(f, b))$
 $\langle \text{proof} \rangle$

8.7 Unions of Functions

lemma *function-Union*:
 $[\text{ALL } x:S. \text{function}(x);$
 $\text{ALL } x:S. \text{ALL } y:S. x \leq y \mid y \leq x \]$
 $\implies \text{function}(\text{Union}(S))$
 $\langle \text{proof} \rangle$

lemma *fun-Union*:
 $[\text{ALL } f:S. \text{EX } C D. f:C \rightarrow D;$
 $\text{ALL } f:S. \text{ALL } y:S. f \leq y \mid y \leq f \] \implies$
 $\text{Union}(S) : \text{domain}(\text{Union}(S)) \rightarrow \text{range}(\text{Union}(S))$
 $\langle \text{proof} \rangle$

lemma *gen-relation-Union* [rule-format]:
 $\forall f \in F. \text{relation}(f) \implies \text{relation}(\text{Union}(F))$

$\langle proof \rangle$

lemmas $Un\text{-}rls = Un\text{-}subset\text{-}iff\ SUM\text{-}Un\text{-}distrib1\ prod\text{-}Un\text{-}distrib2$
 $subset\text{-}trans\ [OF - Un\text{-}upper1]$
 $subset\text{-}trans\ [OF - Un\text{-}upper2]$

lemma $fun\text{-}disjoint\text{-}Un$:
 $[| f: A \rightarrow B; g: C \rightarrow D; A\ Int\ C = 0 |]$
 $\implies (f\ Un\ g) : (A\ Un\ C) \rightarrow (B\ Un\ D)$

$\langle proof \rangle$

lemma $fun\text{-}disjoint\text{-}apply1$: $a \notin domain(g) \implies (f\ Un\ g)'a = f'a$
 $\langle proof \rangle$

lemma $fun\text{-}disjoint\text{-}apply2$: $c \notin domain(f) \implies (f\ Un\ g)'c = g'c$
 $\langle proof \rangle$

8.8 Domain and Range of a Function or Relation

lemma $domain\text{-}of\text{-}fun$: $f : Pi(A,B) \implies domain(f)=A$
 $\langle proof \rangle$

lemma $apply\text{-}rangeI$: $[| f : Pi(A,B); a: A |] \implies f'a : range(f)$
 $\langle proof \rangle$

lemma $range\text{-}of\text{-}fun$: $f : Pi(A,B) \implies f : A \rightarrow range(f)$
 $\langle proof \rangle$

8.9 Extensions of Functions

lemma $fun\text{-}extend$:
 $[| f: A \rightarrow B; c \sim: A |] \implies cons(<c,b>,f) : cons(c,A) \rightarrow cons(b,B)$
 $\langle proof \rangle$

lemma $fun\text{-}extend3$:
 $[| f: A \rightarrow B; c \sim: A; b: B |] \implies cons(<c,b>,f) : cons(c,A) \rightarrow B$
 $\langle proof \rangle$

lemma $extend\text{-}apply$:
 $c \sim: domain(f) \implies cons(<c,b>,f)'a = (if\ a=c\ then\ b\ else\ f'a)$
 $\langle proof \rangle$

lemma $fun\text{-}extend\text{-}apply\ [simp]$:
 $[| f: A \rightarrow B; c \sim: A |] \implies cons(<c,b>,f)'a = (if\ a=c\ then\ b\ else\ f'a)$
 $\langle proof \rangle$

lemmas *singleton-apply* = *apply-equality* [*OF singletonI singleton-fun, simp*]

lemma *cons-fun-eq*:

$c \sim: A \implies \text{cons}(c, A) \rightarrow B = (\bigcup f \in A \rightarrow B. \bigcup b \in B. \{\text{cons}(\langle c, b \rangle, f)\})$
 $\langle \text{proof} \rangle$

lemma *succ-fun-eq*: $\text{succ}(n) \rightarrow B = (\bigcup f \in n \rightarrow B. \bigcup b \in B. \{\text{cons}(\langle n, b \rangle, f)\})$
 $\langle \text{proof} \rangle$

8.10 Function Updates

definition

$\text{update} :: [i, i, i] \Rightarrow i$ **where**
 $\text{update}(f, a, b) == \text{lam } x: \text{cons}(a, \text{domain}(f)). \text{if}(x=a, b, f'x)$

nonterminals

updbinds updbind

syntax

$\text{-updbind} :: [i, i] \Rightarrow \text{updbind} \quad ((\text{-} := / \text{-}))$
 $\quad \quad \quad :: \text{updbind} \Rightarrow \text{updbinds} \quad (\text{-})$
 $\text{-updbinds} :: [\text{updbind}, \text{updbinds}] \Rightarrow \text{updbinds} \quad (\text{-} / \text{-})$
 $\text{-Update} :: [i, \text{updbinds}] \Rightarrow i \quad (\text{-}'((\text{-})') [900, 0] 900)$

translations

$\text{-Update } (f, \text{-updbinds}(b, bs)) == \text{-Update } (\text{-Update}(f, b), bs)$
 $f(x:=y) == \text{CONST } \text{update}(f, x, y)$

lemma *update-apply* [*simp*]: $f(x:=y) \text{ ' } z = (\text{if } z=x \text{ then } y \text{ else } f'z)$
 $\langle \text{proof} \rangle$

lemma *update-idem*: $[\text{if } x = y; f: \text{Pi}(A, B); x: A] \implies f(x:=y) = f$
 $\langle \text{proof} \rangle$

declare *refl* [*THEN update-idem, simp*]

lemma *domain-update* [*simp*]: $\text{domain}(f(x:=y)) = \text{cons}(x, \text{domain}(f))$
 $\langle \text{proof} \rangle$

lemma *update-type*: $[\text{if } f: \text{Pi}(A, B); x: A; y: B(x)] \implies f(x:=y) : \text{Pi}(A, B)$
 $\langle \text{proof} \rangle$

8.11 Monotonicity Theorems

8.11.1 Replacement in its Various Forms

lemma *Replace-mono*: $A \leq B \implies \text{Replace}(A, P) \leq \text{Replace}(B, P)$
<proof>

lemma *RepFun-mono*: $A \leq B \implies \{f(x). x:A\} \leq \{f(x). x:B\}$
<proof>

lemma *Pow-mono*: $A \leq B \implies \text{Pow}(A) \leq \text{Pow}(B)$
<proof>

lemma *Union-mono*: $A \leq B \implies \text{Union}(A) \leq \text{Union}(B)$
<proof>

lemma *UN-mono*:
 $[\mid A \leq C; \ !\!x. x:A \implies B(x) \leq D(x) \mid] \implies (\bigcup x \in A. B(x)) \leq (\bigcup x \in C. D(x))$
<proof>

lemma *Inter-anti-mono*: $[\mid A \leq B; \ A \neq 0 \mid] \implies \text{Inter}(B) \leq \text{Inter}(A)$
<proof>

lemma *cons-mono*: $C \leq D \implies \text{cons}(a, C) \leq \text{cons}(a, D)$
<proof>

lemma *Un-mono*: $[\mid A \leq C; \ B \leq D \mid] \implies A \text{ Un } B \leq C \text{ Un } D$
<proof>

lemma *Int-mono*: $[\mid A \leq C; \ B \leq D \mid] \implies A \text{ Int } B \leq C \text{ Int } D$
<proof>

lemma *Diff-mono*: $[\mid A \leq C; \ D \leq B \mid] \implies A - B \leq C - D$
<proof>

8.11.2 Standard Products, Sums and Function Spaces

lemma *Sigma-mono* [rule-format]:
 $[\mid A \leq C; \ !\!x. x:A \multimap B(x) \leq D(x) \mid] \implies \text{Sigma}(A, B) \leq \text{Sigma}(C, D)$
<proof>

lemma *sum-mono*: $[\mid A \leq C; \ B \leq D \mid] \implies A + B \leq C + D$
<proof>

lemma *Pi-mono*: $B \leq C \implies A \multimap B \leq A \multimap C$
<proof>

lemma *lam-mono*: $A \leq B \implies \text{Lambda}(A, c) \leq \text{Lambda}(B, c)$
 $\langle \text{proof} \rangle$

8.11.3 Converse, Domain, Range, Field

lemma *converse-mono*: $r \leq s \implies \text{converse}(r) \leq \text{converse}(s)$
 $\langle \text{proof} \rangle$

lemma *domain-mono*: $r \leq s \implies \text{domain}(r) \leq \text{domain}(s)$
 $\langle \text{proof} \rangle$

lemmas *domain-rel-subset* = *subset-trans* [OF *domain-mono domain-subset*]

lemma *range-mono*: $r \leq s \implies \text{range}(r) \leq \text{range}(s)$
 $\langle \text{proof} \rangle$

lemmas *range-rel-subset* = *subset-trans* [OF *range-mono range-subset*]

lemma *field-mono*: $r \leq s \implies \text{field}(r) \leq \text{field}(s)$
 $\langle \text{proof} \rangle$

lemma *field-rel-subset*: $r \leq A * A \implies \text{field}(r) \leq A$
 $\langle \text{proof} \rangle$

8.11.4 Images

lemma *image-pair-mono*:
 $[[\text{!! } x \ y. \langle x, y \rangle : r \implies \langle x, y \rangle : s; \ A \leq B]] \implies r^{``}A \leq s^{``}B$
 $\langle \text{proof} \rangle$

lemma *vimage-pair-mono*:
 $[[\text{!! } x \ y. \langle x, y \rangle : r \implies \langle x, y \rangle : s; \ A \leq B]] \implies r^{-``}A \leq s^{-``}B$
 $\langle \text{proof} \rangle$

lemma *image-mono*: $[[r \leq s; \ A \leq B]] \implies r^{``}A \leq s^{``}B$
 $\langle \text{proof} \rangle$

lemma *vimage-mono*: $[[r \leq s; \ A \leq B]] \implies r^{-``}A \leq s^{-``}B$
 $\langle \text{proof} \rangle$

lemma *Collect-mono*:
 $[[A \leq B; \ \text{!!}x. x:A \implies P(x) \dashrightarrow Q(x)]] \implies \text{Collect}(A, P) \leq \text{Collect}(B, Q)$
 $\langle \text{proof} \rangle$

lemmas *basic-monos* = *subset-refl imp-refl disj-mono conj-mono ex-mono*
Collect-mono Part-mono in-mono

lemma *bex-image-simp*:

$[| f : Pi(X, Y); A \subseteq X |] ==> (EX x : f^{\prime\prime}A. P(x)) <-> (EX x:A. P(f^{\prime}x))$
 $\langle proof \rangle$

lemma *ball-image-simp*:

$[| f : Pi(X, Y); A \subseteq X |] ==> (ALL x : f^{\prime\prime}A. P(x)) <-> (ALL x:A. P(f^{\prime}x))$
 $\langle proof \rangle$

end

9 QPair: Quine-Inspired Ordered Pairs and Disjoint Sums

theory *QPair* **imports** *Sum func* **begin**

For non-well-founded data structures in ZF. Does not precisely follow Quine's construction. Thanks to Thomas Forster for suggesting this approach!

W. V. Quine, On Ordered Pairs and Relations, in Selected Logic Papers, 1966.

definition

$QPair :: [i, i] ==> i$ $(<(-;/ -)>)$ **where**
 $<a;b> == a+b$

definition

$qfst :: i ==> i$ **where**
 $qfst(p) == THE a. EX b. p=<a;b>$

definition

$qsnd :: i ==> i$ **where**
 $qsnd(p) == THE b. EX a. p=<a;b>$

definition

$qsplit :: [[i, i] ==> 'a, i] ==> 'a::\}$ **where**
 $qsplit(c,p) == c(qfst(p), qsnd(p))$

definition

$qconverse :: i ==> i$ **where**
 $qconverse(r) == \{z. w:r, EX x y. w=<x;y> \ \& \ z=<y;x>\}$

definition

$QSigma :: [i, i ==> i] ==> i$ **where**
 $QSigma(A,B) == \bigcup_{x \in A} \bigcup_{y \in B(x)} \{<x;y>\}$

syntax

$-QSUM :: [idt, i, i] ==> i$ $((\exists QSUM \text{ :-./ -}) 10)$

translations

$QSUM\ x:A. B \Rightarrow CONST\ QSigma(A, \%x. B)$

abbreviation

$qprod\ (\text{infixr } <*> 80)\ \text{where}$
 $A <*> B == QSigma(A, \%-. B)$

definition

$qsum\ :: [i,i]=>i\ (\text{infixr } <+> 65)\ \text{where}$
 $A <+> B == (\{0\} <*> A) \cup (\{1\} <*> B)$

definition

$QInl\ :: i=>i\ \text{where}$
 $QInl(a) == <0;a>$

definition

$QInr\ :: i=>i\ \text{where}$
 $QInr(b) == <1;b>$

definition

$qcase\ :: [i=>i, i=>i, i]=>i\ \text{where}$
 $qcase(c,d) == qsplit(\%y\ z. cond(y, d(z), c(z)))$

9.1 Quine ordered pairing

lemma $QPair\text{-}empty\ [simp]: <0;0> = 0$
 $\langle proof \rangle$

lemma $QPair\text{-}iff\ [simp]: <a;b> = <c;d> \Leftrightarrow a=c \ \& \ b=d$
 $\langle proof \rangle$

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

lemma $QPair\text{-}inject1: <a;b> = <c;d> \Rightarrow a=c$
 $\langle proof \rangle$

lemma $QPair\text{-}inject2: <a;b> = <c;d> \Rightarrow b=d$
 $\langle proof \rangle$

9.1.1 QSigma: Disjoint union of a family of sets Generalizes Cartesian product

lemma $QSigmaI\ [intro!]: [\ a:A;\ b:B(a)\] \Rightarrow <a;b> : QSigma(A,B)$
 $\langle proof \rangle$

lemma $QSigmaE\ [elim!]:$

$[\ c: QSigma(A,B);$
 $!!x\ y. [\ x:A;\ y:B(x);\ c=<x;y>\] \Rightarrow P$

$\llbracket \rrbracket \implies P$
 $\langle proof \rangle$

lemma *QSigmaE2* [elim!]:
 $\llbracket \langle a; b \rangle : QSigma(A, B); \llbracket a : A; b : B(a) \rrbracket \implies P \rrbracket \implies P$
 $\langle proof \rangle$

lemma *QSigmaD1*: $\langle a; b \rangle : QSigma(A, B) \implies a : A$
 $\langle proof \rangle$

lemma *QSigmaD2*: $\langle a; b \rangle : QSigma(A, B) \implies b : B(a)$
 $\langle proof \rangle$

lemma *QSigma-cong*:
 $\llbracket A = A'; \llbracket !x. x : A' \implies B(x) = B'(x) \rrbracket \implies$
 $QSigma(A, B) = QSigma(A', B')$
 $\langle proof \rangle$

lemma *QSigma-empty1* [simp]: $QSigma(0, B) = 0$
 $\langle proof \rangle$

lemma *QSigma-empty2* [simp]: $A <*> 0 = 0$
 $\langle proof \rangle$

9.1.2 Projections: qfst, qsnd

lemma *qfst-conv* [simp]: $qfst(\langle a; b \rangle) = a$
 $\langle proof \rangle$

lemma *qsnd-conv* [simp]: $qsnd(\langle a; b \rangle) = b$
 $\langle proof \rangle$

lemma *qfst-type* [TC]: $p : QSigma(A, B) \implies qfst(p) : A$
 $\langle proof \rangle$

lemma *qsnd-type* [TC]: $p : QSigma(A, B) \implies qsnd(p) : B(qfst(p))$
 $\langle proof \rangle$

lemma *QPair-qfst-qsnd-eq*: $a : QSigma(A, B) \implies \langle qfst(a); qsnd(a) \rangle = a$
 $\langle proof \rangle$

9.1.3 Eliminator: qsplit

lemma *qsplit* [simp]: $qsplit(\%x y. c(x, y), \langle a; b \rangle) == c(a, b)$
 $\langle proof \rangle$

lemma *qsplit-type* [elim!]:
 $\llbracket p : QSigma(A, B);$
 $\llbracket !x y. \llbracket x : A; y : B(x) \rrbracket \implies c(x, y) : C(\langle x; y \rangle) \rrbracket$

$\llbracket \rrbracket \implies \text{qsplit}(\%x\ y.\ c(x,y),\ p) : C(p)$
 $\langle \text{proof} \rangle$

lemma *expand-qsplit*:

$u : A <*> B \implies R(\text{qsplit}(c,u)) <-> (\text{ALL } x:A.\ \text{ALL } y:B.\ u = <x;y> \dashv\dashv R(c(x,y)))$
 $\langle \text{proof} \rangle$

9.1.4 qsplit for predicates: result type o

lemma *qsplitI*: $R(a,b) \implies \text{qsplit}(R, <a;b>)$
 $\langle \text{proof} \rangle$

lemma *qsplitE*:

$\llbracket \text{qsplit}(R,z); z:QSigma(A,B);$
 $\text{!!}x\ y.\ \llbracket z = <x;y>; R(x,y) \rrbracket \implies P$
 $\llbracket \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *qsplitD*: $\text{qsplit}(R, <a;b>) \implies R(a,b)$
 $\langle \text{proof} \rangle$

9.1.5 qconverse

lemma *qconverseI* [*intro!*]: $<a;b>:r \implies <b;a>:qconverse(r)$
 $\langle \text{proof} \rangle$

lemma *qconverseD* [*elim!*]: $<a;b> : qconverse(r) \implies <b;a> : r$
 $\langle \text{proof} \rangle$

lemma *qconverseE* [*elim!*]:

$\llbracket yx : qconverse(r);$
 $\text{!!}x\ y.\ \llbracket yx = <y;x>; <x;y>:r \rrbracket \implies P$
 $\llbracket \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *qconverse-qconverse*: $r <= QSigma(A,B) \implies qconverse(qconverse(r)) = r$
 $\langle \text{proof} \rangle$

lemma *qconverse-type*: $r <= A <*> B \implies qconverse(r) <= B <*> A$
 $\langle \text{proof} \rangle$

lemma *qconverse-prod*: $qconverse(A <*> B) = B <*> A$
 $\langle \text{proof} \rangle$

lemma *qconverse-empty*: $qconverse(0) = 0$
 $\langle \text{proof} \rangle$

9.2 The Quine-inspired notion of disjoint sum

lemmas *qsum-defs* = *qsum-def* *QInl-def* *QInr-def* *qcase-def*

lemma *QInlI* [*intro!*]: $a : A \implies QInl(a) : A <+> B$
 $\langle proof \rangle$

lemma *QInrI* [*intro!*]: $b : B \implies QInr(b) : A <+> B$
 $\langle proof \rangle$

lemma *qsumE* [*elim!*]:

$$\begin{aligned} & [| u : A <+> B; \\ & \quad !!x. [| x:A; u=QInl(x) |] \implies P; \\ & \quad !!y. [| y:B; u=QInr(y) |] \implies P \\ & |] \implies P \end{aligned}$$

 $\langle proof \rangle$

lemma *QInl-iff* [*iff*]: $QInl(a)=QInl(b) <-> a=b$
 $\langle proof \rangle$

lemma *QInr-iff* [*iff*]: $QInr(a)=QInr(b) <-> a=b$
 $\langle proof \rangle$

lemma *QInl-QInr-iff* [*simp*]: $QInl(a)=QInr(b) <-> False$
 $\langle proof \rangle$

lemma *QInr-QInl-iff* [*simp*]: $QInr(b)=QInl(a) <-> False$
 $\langle proof \rangle$

lemma *qsum-empty* [*simp*]: $0 <+> 0 = 0$
 $\langle proof \rangle$

lemmas *QInl-inject* = *QInl-iff* [*THEN iffD1, standard*]
lemmas *QInr-inject* = *QInr-iff* [*THEN iffD1, standard*]
lemmas *QInl-neq-QInr* = *QInl-QInr-iff* [*THEN iffD1, THEN FalseE, elim!*]
lemmas *QInr-neq-QInl* = *QInr-QInl-iff* [*THEN iffD1, THEN FalseE, elim!*]

lemma *QInlD*: $QInl(a) : A <+> B \implies a : A$
 $\langle proof \rangle$

lemma *QInrD*: $QInr(b) : A <+> B \implies b : B$

$\langle proof \rangle$

lemma *qsum-iff*:

$u: A <+> B <-> (EX\ x. x:A \ \&\ u=QInl(x)) \mid (EX\ y. y:B \ \&\ u=QInr(y))$
 $\langle proof \rangle$

lemma *qsum-subset-iff*: $A <+> B <= C <+> D <-> A <= C \ \&\ B <= D$

$\langle proof \rangle$

lemma *qsum-equal-iff*: $A <+> B = C <+> D <-> A=C \ \&\ B=D$

$\langle proof \rangle$

9.2.1 Eliminator – qcase

lemma *qcase-QInl* [simp]: $qcase(c, d, QInl(a)) = c(a)$

$\langle proof \rangle$

lemma *qcase-QInr* [simp]: $qcase(c, d, QInr(b)) = d(b)$

$\langle proof \rangle$

lemma *qcase-type*:

$$\begin{aligned} & \llbracket u: A <+> B; \\ & \quad !!x. x: A ==> c(x): C(QInl(x)); \\ & \quad !!y. y: B ==> d(y): C(QInr(y)) \\ & \rrbracket ==> qcase(c,d,u) : C(u) \end{aligned}$$

 $\langle proof \rangle$

lemma *Part-QInl*: $Part(A <+> B, QInl) = \{QInl(x). x: A\}$

$\langle proof \rangle$

lemma *Part-QInr*: $Part(A <+> B, QInr) = \{QInr(y). y: B\}$

$\langle proof \rangle$

lemma *Part-QInr2*: $Part(A <+> B, \%x. QInr(h(x))) = \{QInr(y). y: Part(B,h)\}$

$\langle proof \rangle$

lemma *Part-qsum-equality*: $C <= A <+> B ==> Part(C, QInl) \ Un \ Part(C, QInr) = C$

$\langle proof \rangle$

9.2.2 Monotonicity

lemma *QPair-mono*: $\llbracket a <= c; \ b <= d \rrbracket ==> <a;b> <= <c;d>$

$\langle proof \rangle$

lemma *QSigma-mono* [rule-format]:

$$[\mid A \leq C; \text{ ALL } x:A. B(x) \leq D(x) \mid] \implies QSigma(A,B) \leq QSigma(C,D)$$
 $\langle proof \rangle$

lemma *QInl-mono*: $a \leq b \implies QInl(a) \leq QInl(b)$
 $\langle proof \rangle$

lemma *QInr-mono*: $a \leq b \implies QInr(a) \leq QInr(b)$
 $\langle proof \rangle$

lemma *qsum-mono*: $[\mid A \leq C; B \leq D \mid] \implies A <+> B \leq C <+> D$
 $\langle proof \rangle$

end

10 Perm: Injections, Surjections, Bijections, Composition

theory *Perm* **imports** *func* **begin**

definition

comp $:: [i,i] \Rightarrow i$ (**infixr** *O* 60) **where**
 $r \ O \ s == \{xz : domain(s)*range(r) .$
 $EX \ x \ y \ z. xz = \langle x,z \rangle \ \& \ \langle x,y \rangle : s \ \& \ \langle y,z \rangle : r\}$

definition

id $:: i \Rightarrow i$ **where**
 $id(A) == (lam \ x:A. x)$

definition

inj $:: [i,i] \Rightarrow i$ **where**
 $inj(A,B) == \{ f: A \rightarrow B. \text{ ALL } w:A. \text{ ALL } x:A. f'w = f'x \implies w = x \}$

definition

surj $:: [i,i] \Rightarrow i$ **where**
 $surj(A,B) == \{ f: A \rightarrow B . \text{ ALL } y:B. EX \ x:A. f'x = y \}$

definition

bij $:: [i,i] \Rightarrow i$ **where**
 $bij(A,B) == inj(A,B) \ Int \ surj(A,B)$

10.1 Surjections

lemma *surj-is-fun*: $f: \text{surj}(A,B) \implies f: A \multimap B$
 $\langle \text{proof} \rangle$

lemma *fun-is-surj*: $f: \text{Pi}(A,B) \implies f: \text{surj}(A, \text{range}(f))$
 $\langle \text{proof} \rangle$

lemma *surj-range*: $f: \text{surj}(A,B) \implies \text{range}(f) = B$
 $\langle \text{proof} \rangle$

lemma *f-imp-surjective*:
 $\llbracket f: A \multimap B; \forall y. y: B \implies d(y): A; \forall y. y: B \implies f(d(y)) = y \rrbracket$
 $\implies f: \text{surj}(A,B)$
 $\langle \text{proof} \rangle$

lemma *lam-surjective*:
 $\llbracket \forall x. x: A \implies c(x): B;$
 $\forall y. y: B \implies d(y): A;$
 $\forall y. y: B \implies c(d(y)) = y$
 $\rrbracket \implies (\text{lam } x:A. c(x)) : \text{surj}(A,B)$
 $\langle \text{proof} \rangle$

lemma *cantor-surj*: $f \sim: \text{surj}(A, \text{Pow}(A))$
 $\langle \text{proof} \rangle$

10.2 Injections

lemma *inj-is-fun*: $f: \text{inj}(A,B) \implies f: A \multimap B$
 $\langle \text{proof} \rangle$

lemma *inj-equality*:
 $\llbracket \langle a, b \rangle : f; \langle c, b \rangle : f; f: \text{inj}(A,B) \rrbracket \implies a = c$
 $\langle \text{proof} \rangle$

lemma *inj-apply-equality*: $\llbracket f: \text{inj}(A,B); f'a = f'b; a:A; b:A \rrbracket \implies a = b$
 $\langle \text{proof} \rangle$

lemma *f-imp-injective*: $\llbracket f: A \multimap B; \text{ALL } x:A. d(f'x) = x \rrbracket \implies f: \text{inj}(A,B)$
 $\langle \text{proof} \rangle$

lemma *lam-injective*:
 $\llbracket \forall x. x: A \implies c(x): B;$

$$\begin{aligned} & !!x. x:A ==> d(c(x)) = x \] \\ & ==> (lam\ x:A. c(x)) : inj(A,B) \\ & \langle proof \rangle \end{aligned}$$

10.3 Bijections

lemma *bij-is-inj*: $f: bij(A,B) ==> f: inj(A,B)$
 $\langle proof \rangle$

lemma *bij-is-surj*: $f: bij(A,B) ==> f: surj(A,B)$
 $\langle proof \rangle$

lemmas *bij-is-fun* = *bij-is-inj* [*THEN inj-is-fun, standard*]

lemma *lam-bijective*:

$$\begin{aligned} & [\] !!x. x:A ==> c(x): B; \\ & !!y. y:B ==> d(y): A; \\ & !!x. x:A ==> d(c(x)) = x; \\ & !!y. y:B ==> c(d(y)) = y \\ & [\] ==> (lam\ x:A. c(x)) : bij(A,B) \\ & \langle proof \rangle \end{aligned}$$

lemma *RepFun-bijective*: (*ALL* $y : x. EX! y'. f(y') = f(y)$)
 $==> (lam\ z:\{f(y). y:x\}. THE\ y. f(y) = z) : bij(\{f(y). y:x\}, x)$
 $\langle proof \rangle$

10.4 Identity Function

lemma *idI* [*intro!*]: $a:A ==> \langle a,a \rangle : id(A)$
 $\langle proof \rangle$

lemma *idE* [*elim!*]: $[\]\ p: id(A); \]\ !!x.[\]\ x:A; p=\langle x,x \rangle \]\ ==> P \]\ ==> P$
 $\langle proof \rangle$

lemma *id-type*: $id(A) : A \multimap A$
 $\langle proof \rangle$

lemma *id-conv* [*simp*]: $x:A ==> id(A)'x = x$
 $\langle proof \rangle$

lemma *id-mono*: $A \leq B ==> id(A) \leq id(B)$
 $\langle proof \rangle$

lemma *id-subset-inj*: $A \leq B ==> id(A): inj(A,B)$
 $\langle proof \rangle$

lemmas *id-inj* = *subset-refl* [*THEN id-subset-inj, standard*]

lemma *id-surj*: $id(A): surj(A,A)$

$\langle proof \rangle$

lemma *id-bij*: $id(A): bij(A,A)$
 $\langle proof \rangle$

lemma *subset-iff-id*: $A \leq B \iff id(A) : A \rightarrow B$
 $\langle proof \rangle$

id as the identity relation

lemma *id-iff [simp]*: $\langle x,y \rangle \in id(A) \iff x=y \ \& \ y \in A$
 $\langle proof \rangle$

10.5 Converse of a Function

lemma *inj-converse-fun*: $f: inj(A,B) \implies converse(f) : range(f) \rightarrow A$
 $\langle proof \rangle$

The premises are equivalent to saying that *f* is injective...

lemma *left-inverse-lemma*:
 $[[f: A \rightarrow B; \ converse(f): C \rightarrow A; \ a: A]] \implies converse(f) ' (f'a) = a$
 $\langle proof \rangle$

lemma *left-inverse [simp]*: $[[f: inj(A,B); \ a: A]] \implies converse(f) ' (f'a) = a$
 $\langle proof \rangle$

lemma *left-inverse-eq*:
 $[[f \in inj(A,B); \ f ' x = y; \ x \in A]] \implies converse(f) ' y = x$
 $\langle proof \rangle$

lemmas *left-inverse-bij = bij-is-inj [THEN left-inverse, standard]*

lemma *right-inverse-lemma*:
 $[[f: A \rightarrow B; \ converse(f): C \rightarrow A; \ b: C]] \implies f ' (converse(f) ' b) = b$
 $\langle proof \rangle$

lemma *right-inverse [simp]*:
 $[[f: inj(A,B); \ b: range(f)]] \implies f ' (converse(f) ' b) = b$
 $\langle proof \rangle$

lemma *right-inverse-bij*: $[[f: bij(A,B); \ b: B]] \implies f ' (converse(f) ' b) = b$
 $\langle proof \rangle$

10.6 Converses of Injections, Surjections, Bijections

lemma *inj-converse-inj*: $f: inj(A,B) \implies converse(f): inj(range(f), A)$
 $\langle proof \rangle$

lemma *inj-converse-surj*: $f: inj(A,B) \implies converse(f): surj(range(f), A)$

$\langle proof \rangle$

lemma *bij-converse-bij* [TC]: $f: \text{bij}(A,B) \implies \text{converse}(f): \text{bij}(B,A)$
 $\langle proof \rangle$

10.7 Composition of Two Relations

lemma *compI* [intro]: $\llbracket \langle a,b \rangle : s; \langle b,c \rangle : r \rrbracket \implies \langle a,c \rangle : r \circ s$
 $\langle proof \rangle$

lemma *compE* [elim!]:
 $\llbracket xz : r \circ s;$
 $\quad \text{!!}x\ y\ z. \llbracket xz = \langle x,z \rangle; \langle x,y \rangle : s; \langle y,z \rangle : r \rrbracket \implies P \rrbracket$
 $\implies P$
 $\langle proof \rangle$

lemma *compEpair*:
 $\llbracket \langle a,c \rangle : r \circ s;$
 $\quad \text{!!}y. \llbracket \langle a,y \rangle : s; \langle y,c \rangle : r \rrbracket \implies P \rrbracket$
 $\implies P$
 $\langle proof \rangle$

lemma *converse-comp*: $\text{converse}(R \circ S) = \text{converse}(S) \circ \text{converse}(R)$
 $\langle proof \rangle$

10.8 Domain and Range – see Suppes, Section 3.1

lemma *range-comp*: $\text{range}(r \circ s) \leq \text{range}(r)$
 $\langle proof \rangle$

lemma *range-comp-eq*: $\text{domain}(r) \leq \text{range}(s) \implies \text{range}(r \circ s) = \text{range}(r)$
 $\langle proof \rangle$

lemma *domain-comp*: $\text{domain}(r \circ s) \leq \text{domain}(s)$
 $\langle proof \rangle$

lemma *domain-comp-eq*: $\text{range}(s) \leq \text{domain}(r) \implies \text{domain}(r \circ s) = \text{domain}(s)$
 $\langle proof \rangle$

lemma *image-comp*: $(r \circ s)^{''}A = r^{''}(s^{''}A)$
 $\langle proof \rangle$

10.9 Other Results

lemma *comp-mono*: $\llbracket r' \leq r; s' \leq s \rrbracket \implies (r' \circ s') \leq (r \circ s)$
 $\langle proof \rangle$

lemma *comp-rel*: $[[\ s \leq A * B;\ r \leq B * C\]]\implies (r\ O\ s) \leq A * C$
 $\langle proof \rangle$

lemma *comp-assoc*: $(r\ O\ s)\ O\ t = r\ O\ (s\ O\ t)$
 $\langle proof \rangle$

lemma *left-comp-id*: $r \leq A * B \implies id(B)\ O\ r = r$
 $\langle proof \rangle$

lemma *right-comp-id*: $r \leq A * B \implies r\ O\ id(A) = r$
 $\langle proof \rangle$

10.10 Composition Preserves Functions, Injections, and Surjections

lemma *comp-function*: $[[\ function(g);\ function(f)\]]\implies function(f\ O\ g)$
 $\langle proof \rangle$

lemma *comp-fun*: $[[\ g: A \multimap B;\ f: B \multimap C\]]\implies (f\ O\ g) : A \multimap C$
 $\langle proof \rangle$

lemma *comp-fun-apply* [simp]:
 $[[\ g: A \multimap B;\ a:A\]]\implies (f\ O\ g)\ a = f\ (g\ a)$
 $\langle proof \rangle$

lemma *comp-lam*:
 $[[\ !!x. x:A \implies b(x): B\]]$
 $\implies (lam\ y:B. c(y))\ O\ (lam\ x:A. b(x)) = (lam\ x:A. c(b(x)))$
 $\langle proof \rangle$

lemma *comp-inj*:
 $[[\ g: inj(A,B);\ f: inj(B,C)\]]\implies (f\ O\ g) : inj(A,C)$
 $\langle proof \rangle$

lemma *comp-surj*:
 $[[\ g: surj(A,B);\ f: surj(B,C)\]]\implies (f\ O\ g) : surj(A,C)$
 $\langle proof \rangle$

lemma *comp-bij*:
 $[[\ g: bij(A,B);\ f: bij(B,C)\]]\implies (f\ O\ g) : bij(A,C)$
 $\langle proof \rangle$

10.11 Dual Properties of *inj* and *surj*

Useful for proofs from D Pastre. Automatic theorem proving in set theory. Artificial Intelligence, 10:1–27, 1978.

lemma *comp-mem-injD1*:

$$[\mid (f \circ g): inj(A,C); \ g: A \rightarrow B; \ f: B \rightarrow C \mid] \implies g: inj(A,B)$$

<proof>

lemma *comp-mem-injD2*:

$$[\mid (f \circ g): inj(A,C); \ g: surj(A,B); \ f: B \rightarrow C \mid] \implies f: inj(B,C)$$

<proof>

lemma *comp-mem-surjD1*:

$$[\mid (f \circ g): surj(A,C); \ g: A \rightarrow B; \ f: B \rightarrow C \mid] \implies f: surj(B,C)$$

<proof>

lemma *comp-mem-surjD2*:

$$[\mid (f \circ g): surj(A,C); \ g: A \rightarrow B; \ f: inj(B,C) \mid] \implies g: surj(A,B)$$

<proof>

10.11.1 Inverses of Composition

lemma *left-comp-inverse*: $f: inj(A,B) \implies converse(f) \circ f = id(A)$
<proof>

lemma *right-comp-inverse*:

$f: surj(A,B) \implies f \circ converse(f) = id(B)$
<proof>

10.11.2 Proving that a Function is a Bijection

lemma *comp-eq-id-iff*:

$$[\mid f: A \rightarrow B; \ g: B \rightarrow A \mid] \implies f \circ g = id(B) \iff (ALL \ y:B. f'(g'y)=y)$$

<proof>

lemma *fg-imp-bijective*:

$$[\mid f: A \rightarrow B; \ g: B \rightarrow A; \ f \circ g = id(B); \ g \circ f = id(A) \mid] \implies f: bij(A,B)$$

<proof>

lemma *nilpotent-imp-bijective*: $[\mid f: A \rightarrow A; \ f \circ f = id(A) \mid] \implies f: bij(A,A)$
<proof>

lemma *invertible-imp-bijective*:

$$[\mid converse(f): B \rightarrow A; \ f: A \rightarrow B \mid] \implies f: bij(A,B)$$

<proof>

10.11.3 Unions of Functions

See similar theorems in `func.thy`

lemma *inj-disjoint-Un*:

$$\begin{aligned} & \llbracket f: \text{inj}(A,B); \ g: \text{inj}(C,D); \ B \text{ Int } D = 0 \rrbracket \\ & \implies (\text{lam } a: A \text{ Un } C. \text{ if } a:A \text{ then } f'a \text{ else } g'a) : \text{inj}(A \text{ Un } C, B \text{ Un } D) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *surj-disjoint-Un*:

$$\begin{aligned} & \llbracket f: \text{surj}(A,B); \ g: \text{surj}(C,D); \ A \text{ Int } C = 0 \rrbracket \\ & \implies (f \text{ Un } g) : \text{surj}(A \text{ Un } C, B \text{ Un } D) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *bij-disjoint-Un*:

$$\begin{aligned} & \llbracket f: \text{bij}(A,B); \ g: \text{bij}(C,D); \ A \text{ Int } C = 0; \ B \text{ Int } D = 0 \rrbracket \\ & \implies (f \text{ Un } g) : \text{bij}(A \text{ Un } C, B \text{ Un } D) \\ & \langle \text{proof} \rangle \end{aligned}$$

10.11.4 Restrictions as Surjections and Bijections

lemma *surj-image*:

$$f: \text{Pi}(A,B) \implies f: \text{surj}(A, f''A)$$

 $\langle \text{proof} \rangle$

lemma *restrict-image [simp]*: $\text{restrict}(f,A) \text{ `` } B = f \text{ `` } (A \text{ Int } B)$
 $\langle \text{proof} \rangle$

lemma *restrict-inj*:

$$\llbracket f: \text{inj}(A,B); \ C \leq A \rrbracket \implies \text{restrict}(f,C): \text{inj}(C,B)$$

 $\langle \text{proof} \rangle$

lemma *restrict-surj*: $\llbracket f: \text{Pi}(A,B); \ C \leq A \rrbracket \implies \text{restrict}(f,C): \text{surj}(C, f''C)$
 $\langle \text{proof} \rangle$

lemma *restrict-bij*:

$$\llbracket f: \text{inj}(A,B); \ C \leq A \rrbracket \implies \text{restrict}(f,C): \text{bij}(C, f''C)$$

 $\langle \text{proof} \rangle$

10.11.5 Lemmas for Ramsey's Theorem

lemma *inj-weaken-type*: $\llbracket f: \text{inj}(A,B); \ B \leq D \rrbracket \implies f: \text{inj}(A,D)$
 $\langle \text{proof} \rangle$

lemma *inj-succ-restrict*:

$$\llbracket f: \text{inj}(\text{succ}(m), A) \rrbracket \implies \text{restrict}(f,m) : \text{inj}(m, A - \{f'm\})$$

 $\langle \text{proof} \rangle$

```

lemma inj-extend:
  [|  $f: inj(A,B); a \sim A; b \sim B$  |]
  ==>  $cons(<a,b>,f) : inj(cons(a,A), cons(b,B))$ 
<proof>

end

```

11 Tranc1: Relations: Their General Properties and Transitive Closure

```

theory Tranc1 imports Fixedpt Perm begin

```

```

definition
  refl    :: [ $i,i$ ]==> $o$  where
     $refl(A,r) == (ALL x: A. <x,x> : r)$ 

```

```

definition
  irrefl  :: [ $i,i$ ]==> $o$  where
     $irrefl(A,r) == ALL x: A. <x,x> \sim: r$ 

```

```

definition
  sym     ::  $i==>o$  where
     $sym(r) == ALL x y. <x,y>: r \longrightarrow <y,x>: r$ 

```

```

definition
  asym    ::  $i==>o$  where
     $asym(r) == ALL x y. <x,y>:r \longrightarrow \sim <y,x>:r$ 

```

```

definition
  antisym ::  $i==>o$  where
     $antisym(r) == ALL x y. <x,y>:r \longrightarrow <y,x>:r \longrightarrow x=y$ 

```

```

definition
  trans   ::  $i==>o$  where
     $trans(r) == ALL x y z. <x,y>: r \longrightarrow <y,z>: r \longrightarrow <x,z>: r$ 

```

```

definition
  trans-on :: [ $i,i$ ]==> $o$  (trans[-]'(-')) where
     $trans[A](r) == ALL x:A. ALL y:A. ALL z:A. <x,y>: r \longrightarrow <y,z>: r \longrightarrow <x,z>: r$ 

```

```

definition
  rtranc1 ::  $i==>i$  ((-^*) [100] 100) where
     $r^{\wedge *} == lfp(field(r)*field(r), \%s. id(field(r)) \ Un (r \ O \ s))$ 

```

```

definition
  tranc1  ::  $i==>i$  ((-^+) [100] 100) where

```

$$r^{\wedge}+ == r \ O \ r^{\wedge}*$$

definition

equiv :: $[i,i] \Rightarrow o$ **where**
equiv(A,r) == $r \leq A*A \ \& \ refl(A,r) \ \& \ sym(r) \ \& \ trans(r)$

11.1 General properties of relations

11.1.1 irreflexivity

lemma *irreflI*:

$[[\ !x. x:A \Rightarrow \langle x,x \rangle \sim : r \]] \Rightarrow irrefl(A,r)$
 $\langle proof \rangle$

lemma *irreflE*: $[[\ irrefl(A,r); \ x:A \]] \Rightarrow \langle x,x \rangle \sim : r$
 $\langle proof \rangle$

11.1.2 symmetry

lemma *symI*:

$[[\ !x \ y. \langle x,y \rangle : r \Rightarrow \langle y,x \rangle : r \]] \Rightarrow sym(r)$
 $\langle proof \rangle$

lemma *symE*: $[[\ sym(r); \ \langle x,y \rangle : r \]] \Rightarrow \langle y,x \rangle : r$
 $\langle proof \rangle$

11.1.3 antisymmetry

lemma *antisymI*:

$[[\ !x \ y. [\ \langle x,y \rangle : r; \ \langle y,x \rangle : r \] \Rightarrow x=y \]] \Rightarrow antisym(r)$
 $\langle proof \rangle$

lemma *antisymE*: $[[\ antisym(r); \ \langle x,y \rangle : r; \ \langle y,x \rangle : r \]] \Rightarrow x=y$
 $\langle proof \rangle$

11.1.4 transitivity

lemma *transD*: $[[\ trans(r); \ \langle a,b \rangle : r; \ \langle b,c \rangle : r \]] \Rightarrow \langle a,c \rangle : r$
 $\langle proof \rangle$

lemma *trans-onD*:

$[[\ trans[A](r); \ \langle a,b \rangle : r; \ \langle b,c \rangle : r; \ a:A; \ b:A; \ c:A \]] \Rightarrow \langle a,c \rangle : r$
 $\langle proof \rangle$

lemma *trans-imp-trans-on*: $trans(r) \Rightarrow trans[A](r)$
 $\langle proof \rangle$

lemma *trans-on-imp-trans*: $[[trans[A](r); \ r \leq A*A]] \Rightarrow trans(r)$
 $\langle proof \rangle$

11.2 Transitive closure of a relation

lemma *rtrancl-bnd-mono*:

$bnd\text{-}mono(field(r)*field(r), \%s. id(field(r)) \text{ } Un \text{ } (r \text{ } O \text{ } s))$
 $\langle proof \rangle$

lemma *rtrancl-mono*: $r \leq s \implies r^* \leq s^*$

$\langle proof \rangle$

lemmas *rtrancl-unfold* =

rtrancl-bnd-mono [THEN *rtrancl-def* [THEN *def-lfp-unfold*], *standard*]

lemmas *rtrancl-type* = *rtrancl-def* [THEN *def-lfp-subset*, *standard*]

lemma *relation-rtrancl*: $relation(r^*)$

$\langle proof \rangle$

lemma *rtrancl-refl*: $[| a: field(r) |] \implies \langle a, a \rangle : r^*$

$\langle proof \rangle$

lemma *rtrancl-into-rtrancl*: $[| \langle a, b \rangle : r^*; \langle b, c \rangle : r |] \implies \langle a, c \rangle : r^*$

$\langle proof \rangle$

lemma *r-into-rtrancl*: $\langle a, b \rangle : r \implies \langle a, b \rangle : r^*$

$\langle proof \rangle$

lemma *r-subset-rtrancl*: $relation(r) \implies r \leq r^*$

$\langle proof \rangle$

lemma *rtrancl-field*: $field(r^*) = field(r)$

$\langle proof \rangle$

lemma *rtrancl-full-induct* [*case-names initial step, consumes 1*]:

$[| \langle a, b \rangle : r^*;$
 $!!x. x: field(r) \implies P(\langle x, x \rangle);$
 $!!x \ y \ z. [P(\langle x, y \rangle); \langle x, y \rangle : r^*; \langle y, z \rangle : r] \implies P(\langle x, z \rangle) |]$
 $\implies P(\langle a, b \rangle)$
 $\langle proof \rangle$

lemma *rtrancI-induct* [*case-names initial step, induct set: rtrancI*]:

[[$\langle a, b \rangle : r^*$;
 $P(a)$;
 $!!y\ z. [\langle a, y \rangle : r^*; \langle y, z \rangle : r; P(y)] \implies P(z)$
 $] \implies P(b)$

$\langle proof \rangle$

lemma *trans-rtrancI*: $trans(r^*)$

$\langle proof \rangle$

lemmas *rtrancI-trans* = *trans-rtrancI* [*THEN transD, standard*]

lemma *rtrancIE*:

[[$\langle a, b \rangle : r^*$; $(a=b) \implies P$;
 $!!y. [\langle a, y \rangle : r^*; \langle y, b \rangle : r] \implies P$]
 $\implies P$

$\langle proof \rangle$

lemma *trans-trancI*: $trans(r^+)$

$\langle proof \rangle$

lemmas *trans-on-trancI* = *trans-trancI* [*THEN trans-imp-trans-on*]

lemmas *trancI-trans* = *trans-trancI* [*THEN transD, standard*]

lemma *trancI-into-rtrancI*: $\langle a, b \rangle : r^+ \implies \langle a, b \rangle : r^*$

$\langle proof \rangle$

lemma *r-into-trancI*: $\langle a, b \rangle : r \implies \langle a, b \rangle : r^+$

$\langle proof \rangle$

lemma *r-subset-trancI*: $relation(r) \implies r \leq r^+$

$\langle proof \rangle$

lemma *rtrancI-into-trancI1*: $[\langle a, b \rangle : r^*; \langle b, c \rangle : r] \implies \langle a, c \rangle : r^+$

$\langle proof \rangle$

lemma *rtranc1-into-tranc12*:

$\llbracket \langle a, b \rangle : r; \langle b, c \rangle : r^{\wedge *} \rrbracket \implies \langle a, c \rangle : r^{\wedge +}$
 $\langle proof \rangle$

lemma *tranc1-induct* [*case-names initial step, induct set: tranc1*]:

$\llbracket \langle a, b \rangle : r^{\wedge +};$
 $\quad !!y. \llbracket \langle a, y \rangle : r \rrbracket \implies P(y);$
 $\quad !!y z. \llbracket \langle a, y \rangle : r^{\wedge +}; \langle y, z \rangle : r; P(y) \rrbracket \implies P(z)$
 $\rrbracket \implies P(b)$
 $\langle proof \rangle$

lemma *tranc1E*:

$\llbracket \langle a, b \rangle : r^{\wedge +};$
 $\quad \langle a, b \rangle : r \implies P;$
 $\quad !!y. \llbracket \langle a, y \rangle : r^{\wedge +}; \langle y, b \rangle : r \rrbracket \implies P$
 $\rrbracket \implies P$
 $\langle proof \rangle$

lemma *tranc1-type*: $r^{\wedge +} \leq \text{field}(r) * \text{field}(r)$
 $\langle proof \rangle$

lemma *relation-tranc1*: $\text{relation}(r^{\wedge +})$
 $\langle proof \rangle$

lemma *tranc1-subset-times*: $r \subseteq A * A \implies r^{\wedge +} \subseteq A * A$
 $\langle proof \rangle$

lemma *tranc1-mono*: $r \leq s \implies r^{\wedge +} \leq s^{\wedge +}$
 $\langle proof \rangle$

lemma *tranc1-eq-r*: $\llbracket \text{relation}(r); \text{trans}(r) \rrbracket \implies r^{\wedge +} = r$
 $\langle proof \rangle$

lemma *rtranc1-idemp* [*simp*]: $(r^{\wedge *})^{\wedge *} = r^{\wedge *}$
 $\langle proof \rangle$

lemma *rtranc1-subset*: $\llbracket R \leq S; S \leq R^{\wedge *} \rrbracket \implies S^{\wedge *} = R^{\wedge *}$
 $\langle proof \rangle$

lemma *rtranc1-Un-rtranc1*:

$\llbracket \text{relation}(r); \text{relation}(s) \rrbracket \implies (r^{\wedge *} \text{ Un } s^{\wedge *})^{\wedge *} = (r \text{ Un } s)^{\wedge *}$

$\langle proof \rangle$

lemma *rtrancl-converseD*: $\langle x, y \rangle : converse(r)^* \implies \langle x, y \rangle : converse(r^+)$
 $\langle proof \rangle$

lemma *rtrancl-converseI*: $\langle x, y \rangle : converse(r^+) \implies \langle x, y \rangle : converse(r)^*$
 $\langle proof \rangle$

lemma *rtrancl-converse*: $converse(r)^* = converse(r^+)$
 $\langle proof \rangle$

lemma *trancl-converseD*: $\langle a, b \rangle : converse(r)^+ \implies \langle a, b \rangle : converse(r^+)$
 $\langle proof \rangle$

lemma *trancl-converseI*: $\langle x, y \rangle : converse(r^+) \implies \langle x, y \rangle : converse(r)^+$
 $\langle proof \rangle$

lemma *trancl-converse*: $converse(r)^+ = converse(r^+)$
 $\langle proof \rangle$

lemma *converse-trancl-induct* [*case-names initial step, consumes 1*]:

$$\begin{aligned} & [[\langle a, b \rangle : r^+; !!y. \langle y, b \rangle : r \implies P(y); \\ & \quad !!y z. [[\langle y, z \rangle : r; \langle z, b \rangle : r^+; P(z)]] \implies P(y)]] \\ & \implies P(a) \end{aligned}$$

 $\langle proof \rangle$

end

12 WF: Well-Founded Recursion

theory *WF* **imports** *Trancl* **begin**

definition

$wf \quad :: i \Rightarrow o \quad \mathbf{where}$

$wf(r) == ALL Z. Z=0 \mid (EX x:Z. ALL y. \langle y, x \rangle : r \longrightarrow \sim y:Z)$

definition

$wf-on \quad :: [i, i] \Rightarrow o \quad (wf[-]')(-') \quad \mathbf{where}$

$wf-on(A, r) == wf(r \text{ Int } A * A)$

definition

$is-recfun \quad :: [i, i, [i, i] => i, i] => o \text{ where}$
 $is-recfun(r, a, H, f) == (f = (lam x: r - \{\{a\}\}. H(x, restrict(f, r - \{\{x\}\}))))$

definition

$the-recfun \quad :: [i, i, [i, i] => i] => i \text{ where}$
 $the-recfun(r, a, H) == (THE f. is-recfun(r, a, H, f))$

definition

$wftrec \quad :: [i, i, [i, i] => i] => i \text{ where}$
 $wftrec(r, a, H) == H(a, the-recfun(r, a, H))$

definition

$wfrec \quad :: [i, i, [i, i] => i] => i \text{ where}$
 $wfrec(r, a, H) == wftrec(r^+ +, a, \%x f. H(x, restrict(f, r - \{\{x\}\})))$

definition

$wfrec-on \quad :: [i, i, i, [i, i] => i] => i \quad (wfrec[-]'(-, -, -)) \text{ where}$
 $wfrec[A](r, a, H) == wfrec(r \text{ Int } A * A, a, H)$

12.1 Well-Founded Relations**12.1.1 Equivalences between wf and $wf-on$**

lemma $wf-imp-wf-on$: $wf(r) ==> wf[A](r)$
 $\langle proof \rangle$

lemma $wf-on-imp-wf$: $[wf[A](r); r <= A * A] ==> wf(r)$
 $\langle proof \rangle$

lemma $wf-on-field-imp-wf$: $wf[field(r)](r) ==> wf(r)$
 $\langle proof \rangle$

lemma $wf-iff-wf-on-field$: $wf(r) <-> wf[field(r)](r)$
 $\langle proof \rangle$

lemma $wf-on-subset-A$: $[wf[A](r); B <= A] ==> wf[B](r)$
 $\langle proof \rangle$

lemma $wf-on-subset-r$: $[wf[A](r); s <= r] ==> wf[A](s)$
 $\langle proof \rangle$

lemma $wf-subset$: $[wf(s); r <= s] ==> wf(r)$
 $\langle proof \rangle$

12.1.2 Introduction Rules for $wf-on$

If every non-empty subset of A has an r -minimal element then we have $wf[A](r)$.

lemma *wf-onI*:
assumes *prem*: $!!Z\ u. [| Z \leq A; \ u:Z; \ \text{ALL } x:Z. \ \text{EX } y:Z. \ \langle y, x \rangle : r |] \implies \text{False}$
shows $\text{wf}[A](r)$
 $\langle \text{proof} \rangle$

If r allows well-founded induction over A then we have $\text{wf}[A](r)$. Premise is equivalent to $\bigwedge B. \forall x \in A. (\forall y. \langle y, x \rangle \in r \longrightarrow y \in B) \longrightarrow x \in B \implies A \subseteq B$

lemma *wf-onI2*:
assumes *prem*: $!!y\ B. [| \text{ALL } x:A. (\text{ALL } y:A. \ \langle y, x \rangle : r \longrightarrow y:B) \longrightarrow x:B; \ y:A |]$
 $\implies y:B$
shows $\text{wf}[A](r)$
 $\langle \text{proof} \rangle$

12.1.3 Well-founded Induction

Consider the least z in $\text{domain}(r)$ such that $P(z)$ does not hold...

lemma *wf-induct* [*induct set*: *wf*]:
 $[| \text{wf}(r);$
 $\quad !!x. [| \text{ALL } y. \ \langle y, x \rangle : r \longrightarrow P(y) |] \implies P(x) |]$
 $\implies P(a)$
 $\langle \text{proof} \rangle$

lemmas *wf-induct-rule* = *wf-induct* [*rule-format*, *induct set*: *wf*]

The form of this rule is designed to match *wfI*

lemma *wf-induct2*:
 $[| \text{wf}(r); \ a:A; \ \text{field}(r) \leq A;$
 $\quad !!x. [| x:A; \ \text{ALL } y. \ \langle y, x \rangle : r \longrightarrow P(y) |] \implies P(x) |]$
 $\implies P(a)$
 $\langle \text{proof} \rangle$

lemma *field-Int-square*: $\text{field}(r \ \text{Int } A * A) \leq A$
 $\langle \text{proof} \rangle$

lemma *wf-on-induct* [*consumes 2*, *induct set*: *wf-on*]:
 $[| \text{wf}[A](r); \ a:A;$
 $\quad !!x. [| x:A; \ \text{ALL } y:A. \ \langle y, x \rangle : r \longrightarrow P(y) |] \implies P(x)$
 $|] \implies P(a)$
 $\langle \text{proof} \rangle$

lemmas *wf-on-induct-rule* =
wf-on-induct [*rule-format*, *consumes 2*, *induct set*: *wf-on*]

If r allows well-founded induction then we have $\text{wf}(r)$.

lemma *wfI*:
 $[| \text{field}(r) \leq A;$

$$\begin{aligned} & !!y \text{ B}. [\mid ALL \ x:A. (ALL \ y:A. \langle y,x \rangle:r \dashv\dashv y:B) \dashv\dashv x:B; \ y:A] \\ & \quad ==> \ y:B \mid \\ & ==> \ wf(r) \\ & \langle proof \rangle \end{aligned}$$

12.2 Basic Properties of Well-Founded Relations

lemma *wf-not-refl*: $wf(r) ==> <a,a> \sim: r$
 $\langle proof \rangle$

lemma *wf-not-sym* [*rule-format*]: $wf(r) ==> ALL\ x. <a, x>:r \dashv\dashv <x, a> \sim: r$
<proof>

```
lemmas wf-asym = wf-not-sym [THEN swap, standard]
```

lemma *wf-on-not-refl*: $[\mid \text{wf}[A](r); a: A \mid] \implies \langle a, a \rangle \sim: r$
 $\langle \text{proof} \rangle$

lemma *wf-on-not-sym* [rule-format]:

$$[\text{wf}[A](r); \ a:A] \implies ALL\ b:A. \ \langle a,b \rangle:r \dashv\dashv \langle b,a \rangle:r$$

 $\langle proof \rangle$

lemma *wf-on-asm*:

$$\begin{aligned} & \llbracket wf[A](r); \sim Z ==> \langle a, b \rangle : r; \\ & \quad \langle b, a \rangle \sim : r ==> Z; \sim Z ==> a : A; \sim Z ==> b : A \rrbracket ==> Z \\ & \langle proof \rangle \end{aligned}$$

lemma *wf-on-chain3*:

$$\llbracket \text{wf}[A](r); \langle a, b \rangle : r; \langle b, c \rangle : r; \langle c, a \rangle : r; a : A; b : A; c : A \rrbracket \implies P$$

<proof>

transitive closure of a WF relation is WF provided A is downward closed

lemma *wf-on-trancl*:

$$[[\text{wf}[A](r); \ r - \text{“}A \leq A \text{”}]] \implies \text{wf}[A](r^+)$$

<proof>

lemma *wf-trancl*: $wf(r) ==> wf(r^+)$
<proof>

$r = \{ \{a\} \}$ is the set of everything under a in r

lemmas *underI = vimage-singleton-iff* [THEN iffD2, standard]

lemmas *underD = vimage-singleton-iff* *[THEN iffD1, standard]*

12.3 The Predicate *is-recfun*

lemma *is-recfun-type*: $is-recfun(r,a,H,f) ==> f: r - \text{“}\{a\} \rightarrow range(f)\text{”}$

$\langle \text{proof} \rangle$

lemmas *is-recfun-imp-function* = *is-recfun-type* [THEN *fun-is-function*]

lemma *apply-recfun*:

$[[\text{is-recfun}(r, a, H, f); \langle x, a \rangle : r]] \implies f'x = H(x, \text{restrict}(f, r - \{\{x\}\}))$
 $\langle \text{proof} \rangle$

lemma *is-recfun-equal* [rule-format]:

$[[\text{wf}(r); \text{trans}(r); \text{is-recfun}(r, a, H, f); \text{is-recfun}(r, b, H, g)]]$
 $\implies \langle x, a \rangle : r \dashv\dashv \langle x, b \rangle : r \dashv\dashv f'x = g'x$
 $\langle \text{proof} \rangle$

lemma *is-recfun-cut*:

$[[\text{wf}(r); \text{trans}(r);$
 $\text{is-recfun}(r, a, H, f); \text{is-recfun}(r, b, H, g); \langle b, a \rangle : r]]$
 $\implies \text{restrict}(f, r - \{\{b\}\}) = g$
 $\langle \text{proof} \rangle$

12.4 Recursion: Main Existence Lemma

lemma *is-recfun-functional*:

$[[\text{wf}(r); \text{trans}(r); \text{is-recfun}(r, a, H, f); \text{is-recfun}(r, a, H, g)]] \implies f = g$
 $\langle \text{proof} \rangle$

lemma *the-recfun-eq*:

$[[\text{is-recfun}(r, a, H, f); \text{wf}(r); \text{trans}(r)]] \implies \text{the-recfun}(r, a, H) = f$
 $\langle \text{proof} \rangle$

lemma *is-the-recfun*:

$[[\text{is-recfun}(r, a, H, f); \text{wf}(r); \text{trans}(r)]]$
 $\implies \text{is-recfun}(r, a, H, \text{the-recfun}(r, a, H))$
 $\langle \text{proof} \rangle$

lemma *unfold-the-recfun*:

$[[\text{wf}(r); \text{trans}(r)]] \implies \text{is-recfun}(r, a, H, \text{the-recfun}(r, a, H))$
 $\langle \text{proof} \rangle$

12.5 Unfolding *wftrec*(*r*, *a*, *H*)

lemma *the-recfun-cut*:

$[[\text{wf}(r); \text{trans}(r); \langle b, a \rangle : r]]$
 $\implies \text{restrict}(\text{the-recfun}(r, a, H), r - \{\{b\}\}) = \text{the-recfun}(r, b, H)$
 $\langle \text{proof} \rangle$

lemma *wftrec*:

$[[\text{wf}(r); \text{trans}(r)]] \implies$
 $\text{wftrec}(r, a, H) = H(a, \text{lam } x: r - \{\{a\}\}. \text{wftrec}(r, x, H))$

$\langle proof \rangle$

12.5.1 Removal of the Premise $trans(r)$

lemma *wfrec*:

$wf(r) \implies wfrec(r, a, H) = H(a, \text{lam } x: r - \{\{a\}. wfrec(r, x, H)\})$
 $\langle proof \rangle$

lemma *def-wfrec*:

$[\text{!}x. h(x) = wfrec(r, x, H); wf(r)] \implies$
 $h(a) = H(a, \text{lam } x: r - \{\{a\}. h(x)\})$
 $\langle proof \rangle$

lemma *wfrec-type*:

$[wf(r); a:A; field(r) \leq A;$
 $\text{!}x\ u. [x: A; u: Pi(r - \{\{x\}, B)] \implies H(x, u) : B(x)$
 $] \implies wfrec(r, a, H) : B(a)$
 $\langle proof \rangle$

lemma *wfrec-on*:

$[wf[A](r); a: A] \implies$
 $wfrec[A](r, a, H) = H(a, \text{lam } x: (r - \{\{a\}\} Int A. wfrec[A](r, x, H))$
 $\langle proof \rangle$

Minimal-element characterization of well-foundedness

lemma *wf-eq-minimal*:

$wf(r) <-> (ALL\ Q\ x. x:Q \dashrightarrow (EX\ z:Q. ALL\ y. <y, z>:r \dashrightarrow y \sim :Q))$
 $\langle proof \rangle$

end

13 Ordinal: Transitive Sets and Ordinals

theory *Ordinal* **imports** *WF Bool equalities* **begin**

definition

$Memrel \quad :: i \Rightarrow i$ **where**
 $Memrel(A) == \{z: A * A . EX\ x\ y. z = <x, y> \ \& \ x: y \}$

definition

$Transset \quad :: i \Rightarrow o$ **where**
 $Transset(i) == ALL\ x:i. x \leq i$

definition

$Ord \quad :: i \Rightarrow o$ **where**
 $Ord(i) == Transset(i) \ \& \ (ALL\ x:i. Transset(x))$

definition

$lt \quad :: [i,i] \Rightarrow o \text{ (infixl } < 50) \quad \text{where}$
 $i < j \quad == i:j \ \& \ Ord(j)$

definition

$Limit \quad :: i \Rightarrow o \text{ where}$
 $Limit(i) \quad == Ord(i) \ \& \ 0 < i \ \& \ (ALL \ y. \ y < i \ \longrightarrow \ succ(y) < i)$

abbreviation

$le \text{ (infixl } le \ 50) \text{ where}$
 $x \ le \ y == x < succ(y)$

notation (*xsymbols*)

$le \text{ (infixl } \leq 50)$

notation (*HTML output*)

$le \text{ (infixl } \leq 50)$

13.1 Rules for Transset**13.1.1 Three Neat Characterisations of Transset**

lemma *Transset-iff-Pow*: $Transset(A) <-> A \leq Pow(A)$
 $\langle proof \rangle$

lemma *Transset-iff-Union-succ*: $Transset(A) <-> Union(succ(A)) = A$
 $\langle proof \rangle$

lemma *Transset-iff-Union-subset*: $Transset(A) <-> Union(A) \leq A$
 $\langle proof \rangle$

13.1.2 Consequences of Downwards Closure

lemma *Transset-doubleton-D*:
 $[| \ Transset(C); \{a,b\}: C \ |] \Rightarrow a:C \ \& \ b: C$
 $\langle proof \rangle$

lemma *Transset-Pair-D*:
 $[| \ Transset(C); <a,b>: C \ |] \Rightarrow a:C \ \& \ b: C$
 $\langle proof \rangle$

lemma *Transset-includes-domain*:
 $[| \ Transset(C); A*B \leq C; b: B \ |] \Rightarrow A \leq C$
 $\langle proof \rangle$

lemma *Transset-includes-range*:
 $[| \ Transset(C); A*B \leq C; a: A \ |] \Rightarrow B \leq C$
 $\langle proof \rangle$

13.1.3 Closure Properties

lemma *Transset-0*: $\text{Transset}(0)$

$\langle \text{proof} \rangle$

lemma *Transset-Un*:

$[[\text{Transset}(i); \text{Transset}(j)]] ==> \text{Transset}(i \text{ Un } j)$

$\langle \text{proof} \rangle$

lemma *Transset-Int*:

$[[\text{Transset}(i); \text{Transset}(j)]] ==> \text{Transset}(i \text{ Int } j)$

$\langle \text{proof} \rangle$

lemma *Transset-succ*: $\text{Transset}(i) ==> \text{Transset}(\text{succ}(i))$

$\langle \text{proof} \rangle$

lemma *Transset-Pow*: $\text{Transset}(i) ==> \text{Transset}(\text{Pow}(i))$

$\langle \text{proof} \rangle$

lemma *Transset-Union*: $\text{Transset}(A) ==> \text{Transset}(\text{Union}(A))$

$\langle \text{proof} \rangle$

lemma *Transset-Union-family*:

$[[!!i. i:A ==> \text{Transset}(i)]] ==> \text{Transset}(\text{Union}(A))$

$\langle \text{proof} \rangle$

lemma *Transset-Inter-family*:

$[[!!i. i:A ==> \text{Transset}(i)]] ==> \text{Transset}(\text{Inter}(A))$

$\langle \text{proof} \rangle$

lemma *Transset-UN*:

$(!!x. x \in A ==> \text{Transset}(B(x))) ==> \text{Transset} (\bigcup x \in A. B(x))$

$\langle \text{proof} \rangle$

lemma *Transset-INT*:

$(!!x. x \in A ==> \text{Transset}(B(x))) ==> \text{Transset} (\bigcap x \in A. B(x))$

$\langle \text{proof} \rangle$

13.2 Lemmas for Ordinals

lemma *OrdI*:

$[[\text{Transset}(i); !!x. x:i ==> \text{Transset}(x)]] ==> \text{Ord}(i)$

$\langle \text{proof} \rangle$

lemma *Ord-is-Transset*: $\text{Ord}(i) ==> \text{Transset}(i)$

$\langle \text{proof} \rangle$

lemma *Ord-contains-Transset*:

$[[\text{Ord}(i); j:i]] ==> \text{Transset}(j)$

$\langle \text{proof} \rangle$

lemma *Ord-in-Ord*: $[[\text{Ord}(i); j:i]] ==> \text{Ord}(j)$
 $\langle \text{proof} \rangle$

lemma *Ord-in-Ord'*: $[[j:i; \text{Ord}(i)]] ==> \text{Ord}(j)$
 $\langle \text{proof} \rangle$

lemmas *Ord-succD* = *Ord-in-Ord* [*OF* - *succI1*]

lemma *Ord-subset-Ord*: $[[\text{Ord}(i); \text{Transset}(j); j \leq i]] ==> \text{Ord}(j)$
 $\langle \text{proof} \rangle$

lemma *OrdmemD*: $[[j:i; \text{Ord}(i)]] ==> j \leq i$
 $\langle \text{proof} \rangle$

lemma *Ord-trans*: $[[i:j; j:k; \text{Ord}(k)]] ==> i:k$
 $\langle \text{proof} \rangle$

lemma *Ord-succ-subsetI*: $[[i:j; \text{Ord}(j)]] ==> \text{succ}(i) \leq j$
 $\langle \text{proof} \rangle$

13.3 The Construction of Ordinals: 0, succ, Union

lemma *Ord-0* [*iff*, *TC*]: $\text{Ord}(0)$
 $\langle \text{proof} \rangle$

lemma *Ord-succ* [*TC*]: $\text{Ord}(i) ==> \text{Ord}(\text{succ}(i))$
 $\langle \text{proof} \rangle$

lemmas *Ord-1* = *Ord-0* [*THEN* *Ord-succ*]

lemma *Ord-succ-iff* [*iff*]: $\text{Ord}(\text{succ}(i)) <-> \text{Ord}(i)$
 $\langle \text{proof} \rangle$

lemma *Ord-Un* [*intro*, *simp*, *TC*]: $[[\text{Ord}(i); \text{Ord}(j)]] ==> \text{Ord}(i \text{ Un } j)$
 $\langle \text{proof} \rangle$

lemma *Ord-Int* [*TC*]: $[[\text{Ord}(i); \text{Ord}(j)]] ==> \text{Ord}(i \text{ Int } j)$
 $\langle \text{proof} \rangle$

lemma *ON-class*: $\sim (ALL i. i:X <-> \text{Ord}(i))$
 $\langle \text{proof} \rangle$

13.4 \leq is 'less Than' for Ordinals

lemma *ltI*: $[[i:j; \text{Ord}(j)]] ==> i < j$

$\langle proof \rangle$

lemma *ltE*:

$[[i < j; \quad [i:j; \quad Ord(i); \quad Ord(j)]] ==> P] ==> P$
 $\langle proof \rangle$

lemma *ltD*: $i < j ==> i:j$

$\langle proof \rangle$

lemma *not-lt0* [*simp*]: $\sim i < 0$

$\langle proof \rangle$

lemma *lt-Ord*: $j < i ==> Ord(j)$

$\langle proof \rangle$

lemma *lt-Ord2*: $j < i ==> Ord(i)$

$\langle proof \rangle$

lemmas *le-Ord2* = *lt-Ord2* [*THEN Ord-succD*]

lemmas *lt0E* = *not-lt0* [*THEN notE, elim!*]

lemma *lt-trans*: $[[i < j; \quad j < k]] ==> i < k$

$\langle proof \rangle$

lemma *lt-not-sym*: $i < j ==> \sim (j < i)$

$\langle proof \rangle$

lemmas *lt-asy* = *lt-not-sym* [*THEN swap*]

lemma *lt-irrefl* [*elim!*]: $i < i ==> P$

$\langle proof \rangle$

lemma *lt-not-refl*: $\sim i < i$

$\langle proof \rangle$

lemma *le-iff*: $i \leq j \iff i < j \mid (i=j \ \& \ Ord(j))$

$\langle proof \rangle$

lemma *leI*: $i < j ==> i \leq j$

$\langle proof \rangle$

lemma *le-eqI*: $[\mid i=j; \text{Ord}(j) \mid] \implies i \text{ le } j$
 $\langle \text{proof} \rangle$

lemmas *le-refl* = *refl* [THEN *le-eqI*]

lemma *le-refl-iff* [*iff*]: $i \text{ le } i \iff \text{Ord}(i)$
 $\langle \text{proof} \rangle$

lemma *leCI*: $(\sim (i=j \ \& \ \text{Ord}(j))) \implies i < j \implies i \text{ le } j$
 $\langle \text{proof} \rangle$

lemma *leE*:
 $[\mid i \text{ le } j; \ i < j \implies P; \mid i=j; \ \text{Ord}(j) \mid] \implies P \mid] \implies P$
 $\langle \text{proof} \rangle$

lemma *le-anti-sym*: $[\mid i \text{ le } j; \ j \text{ le } i \mid] \implies i=j$
 $\langle \text{proof} \rangle$

lemma *le0-iff* [*simp*]: $i \text{ le } 0 \iff i=0$
 $\langle \text{proof} \rangle$

lemmas *le0D* = *le0-iff* [THEN *iffD1*, *dest!*]

13.5 Natural Deduction Rules for Memrel

lemma *Memrel-iff* [*simp*]: $\langle a, b \rangle : \text{Memrel}(A) \iff a:b \ \& \ a:A \ \& \ b:A$
 $\langle \text{proof} \rangle$

lemma *MemrelI* [*intro!*]: $[\mid a: b; \ a: A; \ b: A \mid] \implies \langle a, b \rangle : \text{Memrel}(A)$
 $\langle \text{proof} \rangle$

lemma *MemrelE* [*elim!*]:
 $[\mid \langle a, b \rangle : \text{Memrel}(A);$
 $\quad [\mid a: A; \ b: A; \ a:b \mid] \implies P \mid]$
 $\implies P$
 $\langle \text{proof} \rangle$

lemma *Memrel-type*: $\text{Memrel}(A) \leq A * A$
 $\langle \text{proof} \rangle$

lemma *Memrel-mono*: $A \leq B \implies \text{Memrel}(A) \leq \text{Memrel}(B)$
 $\langle \text{proof} \rangle$

lemma *Memrel-0* [*simp*]: $\text{Memrel}(0) = 0$
 $\langle \text{proof} \rangle$

lemma *Memrel-1* [*simp*]: $\text{Memrel}(1) = 0$
 $\langle \text{proof} \rangle$

lemma *relation-Memrel*: $\text{relation}(\text{Memrel}(A))$
 $\langle \text{proof} \rangle$

lemma *wf-Memrel*: $\text{wf}(\text{Memrel}(A))$
 $\langle \text{proof} \rangle$

The premise $\text{Ord}(i)$ does not suffice.

lemma *trans-Memrel*:
 $\text{Ord}(i) \implies \text{trans}(\text{Memrel}(i))$
 $\langle \text{proof} \rangle$

However, the following premise is strong enough.

lemma *Transset-trans-Memrel*:
 $\forall j \in i. \text{Transset}(j) \implies \text{trans}(\text{Memrel}(i))$
 $\langle \text{proof} \rangle$

lemma *Transset-Memrel-iff*:
 $\text{Transset}(A) \implies \langle a, b \rangle : \text{Memrel}(A) \iff a : b \ \& \ b : A$
 $\langle \text{proof} \rangle$

13.6 Transfinite Induction

lemma *Transset-induct*:
 $\llbracket i : k; \text{Transset}(k);$
 $\quad \text{!!}x. \llbracket x : k; \text{ALL } y : x. P(y) \rrbracket \implies P(x) \rrbracket$
 $\implies P(i)$
 $\langle \text{proof} \rangle$

lemmas *Ord-induct* [consumes 2] = *Transset-induct* [OF - Ord-is-Transset]
lemmas *Ord-induct-rule* = *Ord-induct* [rule-format, consumes 2]

lemma *trans-induct* [consumes 1]:
 $\llbracket \text{Ord}(i);$
 $\quad \text{!!}x. \llbracket \text{Ord}(x); \text{ALL } y : x. P(y) \rrbracket \implies P(x) \rrbracket$
 $\implies P(i)$
 $\langle \text{proof} \rangle$

lemmas *trans-induct-rule* = *trans-induct* [rule-format, consumes 1]

13.6.1 Proving That \mathfrak{j} is a Linear Ordering on the Ordinals

lemma *Ord-linear* [rule-format]:
 $\text{Ord}(i) \implies (\text{ALL } j. \text{Ord}(j) \dashv\vdash i : j \mid i = j \mid j : i)$
 $\langle \text{proof} \rangle$

lemma *Ord-linear-lt*:

$\llbracket \text{Ord}(i); \text{Ord}(j); i < j \implies P; i = j \implies P; j < i \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *Ord-linear2*:

$\llbracket \text{Ord}(i); \text{Ord}(j); i < j \implies P; j \text{ le } i \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *Ord-linear-le*:

$\llbracket \text{Ord}(i); \text{Ord}(j); i \text{ le } j \implies P; j \text{ le } i \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *le-imp-not-lt*: $j \text{ le } i \implies \sim i < j$

$\langle \text{proof} \rangle$

lemma *not-lt-imp-le*: $\llbracket \sim i < j; \text{Ord}(i); \text{Ord}(j) \rrbracket \implies j \text{ le } i$

$\langle \text{proof} \rangle$

13.6.2 Some Rewrite Rules for \mathfrak{j} , le

lemma *Ord-mem-iff-lt*: $\text{Ord}(j) \implies i:j < \rightarrow i < j$

$\langle \text{proof} \rangle$

lemma *not-lt-iff-le*: $\llbracket \text{Ord}(i); \text{Ord}(j) \rrbracket \implies \sim i < j < \rightarrow j \text{ le } i$

$\langle \text{proof} \rangle$

lemma *not-le-iff-lt*: $\llbracket \text{Ord}(i); \text{Ord}(j) \rrbracket \implies \sim i \text{ le } j < \rightarrow j < i$

$\langle \text{proof} \rangle$

lemma *Ord-0-le*: $\text{Ord}(i) \implies 0 \text{ le } i$

$\langle \text{proof} \rangle$

lemma *Ord-0-lt*: $\llbracket \text{Ord}(i); i \sim 0 \rrbracket \implies 0 < i$

$\langle \text{proof} \rangle$

lemma *Ord-0-lt-iff*: $\text{Ord}(i) \implies i \sim 0 < \rightarrow 0 < i$

$\langle \text{proof} \rangle$

13.7 Results about Less-Than or Equals

lemma *zero-le-succ-iff* [*iff*]: $0 \text{ le succ}(x) < \rightarrow \text{Ord}(x)$

$\langle \text{proof} \rangle$

lemma *subset-imp-le*: $\llbracket j \leq i; \text{Ord}(i); \text{Ord}(j) \rrbracket \implies j \text{ le } i$

$\langle \text{proof} \rangle$

lemma *le-imp-subset*: $i \text{ le } j \implies i \leq j$

$\langle proof \rangle$

lemma *le-subset-iff*: $j \text{ le } i \leftrightarrow j \leq i \ \& \ \text{Ord}(i) \ \& \ \text{Ord}(j)$
 $\langle proof \rangle$

lemma *le-succ-iff*: $i \text{ le } \text{succ}(j) \leftrightarrow i \text{ le } j \mid i = \text{succ}(j) \ \& \ \text{Ord}(i)$
 $\langle proof \rangle$

lemma *all-lt-imp-le*: $[\mid \text{Ord}(i); \text{Ord}(j); \forall x. x < j \implies x < i] \implies j \text{ le } i$
 $\langle proof \rangle$

13.7.1 Transitivity Laws

lemma *lt-trans1*: $[\mid i \text{ le } j; j < k] \implies i < k$
 $\langle proof \rangle$

lemma *lt-trans2*: $[\mid i < j; j \text{ le } k] \implies i < k$
 $\langle proof \rangle$

lemma *le-trans*: $[\mid i \text{ le } j; j \text{ le } k] \implies i \text{ le } k$
 $\langle proof \rangle$

lemma *succ-leI*: $i < j \implies \text{succ}(i) \text{ le } j$
 $\langle proof \rangle$

lemma *succ-leE*: $\text{succ}(i) \text{ le } j \implies i < j$
 $\langle proof \rangle$

lemma *succ-le-iff* [*iff*]: $\text{succ}(i) \text{ le } j \leftrightarrow i < j$
 $\langle proof \rangle$

lemma *succ-le-imp-le*: $\text{succ}(i) \text{ le } \text{succ}(j) \implies i \text{ le } j$
 $\langle proof \rangle$

lemma *lt-subset-trans*: $[\mid i \leq j; j < k; \text{Ord}(i)] \implies i < k$
 $\langle proof \rangle$

lemma *lt-imp-0-lt*: $j < i \implies 0 < i$
 $\langle proof \rangle$

lemma *succ-lt-iff*: $\text{succ}(i) < j \leftrightarrow i < j \ \& \ \text{succ}(i) \neq j$
 $\langle proof \rangle$

lemma *Ord-succ-mem-iff*: $\text{Ord}(j) \implies \text{succ}(i) \in \text{succ}(j) \leftrightarrow i \in j$
 $\langle proof \rangle$

13.7.2 Union and Intersection

lemma *Un-upper1-le*: $[\text{Ord}(i); \text{Ord}(j)] \implies i \text{ le } i \text{ Un } j$
 $\langle \text{proof} \rangle$

lemma *Un-upper2-le*: $[\text{Ord}(i); \text{Ord}(j)] \implies j \text{ le } i \text{ Un } j$
 $\langle \text{proof} \rangle$

lemma *Un-least-lt*: $[i < k; j < k] \implies i \text{ Un } j < k$
 $\langle \text{proof} \rangle$

lemma *Un-least-lt-iff*: $[\text{Ord}(i); \text{Ord}(j)] \implies i \text{ Un } j < k \iff i < k \ \& \ j < k$
 $\langle \text{proof} \rangle$

lemma *Un-least-mem-iff*:
 $[\text{Ord}(i); \text{Ord}(j); \text{Ord}(k)] \implies i \text{ Un } j : k \iff i:k \ \& \ j:k$
 $\langle \text{proof} \rangle$

lemma *Int-greatest-lt*: $[i < k; j < k] \implies i \text{ Int } j < k$
 $\langle \text{proof} \rangle$

lemma *Ord-Un-if*:
 $[\text{Ord}(i); \text{Ord}(j)] \implies i \cup j = (\text{if } j < i \text{ then } i \text{ else } j)$
 $\langle \text{proof} \rangle$

lemma *succ-Un-distrib*:
 $[\text{Ord}(i); \text{Ord}(j)] \implies \text{succ}(i \cup j) = \text{succ}(i) \cup \text{succ}(j)$
 $\langle \text{proof} \rangle$

lemma *lt-Un-iff*:
 $[\text{Ord}(i); \text{Ord}(j)] \implies k < i \cup j \iff k < i \mid k < j$
 $\langle \text{proof} \rangle$

lemma *le-Un-iff*:
 $[\text{Ord}(i); \text{Ord}(j)] \implies k \leq i \cup j \iff k \leq i \mid k \leq j$
 $\langle \text{proof} \rangle$

lemma *Un-upper1-lt*: $[k < i; \text{Ord}(j)] \implies k < i \text{ Un } j$
 $\langle \text{proof} \rangle$

lemma *Un-upper2-lt*: $[k < j; \text{Ord}(i)] \implies k < i \text{ Un } j$
 $\langle \text{proof} \rangle$

lemma *Ord-Union-succ-eq*: $\text{Ord}(i) \implies \bigcup(\text{succ}(i)) = i$
 $\langle \text{proof} \rangle$

13.8 Results about Limits

lemma *Ord-Union* [intro,simp,TC]: $[\![\! \! i. i:A ==> \text{Ord}(i) \! \!]\!] ==> \text{Ord}(\text{Union}(A))$
 $\langle \text{proof} \rangle$

lemma *Ord-UN* [intro,simp,TC]:
 $[\![\! \! x. x:A ==> \text{Ord}(B(x)) \! \!]\!] ==> \text{Ord}(\bigcup_{x \in A} B(x))$
 $\langle \text{proof} \rangle$

lemma *Ord-Inter* [intro,simp,TC]:
 $[\![\! \! i. i:A ==> \text{Ord}(i) \! \!]\!] ==> \text{Ord}(\text{Inter}(A))$
 $\langle \text{proof} \rangle$

lemma *Ord-INT* [intro,simp,TC]:
 $[\![\! \! x. x:A ==> \text{Ord}(B(x)) \! \!]\!] ==> \text{Ord}(\bigcap_{x \in A} B(x))$
 $\langle \text{proof} \rangle$

lemma *UN-least-le*:
 $[\![\text{Ord}(i); \! \! x. x:A ==> b(x) \text{ le } i \! \!]\!] ==> (\bigcup_{x \in A} b(x)) \text{ le } i$
 $\langle \text{proof} \rangle$

lemma *UN-succ-least-lt*:
 $[\![j < i; \! \! x. x:A ==> b(x) < j \! \!]\!] ==> (\bigcup_{x \in A} \text{succ}(b(x))) < i$
 $\langle \text{proof} \rangle$

lemma *UN-upper-lt*:
 $[\![a \in A; i < b(a); \text{Ord}(\bigcup_{x \in A} b(x)) \! \!]\!] ==> i < (\bigcup_{x \in A} b(x))$
 $\langle \text{proof} \rangle$

lemma *UN-upper-le*:
 $[\![a: A; i \text{ le } b(a); \text{Ord}(\bigcup_{x \in A} b(x)) \! \!]\!] ==> i \text{ le } (\bigcup_{x \in A} b(x))$
 $\langle \text{proof} \rangle$

lemma *lt-Union-iff*: $\forall i \in A. \text{Ord}(i) ==> (j < \bigcup(A)) <-> (\exists i \in A. j < i)$
 $\langle \text{proof} \rangle$

lemma *Union-upper-le*:
 $[\![j: J; i \leq j; \text{Ord}(\bigcup(J)) \! \!]\!] ==> i \leq \bigcup J$
 $\langle \text{proof} \rangle$

lemma *le-implies-UN-le-UN*:
 $[\![\! \! x. x:A ==> c(x) \text{ le } d(x) \! \!]\!] ==> (\bigcup_{x \in A} c(x)) \text{ le } (\bigcup_{x \in A} d(x))$
 $\langle \text{proof} \rangle$

lemma *Ord-equality*: $\text{Ord}(i) ==> (\bigcup_{y \in i} \text{succ}(y)) = i$
 $\langle \text{proof} \rangle$

lemma *Ord-Union-subset*: $\text{Ord}(i) \implies \text{Union}(i) \leq i$
 $\langle \text{proof} \rangle$

13.9 Limit Ordinals – General Properties

lemma *Limit-Union-eq*: $\text{Limit}(i) \implies \text{Union}(i) = i$
 $\langle \text{proof} \rangle$

lemma *Limit-is-Ord*: $\text{Limit}(i) \implies \text{Ord}(i)$
 $\langle \text{proof} \rangle$

lemma *Limit-has-0*: $\text{Limit}(i) \implies 0 < i$
 $\langle \text{proof} \rangle$

lemma *Limit-nonzero*: $\text{Limit}(i) \implies i \sim 0$
 $\langle \text{proof} \rangle$

lemma *Limit-has-succ*: $[\text{Limit}(i); j < i] \implies \text{succ}(j) < i$
 $\langle \text{proof} \rangle$

lemma *Limit-succ-lt-iff* [simp]: $\text{Limit}(i) \implies \text{succ}(j) < i \iff (j < i)$
 $\langle \text{proof} \rangle$

lemma *zero-not-Limit* [iff]: $\sim \text{Limit}(0)$
 $\langle \text{proof} \rangle$

lemma *Limit-has-1*: $\text{Limit}(i) \implies 1 < i$
 $\langle \text{proof} \rangle$

lemma *increasing-LimitI*: $[\text{Limit}(l); 0 < l; \forall x \in l. \exists y \in l. x < y] \implies \text{Limit}(l)$
 $\langle \text{proof} \rangle$

lemma *non-succ-LimitI*:
 $[\text{Limit}(i); 0 < i; \forall y. \text{succ}(y) \sim i] \implies \text{Limit}(i)$
 $\langle \text{proof} \rangle$

lemma *succ-LimitE* [elim!]: $\text{Limit}(\text{succ}(i)) \implies P$
 $\langle \text{proof} \rangle$

lemma *not-succ-Limit* [simp]: $\sim \text{Limit}(\text{succ}(i))$
 $\langle \text{proof} \rangle$

lemma *Limit-le-succD*: $[\text{Limit}(i); i \leq \text{succ}(j)] \implies i \leq j$
 $\langle \text{proof} \rangle$

13.9.1 Traditional 3-Way Case Analysis on Ordinals

lemma *Ord-cases-disj*: $\text{Ord}(i) \implies i = 0 \mid (\exists x. \text{Ord}(x) \ \& \ i = \text{succ}(x)) \mid \text{Limit}(i)$
 $\langle \text{proof} \rangle$

lemma *Ord-cases*:

```

  [| Ord(i);
    i=0 ==> P;
    !!j. [| Ord(j); i=succ(j) |] ==> P;
    Limit(i) ==> P
  |] ==> P
<proof>

```

lemma *trans-induct3* [*case-names 0 succ limit, consumes 1*]:

```

  [| Ord(i);
    P(0);
    !!x. [| Ord(x); P(x) |] ==> P(succ(x));
    !!x. [| Limit(x); ALL y:x. P(y) |] ==> P(x)
  |] ==> P(i)
<proof>

```

lemmas *trans-induct3-rule* = *trans-induct3* [*rule-format, case-names 0 succ limit, consumes 1*]

A set of ordinals is either empty, contains its own union, or its union is a limit ordinal.

lemma *Ord-set-cases*:

```

  ∀ i ∈ I. Ord(i) ==> I=0 ∨ ⋃(I) ∈ I ∨ (⋃(I) ∉ I ∧ Limit(⋃(I)))
<proof>

```

If the union of a set of ordinals is a successor, then it is an element of that set.

lemma *Ord-Union-eq-succD*: [|∀ x ∈ X. Ord(x); ⋃ X = succ(j)|] ==> succ(j) ∈ X
 <proof>

lemma *Limit-Union* [*rule-format*]: [| I ≠ 0; ∀ i ∈ I. Limit(i) |] ==> Limit(⋃ I)
 <proof>

end

14 OrdQuant: Special quantifiers

theory *OrdQuant* **imports** *Ordinal* **begin**

14.1 Quantifiers and union operator for ordinals

definition

```

oall :: [i, i => o] => o where
  oall(A, P) == ALL x. x < A --> P(x)

```

definition

$oex :: [i, i \Rightarrow o] \Rightarrow o$ **where**
 $oex(A, P) == EX\ x. x < A \ \& \ P(x)$

definition

$OUnion :: [i, i \Rightarrow i] \Rightarrow i$ **where**
 $OUnion(i, B) == \{z: \bigcup_{x \in i}. B(x). \text{Ord}(i)\}$

syntax

$@oall \quad :: [idt, i, o] \Rightarrow o \quad ((\exists ALL \text{ -<-./ -})\ 10)$
 $@oex \quad :: [idt, i, o] \Rightarrow o \quad ((\exists EX \text{ -<-./ -})\ 10)$
 $@OUNION \quad :: [idt, i, i] \Rightarrow i \quad ((\exists UN \text{ -<-./ -})\ 10)$

translations

$ALL\ x < a. P == CONST\ oall(a, \%x. P)$
 $EX\ x < a. P == CONST\ oex(a, \%x. P)$
 $UN\ x < a. B == CONST\ OUnion(a, \%x. B)$

syntax (*xsymbols*)

$@oall \quad :: [idt, i, o] \Rightarrow o \quad ((\exists \forall \text{ -<-./ -})\ 10)$
 $@oex \quad :: [idt, i, o] \Rightarrow o \quad ((\exists \exists \text{ -<-./ -})\ 10)$
 $@OUNION \quad :: [idt, i, i] \Rightarrow i \quad ((\exists \bigcup \text{ -<-./ -})\ 10)$

syntax (*HTML output*)

$@oall \quad :: [idt, i, o] \Rightarrow o \quad ((\exists \forall \text{ -<-./ -})\ 10)$
 $@oex \quad :: [idt, i, o] \Rightarrow o \quad ((\exists \exists \text{ -<-./ -})\ 10)$
 $@OUNION \quad :: [idt, i, i] \Rightarrow i \quad ((\exists \bigcup \text{ -<-./ -})\ 10)$

14.1.1 simplification of the new quantifiers

lemma $[simp]: (ALL\ x < 0. P(x))$
 $\langle proof \rangle$

lemma $[simp]: \sim (EX\ x < 0. P(x))$
 $\langle proof \rangle$

lemma $[simp]: (ALL\ x < succ(i). P(x)) \text{ -<-> } (Ord(i) \text{ --> } P(i) \ \& \ (ALL\ x < i. P(x)))$
 $\langle proof \rangle$

lemma $[simp]: (EX\ x < succ(i). P(x)) \text{ -<-> } (Ord(i) \ \& \ (P(i) \mid (EX\ x < i. P(x))))$
 $\langle proof \rangle$

14.1.2 Union over ordinals

lemma $Ord-OUN\ [intro, simp]:$
 $[\mid !!x. x < A \Rightarrow Ord(B(x)) \mid] \Rightarrow Ord(\bigcup_{x < A}. B(x))$
 $\langle proof \rangle$

lemma $OUN-upper-lt:$

$$[\mid a < A; \ i < b(a); \text{Ord}(\bigcup x < A. b(x)) \mid] \implies i < (\bigcup x < A. b(x))$$

 $\langle \text{proof} \rangle$

lemma *OUN-upper-le*:

$$[\mid a < A; \ i \leq b(a); \text{Ord}(\bigcup x < A. b(x)) \mid] \implies i \leq (\bigcup x < A. b(x))$$

 $\langle \text{proof} \rangle$

lemma *Limit-OUN-eq*: $\text{Limit}(i) \implies (\bigcup x < i. x) = i$
 $\langle \text{proof} \rangle$

lemma *OUN-least*:

$$(\! \mid x. x < A \implies B(x) \subseteq C \implies (\bigcup x < A. B(x)) \subseteq C$$

 $\langle \text{proof} \rangle$

lemma *OUN-least-le*:

$$[\mid \text{Ord}(i); \ !\mid x. x < A \implies b(x) \leq i \mid] \implies (\bigcup x < A. b(x)) \leq i$$

 $\langle \text{proof} \rangle$

lemma *le-implies-OUN-le-OUN*:

$$[\mid !\mid x. x < A \implies c(x) \leq d(x) \mid] \implies (\bigcup x < A. c(x)) \leq (\bigcup x < A. d(x))$$

 $\langle \text{proof} \rangle$

lemma *OUN-UN-eq*:

$$(\! \mid x. x:A \implies \text{Ord}(B(x)) \implies (\bigcup z < (\bigcup x \in A. B(x)). C(z)) = (\bigcup x \in A. \bigcup z < B(x). C(z))$$

 $\langle \text{proof} \rangle$

lemma *OUN-Union-eq*:

$$(\! \mid x. x:X \implies \text{Ord}(x) \implies (\bigcup z < \text{Union}(X). C(z)) = (\bigcup x \in X. \bigcup z < x. C(z))$$

 $\langle \text{proof} \rangle$

lemma *atomize-oall* [*symmetric, rulify*]:

$$(\! \mid x. x < A \implies P(x) \implies \text{Trueprop} (\text{ALL } x < A. P(x))$$

 $\langle \text{proof} \rangle$

14.1.3 universal quantifier for ordinals

lemma *oallI* [*intro!*]:

$$[\mid !\mid x. x < A \implies P(x) \mid] \implies \text{ALL } x < A. P(x)$$

 $\langle \text{proof} \rangle$

lemma *ospec*: $[\mid \text{ALL } x < A. P(x); \ x < A \mid] \implies P(x)$
 $\langle \text{proof} \rangle$

lemma *oallE*:

$\llbracket \text{ALL } x < A. P(x); P(x) \implies Q; \sim x < A \implies Q \rrbracket \implies Q$
 $\langle \text{proof} \rangle$

lemma *rev-oallE* [*elim*]:

$\llbracket \text{ALL } x < A. P(x); \sim x < A \implies Q; P(x) \implies Q \rrbracket \implies Q$
 $\langle \text{proof} \rangle$

lemma *oall-simp* [*simp*]: $(\text{ALL } x < a. \text{True}) <-> \text{True}$
 $\langle \text{proof} \rangle$

lemma *oall-cong* [*cong*]:

$\llbracket a = a'; \llbracket \text{!!}x. x < a' \implies P(x) <-> P'(x) \rrbracket \implies \text{oall}(a, \%x. P(x)) <-> \text{oall}(a', \%x. P'(x))$
 $\langle \text{proof} \rangle$

14.1.4 existential quantifier for ordinals

lemma *oexI* [*intro*]:

$\llbracket P(x); x < A \rrbracket \implies \text{EX } x < A. P(x)$
 $\langle \text{proof} \rangle$

lemma *oexCI*:

$\llbracket \text{ALL } x < A. \sim P(x) \implies P(a); a < A \rrbracket \implies \text{EX } x < A. P(x)$
 $\langle \text{proof} \rangle$

lemma *oexE* [*elim!*]:

$\llbracket \text{EX } x < A. P(x); \llbracket \text{!!}x. \llbracket x < A; P(x) \rrbracket \implies Q \rrbracket \implies Q$
 $\langle \text{proof} \rangle$

lemma *oex-cong* [*cong*]:

$\llbracket a = a'; \llbracket \text{!!}x. x < a' \implies P(x) <-> P'(x) \rrbracket \implies \text{oex}(a, \%x. P(x)) <-> \text{oex}(a', \%x. P'(x))$
 $\langle \text{proof} \rangle$

14.1.5 Rules for Ordinal-Indexed Unions

lemma *OUN-I* [*intro*]: $\llbracket a < i; b : B(a) \rrbracket \implies b : (\bigcup z < i. B(z))$
 $\langle \text{proof} \rangle$

lemma *OUN-E* [*elim!*]:

$\llbracket b : (\bigcup z < i. B(z)); \llbracket \text{!!}a. \llbracket b : B(a); a < i \rrbracket \implies R \rrbracket \implies R$
 $\langle \text{proof} \rangle$

lemma *OUN-iff*: $b : (\bigcup x < i. B(x)) <-> (\text{EX } x < i. b : B(x))$
 $\langle \text{proof} \rangle$

lemma *OUN-cong* [*cong*]:

$\llbracket i=j; \text{!!}x. x<j \implies C(x)=D(x) \rrbracket \implies (\bigcup x<i. C(x)) = (\bigcup x<j. D(x))$
 $\langle \text{proof} \rangle$

lemma *lt-induct*:

$\llbracket i<k; \text{!!}x. \llbracket x<k; \text{ALL } y<x. P(y) \rrbracket \implies P(x) \rrbracket \implies P(i)$
 $\langle \text{proof} \rangle$

14.2 Quantification over a class

definition

rall $:: [i=>o, i=>o] => o$ **where**
rall(*M*, *P*) == *ALL* *x*. *M*(*x*) \longrightarrow *P*(*x*)

definition

rex $:: [i=>o, i=>o] => o$ **where**
rex(*M*, *P*) == *EX* *x*. *M*(*x*) & *P*(*x*)

syntax

@*rall* $:: [pttrn, i=>o, o] => o$ $((\exists \text{ALL } [-]. / -) 10)$
 @*rex* $:: [pttrn, i=>o, o] => o$ $((\exists \text{EX } [-]. / -) 10)$

syntax (*xsymbols*)

@*rall* $:: [pttrn, i=>o, o] => o$ $((\exists \forall [-]. / -) 10)$
 @*rex* $:: [pttrn, i=>o, o] => o$ $((\exists \exists [-]. / -) 10)$

syntax (*HTML output*)

@*rall* $:: [pttrn, i=>o, o] => o$ $((\exists \forall [-]. / -) 10)$
 @*rex* $:: [pttrn, i=>o, o] => o$ $((\exists \exists [-]. / -) 10)$

translations

ALL *x*[*M*]. *P* == *CONST* *rall*(*M*, %*x*. *P*)
EX *x*[*M*]. *P* == *CONST* *rex*(*M*, %*x*. *P*)

14.2.1 Relativized universal quantifier

lemma *rallI* [*intro!*]: $\llbracket \text{!!}x. M(x) \implies P(x) \rrbracket \implies \text{ALL } x[M]. P(x)$
 $\langle \text{proof} \rangle$

lemma *rspec*: $\llbracket \text{ALL } x[M]. P(x); M(x) \rrbracket \implies P(x)$
 $\langle \text{proof} \rangle$

lemma *rev-rallE* [*elim*]:

$\llbracket \text{ALL } x[M]. P(x); \sim M(x) \implies Q; P(x) \implies Q \rrbracket \implies Q$
 $\langle \text{proof} \rangle$

lemma *rallE*: $\llbracket \text{ALL } x[M]. P(x); P(x) \implies Q; \sim M(x) \implies Q \rrbracket \implies Q$
 $\langle \text{proof} \rangle$

lemma *rall-triv* [*simp*]: $(ALL\ x[M].\ P) <-> ((EX\ x.\ M(x)) \dashv\vdash P)$
 $\langle proof \rangle$

lemma *rall-cong* [*cong*]:
 $(!!x.\ M(x) ==> P(x) <-> P'(x)) ==> (ALL\ x[M].\ P(x)) <-> (ALL\ x[M].\ P'(x))$
 $\langle proof \rangle$

14.2.2 Relativized existential quantifier

lemma *rexI* [*intro*]: $[| P(x); M(x) |] ==> EX\ x[M].\ P(x)$
 $\langle proof \rangle$

lemma *rev-rexI*: $[| M(x); P(x) |] ==> EX\ x[M].\ P(x)$
 $\langle proof \rangle$

lemma *rexCI*: $[| ALL\ x[M].\ \sim P(x) ==> P(a); M(a) |] ==> EX\ x[M].\ P(x)$
 $\langle proof \rangle$

lemma *rexE* [*elim!*]: $[| EX\ x[M].\ P(x); !!x.\ [| M(x); P(x) |] ==> Q |] ==> Q$
 $\langle proof \rangle$

lemma *rex-triv* [*simp*]: $(EX\ x[M].\ P) <-> ((EX\ x.\ M(x)) \& P)$
 $\langle proof \rangle$

lemma *rex-cong* [*cong*]:
 $(!!x.\ M(x) ==> P(x) <-> P'(x)) ==> (EX\ x[M].\ P(x)) <-> (EX\ x[M].\ P'(x))$
 $\langle proof \rangle$

lemma *rall-is-ball* [*simp*]: $(\forall x[\%z.\ z \in A].\ P(x)) <-> (\forall x \in A.\ P(x))$
 $\langle proof \rangle$

lemma *rex-is-bex* [*simp*]: $(\exists x[\%z.\ z \in A].\ P(x)) <-> (\exists x \in A.\ P(x))$
 $\langle proof \rangle$

lemma *atomize-rall*: $(!!x.\ M(x) ==> P(x)) == \text{Trueprop}\ (ALL\ x[M].\ P(x))$
 $\langle proof \rangle$

declare *atomize-rall* [*symmetric, rulify*]

lemma *rall-simps1*:
 $(ALL\ x[M].\ P(x) \& Q) <-> (ALL\ x[M].\ P(x)) \& ((ALL\ x[M].\ False) | Q)$
 $(ALL\ x[M].\ P(x) | Q) <-> ((ALL\ x[M].\ P(x)) | Q)$
 $(ALL\ x[M].\ P(x) \dashv\vdash Q) <-> ((EX\ x[M].\ P(x)) \dashv\vdash Q)$

$(\sim (ALL\ x[M].\ P(x))) <-> (EX\ x[M].\ \sim P(x))$
 $\langle proof \rangle$

lemma *rall-simps2*:

$(ALL\ x[M].\ P \ \&\ Q(x)) <-> ((ALL\ x[M].\ False) \mid P) \ \&\ (ALL\ x[M].\ Q(x))$
 $(ALL\ x[M].\ P \mid Q(x)) <-> (P \mid (ALL\ x[M].\ Q(x)))$
 $(ALL\ x[M].\ P \dashrightarrow Q(x)) <-> (P \dashrightarrow (ALL\ x[M].\ Q(x)))$
 $\langle proof \rangle$

lemmas *rall-simps* [simp] = *rall-simps1* *rall-simps2*

lemma *rall-conj-distrib*:

$(ALL\ x[M].\ P(x) \ \&\ Q(x)) <-> ((ALL\ x[M].\ P(x)) \ \&\ (ALL\ x[M].\ Q(x)))$
 $\langle proof \rangle$

lemma *rex-simps1*:

$(EX\ x[M].\ P(x) \ \&\ Q) <-> ((EX\ x[M].\ P(x)) \ \&\ Q)$
 $(EX\ x[M].\ P(x) \mid Q) <-> (EX\ x[M].\ P(x)) \mid ((EX\ x[M].\ True) \ \&\ Q)$
 $(EX\ x[M].\ P(x) \dashrightarrow Q) <-> ((ALL\ x[M].\ P(x)) \dashrightarrow ((EX\ x[M].\ True) \ \&\ Q))$
 $(\sim (EX\ x[M].\ P(x))) <-> (ALL\ x[M].\ \sim P(x))$
 $\langle proof \rangle$

lemma *rex-simps2*:

$(EX\ x[M].\ P \ \&\ Q(x)) <-> (P \ \&\ (EX\ x[M].\ Q(x)))$
 $(EX\ x[M].\ P \mid Q(x)) <-> ((EX\ x[M].\ True) \ \&\ P) \mid (EX\ x[M].\ Q(x))$
 $(EX\ x[M].\ P \dashrightarrow Q(x)) <-> (((ALL\ x[M].\ False) \mid P) \dashrightarrow (EX\ x[M].\ Q(x)))$
 $\langle proof \rangle$

lemmas *rex-simps* [simp] = *rex-simps1* *rex-simps2*

lemma *rex-disj-distrib*:

$(EX\ x[M].\ P(x) \mid Q(x)) <-> ((EX\ x[M].\ P(x)) \mid (EX\ x[M].\ Q(x)))$
 $\langle proof \rangle$

14.2.3 One-point rule for bounded quantifiers

lemma *rex-triv-one-point1* [simp]: $(EX\ x[M].\ x=a) <-> (M(a))$
 $\langle proof \rangle$

lemma *rex-triv-one-point2* [simp]: $(EX\ x[M].\ a=x) <-> (M(a))$
 $\langle proof \rangle$

lemma *rex-one-point1* [simp]: $(EX\ x[M].\ x=a \ \&\ P(x)) <-> (M(a) \ \&\ P(a))$
 $\langle proof \rangle$

lemma *rex-one-point2* [simp]: $(EX\ x[M].\ a=x \ \&\ P(x)) <-> (M(a) \ \&\ P(a))$
 $\langle proof \rangle$

lemma *rall-one-point1* [simp]: $(\text{ALL } x[M]. x=a \dashrightarrow P(x)) \dashv\vdash (M(a) \dashrightarrow P(a))$
 $\langle \text{proof} \rangle$

lemma *rall-one-point2* [simp]: $(\text{ALL } x[M]. a=x \dashrightarrow P(x)) \dashv\vdash (M(a) \dashrightarrow P(a))$
 $\langle \text{proof} \rangle$

14.2.4 Sets as Classes

definition

setclass :: $[i, i] \Rightarrow o$ $(\#\# \text{ } [40] \text{ } 40)$ **where**
setclass(*A*) == $\%x. x : A$

lemma *setclass-iff* [simp]: $\text{setclass}(A, x) \dashv\vdash x : A$
 $\langle \text{proof} \rangle$

lemma *rall-setclass-is-ball* [simp]: $(\forall x[\#\#A]. P(x)) \dashv\vdash (\forall x \in A. P(x))$
 $\langle \text{proof} \rangle$

lemma *rex-setclass-is-bex* [simp]: $(\exists x[\#\#A]. P(x)) \dashv\vdash (\exists x \in A. P(x))$
 $\langle \text{proof} \rangle$

$\langle ML \rangle$

Setting up the one-point-rule simproc

$\langle ML \rangle$

end

15 Nat-ZF: The Natural numbers As a Least Fixed Point

theory *Nat-ZF* **imports** *OrdQuant Bool* **begin**

definition

nat :: *i* **where**
nat == $\text{lfp}(\text{Inf}, \%X. \{0\} \text{ Un } \{\text{succ}(i). i:X\})$

definition

quasinat :: *i* \Rightarrow *o* **where**
quasinat(*n*) == $n=0 \mid (\exists m. n = \text{succ}(m))$

definition

nat-case :: $[i, i=>i, i]=>i$ **where**
nat-case(*a,b,k*) == *THE* *y. k=0 & y=a | (EX x. k=succ(x) & y=b(x))*

definition

nat-rec :: $[i, i, [i,i]=>i]=>i$ **where**
nat-rec(*k,a,b*) ==
wfrec(*Memrel*(*nat*), *k*, %*n f. nat-case*(*a*, %*m. b*(*m*, *f*'*m*), *n*))

definition

Le :: *i* **where**
Le == $\{<x,y>:nat*nat. x \text{ le } y\}$

definition

Lt :: *i* **where**
Lt == $\{<x, y>:nat*nat. x < y\}$

definition

Ge :: *i* **where**
Ge == $\{<x,y>:nat*nat. y \text{ le } x\}$

definition

Gt :: *i* **where**
Gt == $\{<x,y>:nat*nat. y < x\}$

definition

greater-than :: $i=>i$ **where**
greater-than(*n*) == $\{i:nat. n < i\}$

No need for a less-than operator: a natural number is its list of predecessors!

lemma *nat-bnd-mono*: *bnd-mono*(*Inf*, %*X. {0} Un {succ(i). i:X}*)
 <proof>

lemmas *nat-unfold* = *nat-bnd-mono* [*THEN nat-def* [*THEN def-lfp-unfold*], *standard*]

lemma *nat-0I* [*iff, TC*]: *0* : *nat*
 <proof>

lemma *nat-succI* [*intro!, TC*]: *n* : *nat* ==> *succ*(*n*) : *nat*
 <proof>

lemma *nat-1I* [*iff, TC*]: *1* : *nat*
 <proof>

lemma *nat-2I* [*iff*, *TC*]: $2 : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *bool-subset-nat*: $\text{bool} \leq \text{nat}$
 $\langle \text{proof} \rangle$

lemmas *bool-into-nat* = *bool-subset-nat* [*THEN subsetD*, *standard*]

15.1 Injectivity Properties and Induction

lemma *nat-induct* [*case-names 0 succ*, *induct set: nat*]:
 $\llbracket n : \text{nat}; P(0); \forall x. \llbracket x : \text{nat}; P(x) \rrbracket \implies P(\text{succ}(x)) \rrbracket \implies P(n)$
 $\langle \text{proof} \rangle$

lemma *natE*:
 $\llbracket n : \text{nat}; n=0 \implies P; \forall x. \llbracket x : \text{nat}; n=\text{succ}(x) \rrbracket \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *nat-into-Ord* [*simp*]: $n : \text{nat} \implies \text{Ord}(n)$
 $\langle \text{proof} \rangle$

lemmas *nat-0-le* = *nat-into-Ord* [*THEN Ord-0-le*, *standard*]

lemmas *nat-le-refl* = *nat-into-Ord* [*THEN le-refl*, *standard*]

lemma *Ord-nat* [*iff*]: $\text{Ord}(\text{nat})$
 $\langle \text{proof} \rangle$

lemma *Limit-nat* [*iff*]: $\text{Limit}(\text{nat})$
 $\langle \text{proof} \rangle$

lemma *naturals-not-limit*: $a \in \text{nat} \implies \sim \text{Limit}(a)$
 $\langle \text{proof} \rangle$

lemma *succ-natD*: $\text{succ}(i) : \text{nat} \implies i : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *nat-succ-iff* [*iff*]: $\text{succ}(n) : \text{nat} \iff n : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *nat-le-Limit*: $\text{Limit}(i) \implies \text{nat le } i$
 $\langle \text{proof} \rangle$

lemmas *succ-in-naturalD* = *Ord-trans* [*OF succI1* - *nat-into-Ord*]

lemma *lt-nat-in-nat*: $\llbracket m < n; n : \text{nat} \rrbracket \implies m : \text{nat}$

$\langle \text{proof} \rangle$

lemma *le-in-nat*: $[[\ m \text{ le } n; \ n:\text{nat} \]] \implies m:\text{nat}$
 $\langle \text{proof} \rangle$

15.2 Variations on Mathematical Induction

lemmas *complete-induct* = *Ord-induct* [*OF* - *Ord-nat*, *case-names less*, *consumes 1*]

lemmas *complete-induct-rule* =
complete-induct [*rule-format*, *case-names less*, *consumes 1*]

lemma *nat-induct-from-lemma* [*rule-format*]:
 $[[\ n:\text{nat}; \ m:\text{nat};$
 $\quad !!x. [[\ x:\text{nat}; \ m \text{ le } x; \ P(x) \]] \implies P(\text{succ}(x)) \]]$
 $\implies m \text{ le } n \dashv\vdash P(m) \dashv\vdash P(n)$
 $\langle \text{proof} \rangle$

lemma *nat-induct-from*:
 $[[\ m \text{ le } n; \ m:\text{nat}; \ n:\text{nat};$
 $\quad P(m);$
 $\quad !!x. [[\ x:\text{nat}; \ m \text{ le } x; \ P(x) \]] \implies P(\text{succ}(x)) \]]$
 $\implies P(n)$
 $\langle \text{proof} \rangle$

lemma *diff-induct* [*case-names 0 0-succ succ-succ*, *consumes 2*]:
 $[[\ m:\text{nat}; \ n:\text{nat};$
 $\quad !!x. x:\text{nat} \implies P(x,0);$
 $\quad !!y. y:\text{nat} \implies P(0,\text{succ}(y));$
 $\quad !!x\ y. [[\ x:\text{nat}; \ y:\text{nat}; \ P(x,y) \]] \implies P(\text{succ}(x),\text{succ}(y)) \]]$
 $\implies P(m,n)$
 $\langle \text{proof} \rangle$

lemma *succ-lt-induct-lemma* [*rule-format*]:
 $m:\text{nat} \implies P(m,\text{succ}(m)) \dashv\vdash (\text{ALL } x:\text{nat}. P(m,x) \dashv\vdash P(m,\text{succ}(x)))$
 $\dashv\vdash$
 $(\text{ALL } n:\text{nat}. m < n \dashv\vdash P(m,n))$
 $\langle \text{proof} \rangle$

lemma *succ-lt-induct*:
 $[[\ m < n; \ n:\text{nat};$
 $\quad P(m,\text{succ}(m));$

$$\begin{aligned} & !!x. [\mid x: \text{nat}; \ P(m,x) \mid] ==> P(m, \text{succ}(x)) \mid \\ & ==> P(m,n) \\ & \langle \text{proof} \rangle \end{aligned}$$

15.3 quasinat: to allow a case-split rule for *nat-case*

True if the argument is zero or any successor

lemma *[iff]: quasinat(0)*
 $\langle \text{proof} \rangle$

lemma *[iff]: quasinat(succ(x))*
 $\langle \text{proof} \rangle$

lemma *nat-imp-quasinat: n ∈ nat ==> quasinat(n)*
 $\langle \text{proof} \rangle$

lemma *non-nat-case: ~ quasinat(x) ==> nat-case(a,b,x) = 0*
 $\langle \text{proof} \rangle$

lemma *nat-cases-disj: k=0 | (∃ y. k = succ(y)) | ~ quasinat(k)*
 $\langle \text{proof} \rangle$

lemma *nat-cases:*

$$[\mid k=0 ==> P; \ !y. k = \text{succ}(y) ==> P; \ \sim \text{quasinat}(k) ==> P \mid] ==> P$$
 $\langle \text{proof} \rangle$

lemma *nat-case-0 [simp]: nat-case(a,b,0) = a*
 $\langle \text{proof} \rangle$

lemma *nat-case-succ [simp]: nat-case(a,b,succ(n)) = b(n)*
 $\langle \text{proof} \rangle$

lemma *nat-case-type [TC]:*

$$\begin{aligned} & [\mid n: \text{nat}; \ a: C(0); \ !m. m: \text{nat} ==> b(m): C(\text{succ}(m)) \mid] \\ & ==> \text{nat-case}(a,b,n) : C(n) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *split-nat-case:*

$$\begin{aligned} & P(\text{nat-case}(a,b,k)) <-> \\ & ((k=0 \dashrightarrow P(a)) \ \& \ (\forall x. k=\text{succ}(x) \dashrightarrow P(b(x))) \ \& \ (\sim \text{quasinat}(k) \longrightarrow \\ & P(0))) \\ & \langle \text{proof} \rangle \end{aligned}$$

15.4 Recursion on the Natural Numbers

lemma *nat-rec-0: nat-rec(0,a,b) = a*
 $\langle \text{proof} \rangle$

lemma *nat-rec-succ*: $m: \text{nat} \implies \text{nat-rec}(\text{succ}(m), a, b) = b(m, \text{nat-rec}(m, a, b))$
 $\langle \text{proof} \rangle$

lemma *Un-nat-type* [TC]: $[\mid i: \text{nat}; j: \text{nat} \mid] \implies i \text{ Un } j: \text{nat}$
 $\langle \text{proof} \rangle$

lemma *Int-nat-type* [TC]: $[\mid i: \text{nat}; j: \text{nat} \mid] \implies i \text{ Int } j: \text{nat}$
 $\langle \text{proof} \rangle$

lemma *nat-nonempty* [simp]: $\text{nat} \sim = 0$
 $\langle \text{proof} \rangle$

A natural number is the set of its predecessors

lemma *nat-eq-Collect-lt*: $i \in \text{nat} \implies \{j \in \text{nat}. j < i\} = i$
 $\langle \text{proof} \rangle$

lemma *Le-iff* [iff]: $\langle x, y \rangle : \text{Le} \iff x \text{ le } y \ \& \ x : \text{nat} \ \& \ y : \text{nat}$
 $\langle \text{proof} \rangle$

end

16 Inductive-ZF: Inductive and Coinductive Definitions

theory *Inductive-ZF*
imports *Fixedpt QPair Nat-ZF*
uses
 (*ind-syntax.ML*)
 (*Tools/cartprod.ML*)
 (*Tools/ind-cases.ML*)
 (*Tools/inductive-package.ML*)
 (*Tools/induct-tacs.ML*)
 (*Tools/primrec-package.ML*)
begin

lemma *def-swap-iff*: $a == b \implies a = c \iff c = b$
 $\langle \text{proof} \rangle$

lemma *def-trans*: $f == g \implies g(a) = b \implies f(a) = b$
 $\langle \text{proof} \rangle$

lemma *refl-thin*: $!!P. a = a \implies P \implies P \ \langle \text{proof} \rangle$

$\langle ML \rangle$

end

17 Epsilon: Epsilon Induction and Recursion

theory *Epsilon* imports *Nat-ZF* begin

definition

$eclose :: i \Rightarrow i$ **where**
 $eclose(A) == \bigcup n \in nat. nat-rec(n, A, \%m r. Union(r))$

definition

$transrec :: [i, [i, i] \Rightarrow i] \Rightarrow i$ **where**
 $transrec(a, H) == wfrec(Memrel(eclose(\{a\})), a, H)$

definition

$rank :: i \Rightarrow i$ **where**
 $rank(a) == transrec(a, \%x f. \bigcup y \in x. succ(f'y))$

definition

$transrec2 :: [i, i, [i, i] \Rightarrow i] \Rightarrow i$ **where**
 $transrec2(k, a, b) ==$
 $transrec(k,$
 $\%i r. if(i=0, a,$
 $if(EX j. i=succ(j),$
 $b(THF j. i=succ(j), r'(THF j. i=succ(j))),$
 $\bigcup j < i. r'j)))$

definition

$recursor :: [i, [i, i] \Rightarrow i, i] \Rightarrow i$ **where**
 $recursor(a, b, k) == transrec(k, \%n f. nat-case(a, \%m. b(m, f'm), n))$

definition

$rec :: [i, i, [i, i] \Rightarrow i] \Rightarrow i$ **where**
 $rec(k, a, b) == recursor(a, b, k)$

17.1 Basic Closure Properties

lemma *arg-subset-eclose*: $A \leq eclose(A)$

$\langle proof \rangle$

lemmas *arg-into-eclose* = *arg-subset-eclose* [*THEN subsetD, standard*]

lemma *Transset-eclose*: $Transset(eclose(A))$

$\langle proof \rangle$

lemmas *eclose-subset* =
Transset-eclose [*unfolded Transset-def*, *THEN bspec*, *standard*]

lemmas *ecloseD* = *eclose-subset* [*THEN subsetD*, *standard*]

lemmas *arg-in-eclose-sing* = *arg-subset-eclose* [*THEN singleton-subsetD*]
lemmas *arg-into-eclose-sing* = *arg-in-eclose-sing* [*THEN ecloseD*, *standard*]

lemmas *eclose-induct* =
Transset-induct [*OF - Transset-eclose*, *induct set: eclose*]

lemma *eps-induct*:

$$[[\text{!!}x. \text{ALL } y:x. P(y) ==> P(x)]] ==> P(a)$$
<proof>

17.2 Leastness of *eclose*

lemma *eclose-least-lemma*:

$$[[\text{Transset}(X); A \leq X; n: \text{nat}]] ==> \text{nat-rec}(n, A, \%m r. \text{Union}(r)) \leq X$$
<proof>

lemma *eclose-least*:

$$[[\text{Transset}(X); A \leq X]] ==> \text{eclose}(A) \leq X$$
<proof>

lemma *eclose-induct-down* [*consumes 1*]:

$$\begin{aligned} &[[a: \text{eclose}(b); \\ &\quad \text{!!}y. [[y: b]] ==> P(y); \\ &\quad \text{!!}y z. [[y: \text{eclose}(b); P(y); z: y]] ==> P(z) \\ &]] ==> P(a) \end{aligned}$$
<proof>

lemma *Transset-eclose-eq-arg*: $\text{Transset}(X) ==> \text{eclose}(X) = X$
<proof>

A transitive set either is empty or contains the empty set.

lemma *Transset-0-lemma* [*rule-format*]: $\text{Transset}(A) ==> x \in A \dashv\dashv 0 \in A$
<proof>

lemma *Transset-0-disj*: $\text{Transset}(A) ==> A = 0 \mid 0 \in A$
<proof>

17.3 Epsilon Recursion

lemma *mem-eclose-trans*: $[[A: \text{eclose}(B); B: \text{eclose}(C)]] ==> A: \text{eclose}(C)$

$\langle proof \rangle$

lemma *mem-eclose-sing-trans*:

$\llbracket A: \text{eclose}(\{B\}); B: \text{eclose}(\{C\}) \rrbracket \implies A: \text{eclose}(\{C\})$
 $\langle proof \rangle$

lemma *under-Memrel*: $\llbracket \text{Transset}(i); j:i \rrbracket \implies \text{Memrel}(i) - \{j\} = j$
 $\langle proof \rangle$

lemma *lt-Memrel*: $j < i \implies \text{Memrel}(i) - \{j\} = j$
 $\langle proof \rangle$

lemmas *under-Memrel-eclose* = *Transset-eclose* [THEN *under-Memrel*, *standard*]

lemmas *wfrec-ssubst* = *wf-Memrel* [THEN *wfrec*, THEN *ssubst*]

lemma *wfrec-eclose-eq*:

$\llbracket k: \text{eclose}(\{j\}); j: \text{eclose}(\{i\}) \rrbracket \implies$
 $\text{wfrec}(\text{Memrel}(\text{eclose}(\{i\})), k, H) = \text{wfrec}(\text{Memrel}(\text{eclose}(\{j\})), k, H)$
 $\langle proof \rangle$

lemma *wfrec-eclose-eq2*:

$k: i \implies \text{wfrec}(\text{Memrel}(\text{eclose}(\{i\})), k, H) = \text{wfrec}(\text{Memrel}(\text{eclose}(\{k\})), k, H)$
 $\langle proof \rangle$

lemma *transrec*: $\text{transrec}(a, H) = H(a, \text{lam } x:a. \text{transrec}(x, H))$
 $\langle proof \rangle$

lemma *def-transrec*:

$\llbracket !!x. f(x) == \text{transrec}(x, H) \rrbracket \implies f(a) = H(a, \text{lam } x:a. f(x))$
 $\langle proof \rangle$

lemma *transrec-type*:

$\llbracket !!x u. \llbracket x: \text{eclose}(\{a\}); u: \text{Pi}(x, B) \rrbracket \implies H(x, u) : B(x) \rrbracket$
 $\implies \text{transrec}(a, H) : B(a)$
 $\langle proof \rangle$

lemma *eclose-sing-Ord*: $\text{Ord}(i) \implies \text{eclose}(\{i\}) \leq \text{succ}(i)$
 $\langle proof \rangle$

lemma *succ-subset-eclose-sing*: $\text{succ}(i) \leq \text{eclose}(\{i\})$
 $\langle proof \rangle$

lemma *eclose-sing-Ord-eq*: $\text{Ord}(i) \implies \text{eclose}(\{i\}) = \text{succ}(i)$
 $\langle proof \rangle$

lemma *Ord-transrec-type*:
assumes *jini*: $j: i$
and *ordi*: $\text{Ord}(i)$
and *minor*: $\llbracket x: i; \ u: \text{Pi}(x, B) \rrbracket \implies H(x, u) : B(x)$
shows $\text{transrec}(j, H) : B(j)$
 $\langle \text{proof} \rangle$

17.4 Rank

lemma *rank*: $\text{rank}(a) = (\bigcup y \in a. \text{succ}(\text{rank}(y)))$
 $\langle \text{proof} \rangle$

lemma *Ord-rank* [*simp*]: $\text{Ord}(\text{rank}(a))$
 $\langle \text{proof} \rangle$

lemma *rank-of-Ord*: $\text{Ord}(i) \implies \text{rank}(i) = i$
 $\langle \text{proof} \rangle$

lemma *rank-lt*: $a < b \implies \text{rank}(a) < \text{rank}(b)$
 $\langle \text{proof} \rangle$

lemma *eclose-rank-lt*: $a: \text{eclose}(b) \implies \text{rank}(a) < \text{rank}(b)$
 $\langle \text{proof} \rangle$

lemma *rank-mono*: $a \leq b \implies \text{rank}(a) \leq \text{rank}(b)$
 $\langle \text{proof} \rangle$

lemma *rank-Pow*: $\text{rank}(\text{Pow}(a)) = \text{succ}(\text{rank}(a))$
 $\langle \text{proof} \rangle$

lemma *rank-0* [*simp*]: $\text{rank}(0) = 0$
 $\langle \text{proof} \rangle$

lemma *rank-succ* [*simp*]: $\text{rank}(\text{succ}(x)) = \text{succ}(\text{rank}(x))$
 $\langle \text{proof} \rangle$

lemma *rank-Union*: $\text{rank}(\text{Union}(A)) = (\bigcup x \in A. \text{rank}(x))$
 $\langle \text{proof} \rangle$

lemma *rank-eclose*: $\text{rank}(\text{eclose}(a)) = \text{rank}(a)$
 $\langle \text{proof} \rangle$

lemma *rank-pair1*: $\text{rank}(a) < \text{rank}(\langle a, b \rangle)$
 $\langle \text{proof} \rangle$

lemma *rank-pair2*: $\text{rank}(b) < \text{rank}(\langle a, b \rangle)$
 $\langle \text{proof} \rangle$

lemma *the-equality-if*:

$P(a) ==> (THE\ x.\ P(x)) = (if\ (EX!x.\ P(x))\ then\ a\ else\ 0)$
 $\langle proof \rangle$

lemma *rank-apply*: $[|i : domain(f); function(f)|] ==> rank(f^i) < rank(f)$
 $\langle proof \rangle$

17.5 Corollaries of Leastness

lemma *mem-eclose-subset*: $A:B ==> eclose(A) \leq eclose(B)$
 $\langle proof \rangle$

lemma *eclose-mono*: $A \leq B ==> eclose(A) \leq eclose(B)$
 $\langle proof \rangle$

lemma *eclose-idem*: $eclose(eclose(A)) = eclose(A)$
 $\langle proof \rangle$

lemma *transrec2-0* [simp]: $transrec2(0, a, b) = a$
 $\langle proof \rangle$

lemma *transrec2-succ* [simp]: $transrec2(succ(i), a, b) = b(i, transrec2(i, a, b))$
 $\langle proof \rangle$

lemma *transrec2-Limit*:

$Limit(i) ==> transrec2(i, a, b) = (\bigcup j < i. transrec2(j, a, b))$
 $\langle proof \rangle$

lemma *def-transrec2*:

$(!!x. f(x) == transrec2(x, a, b))$
 $==> f(0) = a \ \&$
 $f(succ(i)) = b(i, f(i)) \ \&$
 $(Limit(K) --> f(K) = (\bigcup j < K. f(j)))$
 $\langle proof \rangle$

lemmas *recursor-lemma* = *recursor-def* [THEN *def-transrec*, THEN *trans*]

lemma *recursor-0*: $recursor(a, b, 0) = a$
 $\langle proof \rangle$

lemma *recursor-succ*: $\text{recursor}(a, b, \text{succ}(m)) = b(m, \text{recursor}(a, b, m))$
 $\langle \text{proof} \rangle$

lemma *rec-0* [*simp*]: $\text{rec}(0, a, b) = a$
 $\langle \text{proof} \rangle$

lemma *rec-succ* [*simp*]: $\text{rec}(\text{succ}(m), a, b) = b(m, \text{rec}(m, a, b))$
 $\langle \text{proof} \rangle$

lemma *rec-type*:

$$\begin{aligned} & \llbracket n: \text{nat}; \\ & \quad a: C(0); \\ & \quad !!m\ z. \llbracket m: \text{nat};\ z: C(m) \rrbracket \implies b(m, z): C(\text{succ}(m)) \rrbracket \\ & \implies \text{rec}(n, a, b) : C(n) \end{aligned}$$

 $\langle \text{proof} \rangle$

$\langle \text{ML} \rangle$

end

18 Order: Partial and Total Orderings: Basic Definitions and Properties

theory *Order* **imports** *WF Perm* **begin**

We adopt the following convention: *ord* is used for strict orders and *order* is used for their reflexive counterparts.

definition

$$\begin{aligned} \text{part-ord} &:: [i, i] \Rightarrow o & \textbf{where} \\ \text{part-ord}(A, r) &== \text{irrefl}(A, r) \ \& \ \text{trans}[A](r) \end{aligned}$$

definition

$$\begin{aligned} \text{linear} &:: [i, i] \Rightarrow o & \textbf{where} \\ \text{linear}(A, r) &== (\text{ALL } x:A. \text{ ALL } y:A. \langle x, y \rangle : r \mid x=y \mid \langle y, x \rangle : r) \end{aligned}$$

definition

$$\begin{aligned} \text{tot-ord} &:: [i, i] \Rightarrow o & \textbf{where} \\ \text{tot-ord}(A, r) &== \text{part-ord}(A, r) \ \& \ \text{linear}(A, r) \end{aligned}$$

definition

$$\text{preorder-on}(A, r) \equiv \text{refl}(A, r) \ \& \ \text{trans}[A](r)$$

definition

$$\text{partial-order-on}(A, r) \equiv \text{preorder-on}(A, r) \ \& \ \text{antisym}(r)$$

abbreviation

$$Preorder(r) \equiv preorder-on(field(r), r)$$
abbreviation

$$Partial-order(r) \equiv partial-order-on(field(r), r)$$
definition

$$\begin{aligned} well-ord &:: [i, i] \Rightarrow o & \textbf{where} \\ well-ord(A, r) &== tot-ord(A, r) \ \& \ wf[A](r) \end{aligned}$$
definition

$$\begin{aligned} mono-map &:: [i, i, i, i] \Rightarrow i & \textbf{where} \\ mono-map(A, r, B, s) &== \\ &\{f: A \rightarrow B. \ ALL \ x:A. \ ALL \ y:A. \ \langle x, y \rangle : r \longrightarrow \langle f'x, f'y \rangle : s\} \end{aligned}$$
definition

$$\begin{aligned} ord-iso &:: [i, i, i, i] \Rightarrow i & \textbf{where} \\ ord-iso(A, r, B, s) &== \\ &\{f: bij(A, B). \ ALL \ x:A. \ ALL \ y:A. \ \langle x, y \rangle : r \longleftrightarrow \langle f'x, f'y \rangle : s\} \end{aligned}$$
definition

$$\begin{aligned} pred &:: [i, i, i] \Rightarrow i & \textbf{where} \\ pred(A, x, r) &== \{y:A. \ \langle y, x \rangle : r\} \end{aligned}$$
definition

$$\begin{aligned} ord-iso-map &:: [i, i, i, i] \Rightarrow i & \textbf{where} \\ ord-iso-map(A, r, B, s) &== \\ &\bigcup x \in A. \bigcup y \in B. \bigcup f \in ord-iso(pred(A, x, r), r, pred(B, y, s), s). \{\langle x, y \rangle\} \end{aligned}$$
definition

$$\begin{aligned} first &:: [i, i, i] \Rightarrow o & \textbf{where} \\ first(u, X, R) &== u:X \ \& \ (ALL \ v:X. \ v \sim u \longrightarrow \langle u, v \rangle : R) \end{aligned}$$
notation (*xsymbols*)
$$ord-iso \ ((\langle -, - \rangle \cong / \langle -, - \rangle) \ 51)$$
18.1 Immediate Consequences of the Definitions**lemma** *part-ord-Imp-asym*:
$$part-ord(A, r) \implies asym(r \ Int \ A * A)$$

<proof>

lemma *linearE*:
$$\begin{aligned} &[[\ linear(A, r); \ x:A; \ y:A; \\ &\quad \langle x, y \rangle : r \implies P; \ x=y \implies P; \ \langle y, x \rangle : r \implies P \] \\ &\implies P \end{aligned}$$

<proof>

lemma *well-ordI*:

$\llbracket \text{wf}[A](r); \text{linear}(A,r) \rrbracket \implies \text{well-ord}(A,r)$
 $\langle \text{proof} \rangle$

lemma *well-ord-is-wf*:

$\text{well-ord}(A,r) \implies \text{wf}[A](r)$
 $\langle \text{proof} \rangle$

lemma *well-ord-is-trans-on*:

$\text{well-ord}(A,r) \implies \text{trans}[A](r)$
 $\langle \text{proof} \rangle$

lemma *well-ord-is-linear*: $\text{well-ord}(A,r) \implies \text{linear}(A,r)$

$\langle \text{proof} \rangle$

lemma *pred-iff*: $y : \text{pred}(A,x,r) \iff \langle y,x \rangle : r \ \& \ y:A$

$\langle \text{proof} \rangle$

lemmas *predI* = *conjI* [*THEN pred-iff* [*THEN iffD2*]]

lemma *predE*: $\llbracket y : \text{pred}(A,x,r); \llbracket y:A; \langle y,x \rangle : r \rrbracket \implies P \rrbracket \implies P$

$\langle \text{proof} \rangle$

lemma *pred-subset-under*: $\text{pred}(A,x,r) \leq r - \{x\}$

$\langle \text{proof} \rangle$

lemma *pred-subset*: $\text{pred}(A,x,r) \leq A$

$\langle \text{proof} \rangle$

lemma *pred-pred-eq*:

$\text{pred}(\text{pred}(A,x,r), y, r) = \text{pred}(A,x,r) \text{ Int } \text{pred}(A,y,r)$

$\langle \text{proof} \rangle$

lemma *trans-pred-pred-eq*:

$\llbracket \text{trans}[A](r); \langle y,x \rangle : r; x:A; y:A \rrbracket$
 $\implies \text{pred}(\text{pred}(A,x,r), y, r) = \text{pred}(A,y,r)$

$\langle \text{proof} \rangle$

18.2 Restricting an Ordering's Domain

lemma *part-ord-subset*:

$\llbracket \text{part-ord}(A,r); B \leq A \rrbracket \implies \text{part-ord}(B,r)$

$\langle proof \rangle$

lemma *linear-subset*:

$\llbracket linear(A,r); B \leq A \rrbracket ==> linear(B,r)$
 $\langle proof \rangle$

lemma *tot-ord-subset*:

$\llbracket tot-ord(A,r); B \leq A \rrbracket ==> tot-ord(B,r)$
 $\langle proof \rangle$

lemma *well-ord-subset*:

$\llbracket well-ord(A,r); B \leq A \rrbracket ==> well-ord(B,r)$
 $\langle proof \rangle$

lemma *irrefl-Int-iff*: $irrefl(A,r \text{ Int } A*A) <-> irrefl(A,r)$
 $\langle proof \rangle$

lemma *trans-on-Int-iff*: $trans[A](r \text{ Int } A*A) <-> trans[A](r)$
 $\langle proof \rangle$

lemma *part-ord-Int-iff*: $part-ord(A,r \text{ Int } A*A) <-> part-ord(A,r)$
 $\langle proof \rangle$

lemma *linear-Int-iff*: $linear(A,r \text{ Int } A*A) <-> linear(A,r)$
 $\langle proof \rangle$

lemma *tot-ord-Int-iff*: $tot-ord(A,r \text{ Int } A*A) <-> tot-ord(A,r)$
 $\langle proof \rangle$

lemma *wf-on-Int-iff*: $wf[A](r \text{ Int } A*A) <-> wf[A](r)$
 $\langle proof \rangle$

lemma *well-ord-Int-iff*: $well-ord(A,r \text{ Int } A*A) <-> well-ord(A,r)$
 $\langle proof \rangle$

18.3 Empty and Unit Domains

lemma *wf-on-any-0*: $wf[A](0)$
 $\langle proof \rangle$

18.3.1 Relations over the Empty Set

lemma *irrefl-0*: $irrefl(0,r)$
 $\langle proof \rangle$

lemma *trans-on-0*: $trans[0](r)$
 $\langle proof \rangle$

lemma *part-ord-0*: *part-ord*(0,r)
 <proof>

lemma *linear-0*: *linear*(0,r)
 <proof>

lemma *tot-ord-0*: *tot-ord*(0,r)
 <proof>

lemma *wf-on-0*: *wf*[0](r)
 <proof>

lemma *well-ord-0*: *well-ord*(0,r)
 <proof>

18.3.2 The Empty Relation Well-Orders the Unit Set

by Grabczewski

lemma *tot-ord-unit*: *tot-ord*({a},0)
 <proof>

lemma *well-ord-unit*: *well-ord*({a},0)
 <proof>

18.4 Order-Isomorphisms

Suppes calls them "similarities"

lemma *mono-map-is-fun*: *f*: *mono-map*(A,r,B,s) ==> *f*: A->B
 <proof>

lemma *mono-map-is-inj*:
 [| *linear*(A,r); *wf*[B](s); *f*: *mono-map*(A,r,B,s) |] ==> *f*: *inj*(A,B)
 <proof>

lemma *ord-isoI*:
 [| *f*: *bij*(A, B);
 !!x y. [| *x*:A; *y*:A |] ==> <*x*, *y*> : r <-> <*f*'*x*, *f*'*y*> : s |]
 ==> *f*: *ord-iso*(A,r,B,s)
 <proof>

lemma *ord-iso-is-mono-map*:
f: *ord-iso*(A,r,B,s) ==> *f*: *mono-map*(A,r,B,s)
 <proof>

lemma *ord-iso-is-bij*:
f: *ord-iso*(A,r,B,s) ==> *f*: *bij*(A,B)
 <proof>

lemma *ord-iso-apply*:

$[| f: \text{ord-iso}(A, r, B, s); \langle x, y \rangle: r; x:A; y:A |] ==> \langle f'x, f'y \rangle: s$
 $\langle \text{proof} \rangle$

lemma *ord-iso-converse*:

$[| f: \text{ord-iso}(A, r, B, s); \langle x, y \rangle: s; x:B; y:B |]$
 $==> \langle \text{converse}(f) 'x, \text{converse}(f) 'y \rangle: r$
 $\langle \text{proof} \rangle$

lemma *ord-iso-refl*: $\text{id}(A): \text{ord-iso}(A, r, A, r)$

$\langle \text{proof} \rangle$

lemma *ord-iso-sym*: $f: \text{ord-iso}(A, r, B, s) ==> \text{converse}(f): \text{ord-iso}(B, s, A, r)$

$\langle \text{proof} \rangle$

lemma *mono-map-trans*:

$[| g: \text{mono-map}(A, r, B, s); f: \text{mono-map}(B, s, C, t) |]$
 $==> (f \circ g): \text{mono-map}(A, r, C, t)$
 $\langle \text{proof} \rangle$

lemma *ord-iso-trans*:

$[| g: \text{ord-iso}(A, r, B, s); f: \text{ord-iso}(B, s, C, t) |]$
 $==> (f \circ g): \text{ord-iso}(A, r, C, t)$
 $\langle \text{proof} \rangle$

lemma *mono-ord-isoI*:

$[| f: \text{mono-map}(A, r, B, s); g: \text{mono-map}(B, s, A, r);$
 $f \circ g = \text{id}(B); g \circ f = \text{id}(A) |] ==> f: \text{ord-iso}(A, r, B, s)$
 $\langle \text{proof} \rangle$

lemma *well-ord-mono-ord-isoI*:

$[| \text{well-ord}(A, r); \text{well-ord}(B, s);$
 $f: \text{mono-map}(A, r, B, s); \text{converse}(f): \text{mono-map}(B, s, A, r) |]$
 $==> f: \text{ord-iso}(A, r, B, s)$
 $\langle \text{proof} \rangle$

lemma *part-ord-ord-iso*:

$\llbracket \text{part-ord}(B,s); f: \text{ord-iso}(A,r,B,s) \rrbracket \implies \text{part-ord}(A,r)$
 $\langle \text{proof} \rangle$

lemma *linear-ord-iso*:

$\llbracket \text{linear}(B,s); f: \text{ord-iso}(A,r,B,s) \rrbracket \implies \text{linear}(A,r)$
 $\langle \text{proof} \rangle$

lemma *wf-on-ord-iso*:

$\llbracket \text{wf}[B](s); f: \text{ord-iso}(A,r,B,s) \rrbracket \implies \text{wf}[A](r)$
 $\langle \text{proof} \rangle$

lemma *well-ord-ord-iso*:

$\llbracket \text{well-ord}(B,s); f: \text{ord-iso}(A,r,B,s) \rrbracket \implies \text{well-ord}(A,r)$
 $\langle \text{proof} \rangle$

18.5 Main results of Kunen, Chapter 1 section 6

lemma *well-ord-iso-subset-lemma*:

$\llbracket \text{well-ord}(A,r); f: \text{ord-iso}(A,r, A',r); A' \leq A; y: A \rrbracket$
 $\implies \sim <f'y, y>: r$
 $\langle \text{proof} \rangle$

lemma *well-ord-iso-predE*:

$\llbracket \text{well-ord}(A,r); f: \text{ord-iso}(A, r, \text{pred}(A,x,r), r); x:A \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *well-ord-iso-pred-eq*:

$\llbracket \text{well-ord}(A,r); f: \text{ord-iso}(\text{pred}(A,a,r), r, \text{pred}(A,c,r), r);$
 $a:A; c:A \rrbracket \implies a=c$
 $\langle \text{proof} \rangle$

lemma *ord-iso-image-pred*:

$\llbracket f: \text{ord-iso}(A,r,B,s); a:A \rrbracket \implies f \text{ `` } \text{pred}(A,a,r) = \text{pred}(B, f'a, s)$
 $\langle \text{proof} \rangle$

lemma *ord-iso-restrict-image*:

$\llbracket f: \text{ord-iso}(A,r,B,s); C \leq A \rrbracket$
 $\implies \text{restrict}(f,C): \text{ord-iso}(C, r, f''C, s)$
 $\langle \text{proof} \rangle$

lemma *ord-iso-restrict-pred*:

$\llbracket f: \text{ord-iso}(A,r,B,s); a:A \rrbracket$
 $\implies \text{restrict}(f, \text{pred}(A,a,r)): \text{ord-iso}(\text{pred}(A,a,r), r, \text{pred}(B, f'a, s), s)$

$\langle \text{proof} \rangle$

lemma *well-ord-iso-preserving*:

$[[\text{well-ord}(A,r); \text{well-ord}(B,s); \langle a,c \rangle : r;$
 $f : \text{ord-iso}(\text{pred}(A,a,r), r, \text{pred}(B,b,s), s);$
 $g : \text{ord-iso}(\text{pred}(A,c,r), r, \text{pred}(B,d,s), s);$
 $a:A; c:A; b:B; d:B]] \implies \langle b,d \rangle : s$

$\langle \text{proof} \rangle$

lemma *well-ord-iso-unique-lemma*:

$[[\text{well-ord}(A,r);$
 $f : \text{ord-iso}(A,r, B,s); g : \text{ord-iso}(A,r, B,s); y : A]]$
 $\implies \sim \langle g'y, f'y \rangle : s$

$\langle \text{proof} \rangle$

lemma *well-ord-iso-unique*: $[[\text{well-ord}(A,r);$

$f : \text{ord-iso}(A,r, B,s); g : \text{ord-iso}(A,r, B,s)]]$ $\implies f = g$

$\langle \text{proof} \rangle$

18.6 Towards Kunen's Theorem 6.3: Linearity of the Similarity Relation

lemma *ord-iso-map-subset*: $\text{ord-iso-map}(A,r,B,s) \leq A * B$

$\langle \text{proof} \rangle$

lemma *domain-ord-iso-map*: $\text{domain}(\text{ord-iso-map}(A,r,B,s)) \leq A$

$\langle \text{proof} \rangle$

lemma *range-ord-iso-map*: $\text{range}(\text{ord-iso-map}(A,r,B,s)) \leq B$

$\langle \text{proof} \rangle$

lemma *converse-ord-iso-map*:

$\text{converse}(\text{ord-iso-map}(A,r,B,s)) = \text{ord-iso-map}(B,s,A,r)$

$\langle \text{proof} \rangle$

lemma *function-ord-iso-map*:

$\text{well-ord}(B,s) \implies \text{function}(\text{ord-iso-map}(A,r,B,s))$

$\langle \text{proof} \rangle$

lemma *ord-iso-map-fun*: $\text{well-ord}(B,s) \implies \text{ord-iso-map}(A,r,B,s)$

$: \text{domain}(\text{ord-iso-map}(A,r,B,s)) \rightarrow \text{range}(\text{ord-iso-map}(A,r,B,s))$

$\langle \text{proof} \rangle$

lemma *ord-iso-map-mono-map*:

$[[\text{well-ord}(A,r); \text{well-ord}(B,s)]]$

$$\begin{aligned} & \implies \text{ord-iso-map}(A, r, B, s) \\ & \quad : \text{mono-map}(\text{domain}(\text{ord-iso-map}(A, r, B, s)), r, \\ & \quad \quad \text{range}(\text{ord-iso-map}(A, r, B, s)), s) \end{aligned}$$
 $\langle \text{proof} \rangle$

lemma *ord-iso-map-ord-iso*:

$$\begin{aligned} & [\text{well-ord}(A, r); \text{well-ord}(B, s)] \implies \text{ord-iso-map}(A, r, B, s) \\ & \quad : \text{ord-iso}(\text{domain}(\text{ord-iso-map}(A, r, B, s)), r, \\ & \quad \quad \text{range}(\text{ord-iso-map}(A, r, B, s)), s) \end{aligned}$$
 $\langle \text{proof} \rangle$

lemma *domain-ord-iso-map-subset*:

$$\begin{aligned} & [\text{well-ord}(A, r); \text{well-ord}(B, s); \\ & \quad a: A; a \sim: \text{domain}(\text{ord-iso-map}(A, r, B, s))] \\ & \implies \text{domain}(\text{ord-iso-map}(A, r, B, s)) \leq \text{pred}(A, a, r) \end{aligned}$$
 $\langle \text{proof} \rangle$

lemma *domain-ord-iso-map-cases*:

$$\begin{aligned} & [\text{well-ord}(A, r); \text{well-ord}(B, s)] \\ & \implies \text{domain}(\text{ord-iso-map}(A, r, B, s)) = A \mid \\ & \quad (\exists x: A. \text{domain}(\text{ord-iso-map}(A, r, B, s)) = \text{pred}(A, x, r)) \end{aligned}$$
 $\langle \text{proof} \rangle$

lemma *range-ord-iso-map-cases*:

$$\begin{aligned} & [\text{well-ord}(A, r); \text{well-ord}(B, s)] \\ & \implies \text{range}(\text{ord-iso-map}(A, r, B, s)) = B \mid \\ & \quad (\exists y: B. \text{range}(\text{ord-iso-map}(A, r, B, s)) = \text{pred}(B, y, s)) \end{aligned}$$
 $\langle \text{proof} \rangle$

Kunen's Theorem 6.3: Fundamental Theorem for Well-Ordered Sets

theorem *well-ord-trichotomy*:

$$\begin{aligned} & [\text{well-ord}(A, r); \text{well-ord}(B, s)] \\ & \implies \text{ord-iso-map}(A, r, B, s) : \text{ord-iso}(A, r, B, s) \mid \\ & \quad (\exists x: A. \text{ord-iso-map}(A, r, B, s) : \text{ord-iso}(\text{pred}(A, x, r), r, B, s)) \mid \\ & \quad (\exists y: B. \text{ord-iso-map}(A, r, B, s) : \text{ord-iso}(A, r, \text{pred}(B, y, s), s)) \end{aligned}$$
 $\langle \text{proof} \rangle$

18.7 Miscellaneous Results by Krzysztof Grabczewski

lemma *irrefl-converse*: $\text{irrefl}(A, r) \implies \text{irrefl}(A, \text{converse}(r))$
 $\langle \text{proof} \rangle$

lemma *trans-on-converse*: $\text{trans}[A](r) \implies \text{trans}[A](\text{converse}(r))$
 $\langle \text{proof} \rangle$

lemma *part-ord-converse*: $\text{part-ord}(A, r) \implies \text{part-ord}(A, \text{converse}(r))$
 $\langle \text{proof} \rangle$

lemma *linear-converse*: $\text{linear}(A, r) \implies \text{linear}(A, \text{converse}(r))$
 $\langle \text{proof} \rangle$

lemma *tot-ord-converse*: $\text{tot-ord}(A, r) \implies \text{tot-ord}(A, \text{converse}(r))$
 $\langle \text{proof} \rangle$

lemma *first-is-elem*: $\text{first}(b, B, r) \implies b : B$
 $\langle \text{proof} \rangle$

lemma *well-ord-imp-ex1-first*:
 $\llbracket \text{well-ord}(A, r); B \leq A; B \sim 0 \rrbracket \implies (\text{EX! } b. \text{first}(b, B, r))$
 $\langle \text{proof} \rangle$

lemma *the-first-in*:
 $\llbracket \text{well-ord}(A, r); B \leq A; B \sim 0 \rrbracket \implies (\text{THE } b. \text{first}(b, B, r)) : B$
 $\langle \text{proof} \rangle$

18.8 Lemmas for the Reflexive Orders

lemma *subset-vimage-vimage-iff*:
 $\llbracket \text{Preorder}(r); A \subseteq \text{field}(r); B \subseteq \text{field}(r) \rrbracket \implies$
 $r - \text{“ } A \subseteq r - \text{“ } B < - > (\text{ALL } a : A. \text{EX } b : B. < a, b > : r)$
 $\langle \text{proof} \rangle$

lemma *subset-vimage1-vimage1-iff*:
 $\llbracket \text{Preorder}(r); a : \text{field}(r); b : \text{field}(r) \rrbracket \implies$
 $r - \text{“ } \{a\} \subseteq r - \text{“ } \{b\} < - > < a, b > : r$
 $\langle \text{proof} \rangle$

lemma *Refl-antisym-eq-Image1-Image1-iff*:
 $\llbracket \text{refl}(\text{field}(r), r); \text{antisym}(r); a : \text{field}(r); b : \text{field}(r) \rrbracket \implies$
 $r - \text{“ } \{a\} = r - \text{“ } \{b\} < - > a = b$
 $\langle \text{proof} \rangle$

lemma *Partial-order-eq-Image1-Image1-iff*:
 $\llbracket \text{Partial-order}(r); a : \text{field}(r); b : \text{field}(r) \rrbracket \implies$
 $r - \text{“ } \{a\} = r - \text{“ } \{b\} < - > a = b$
 $\langle \text{proof} \rangle$

lemma *Refl-antisym-eq-vimage1-vimage1-iff*:
 $\llbracket \text{refl}(\text{field}(r), r); \text{antisym}(r); a : \text{field}(r); b : \text{field}(r) \rrbracket \implies$
 $r - \text{“ } \{a\} = r - \text{“ } \{b\} < - > a = b$
 $\langle \text{proof} \rangle$

lemma *Partial-order-eq-vimage1-vimage1-iff*:

$$[\text{Partial-order}(r); a : \text{field}(r); b : \text{field}(r)] \implies$$

$$r -'' \{a\} = r -'' \{b\} \iff a = b$$

$$\langle \text{proof} \rangle$$

end

19 OrderArith: Combining Orderings: Foundations of Ordinal Arithmetic

theory *OrderArith* **imports** *Order Sum Ordinal* **begin**

definition

$radd :: [i, i, i, i] \Rightarrow i$ **where**
 $radd(A, r, B, s) ==$

$$\{z: (A+B) * (A+B).$$

$$(EX\ x\ y. z = \langle Inl(x), Inr(y) \rangle) \mid$$

$$(EX\ x'\ x. z = \langle Inl(x'), Inl(x) \rangle \ \& \ \langle x', x \rangle : r) \mid$$

$$(EX\ y'\ y. z = \langle Inr(y'), Inr(y) \rangle \ \& \ \langle y', y \rangle : s)\}$$

definition

$rmult :: [i, i, i, i] \Rightarrow i$ **where**
 $rmult(A, r, B, s) ==$

$$\{z: (A*B) * (A*B).$$

$$EX\ x'\ y'\ x\ y. z = \langle \langle x', y' \rangle, \langle x, y \rangle \rangle \ \&$$

$$(\langle x', x \rangle : r \mid (x' = x \ \& \ \langle y', y \rangle : s))\}$$

definition

$rvimage :: [i, i, i] \Rightarrow i$ **where**
 $rvimage(A, f, r) == \{z: A*A. EX\ x\ y. z = \langle x, y \rangle \ \& \ \langle f'x, f'y \rangle : r\}$

definition

$measure :: [i, i \Rightarrow i] \Rightarrow i$ **where**
 $measure(A, f) == \{\langle x, y \rangle : A*A. f(x) < f(y)\}$

19.1 Addition of Relations – Disjoint Sum

19.1.1 Rewrite rules. Can be used to obtain introduction rules

lemma *radd-Inl-Inr-iff* [*iff*]:

$$\langle Inl(a), Inr(b) \rangle : radd(A, r, B, s) \iff a:A \ \& \ b:B$$

$$\langle \text{proof} \rangle$$

lemma *radd-Inl-iff* [*iff*]:

$\langle \text{Inl}(a'), \text{Inl}(a) \rangle : \text{radd}(A, r, B, s) \leftrightarrow a':A \ \& \ a:A \ \& \ \langle a', a \rangle : r$
 $\langle \text{proof} \rangle$

lemma *radd-Inr-iff* [iff]:

$\langle \text{Inr}(b'), \text{Inr}(b) \rangle : \text{radd}(A, r, B, s) \leftrightarrow b':B \ \& \ b:B \ \& \ \langle b', b \rangle : s$
 $\langle \text{proof} \rangle$

lemma *radd-Inr-Inl-iff* [simp]:

$\langle \text{Inr}(b), \text{Inl}(a) \rangle : \text{radd}(A, r, B, s) \leftrightarrow \text{False}$
 $\langle \text{proof} \rangle$

declare *radd-Inr-Inl-iff* [THEN iffD1, dest!]

19.1.2 Elimination Rule

lemma *raddE*:

$\llbracket \langle p', p \rangle : \text{radd}(A, r, B, s);$
 $\quad !!x \ y. \llbracket p' = \text{Inl}(x); x:A; p = \text{Inr}(y); y:B \rrbracket \implies Q;$
 $\quad !!x' \ x. \llbracket p' = \text{Inl}(x'); p = \text{Inl}(x); \langle x', x \rangle : r; x':A; x:A \rrbracket \implies Q;$
 $\quad !!y' \ y. \llbracket p' = \text{Inr}(y'); p = \text{Inr}(y); \langle y', y \rangle : s; y':B; y:B \rrbracket \implies Q$
 $\rrbracket \implies Q$
 $\langle \text{proof} \rangle$

19.1.3 Type checking

lemma *radd-type*: $\text{radd}(A, r, B, s) \leq (A+B) * (A+B)$
 $\langle \text{proof} \rangle$

lemmas *field-radd* = *radd-type* [THEN field-rel-subset]

19.1.4 Linearity

lemma *linear-radd*:

$\llbracket \text{linear}(A, r); \text{linear}(B, s) \rrbracket \implies \text{linear}(A+B, \text{radd}(A, r, B, s))$
 $\langle \text{proof} \rangle$

19.1.5 Well-foundedness

lemma *wf-on-radd*: $\llbracket \text{wf}[A](r); \text{wf}[B](s) \rrbracket \implies \text{wf}[A+B](\text{radd}(A, r, B, s))$
 $\langle \text{proof} \rangle$

lemma *wf-radd*: $\llbracket \text{wf}(r); \text{wf}(s) \rrbracket \implies \text{wf}(\text{radd}(\text{field}(r), r, \text{field}(s), s))$
 $\langle \text{proof} \rangle$

lemma *well-ord-radd*:

$\llbracket \text{well-ord}(A, r); \text{well-ord}(B, s) \rrbracket \implies \text{well-ord}(A+B, \text{radd}(A, r, B, s))$
 $\langle \text{proof} \rangle$

19.1.6 An *ord-iso* congruence law

lemma *sum-bij*:

$$\begin{aligned} & \llbracket f: \text{bij}(A, C); \quad g: \text{bij}(B, D) \rrbracket \\ & \implies (\text{lam } z: A+B. \text{case}(\%x. \text{Inl}(f'x), \%y. \text{Inr}(g'y), z)) : \text{bij}(A+B, C+D) \end{aligned}$$

 $\langle \text{proof} \rangle$

lemma *sum-ord-iso-cong*:

$$\begin{aligned} & \llbracket f: \text{ord-iso}(A, r, A', r'); \quad g: \text{ord-iso}(B, s, B', s') \rrbracket \implies \\ & \quad (\text{lam } z: A+B. \text{case}(\%x. \text{Inl}(f'x), \%y. \text{Inr}(g'y), z)) \\ & \quad : \text{ord-iso}(A+B, \text{radd}(A, r, B, s), A'+B', \text{radd}(A', r', B', s')) \end{aligned}$$

 $\langle \text{proof} \rangle$

lemma *sum-disjoint-bij*: $A \text{ Int } B = 0 \implies$

$$(\text{lam } z: A+B. \text{case}(\%x. x, \%y. y, z)) : \text{bij}(A+B, A \text{ Un } B)$$

 $\langle \text{proof} \rangle$

19.1.7 Associativity

lemma *sum-assoc-bij*:

$$\begin{aligned} & (\text{lam } z: (A+B)+C. \text{case}(\text{case}(\text{Inl}, \%y. \text{Inr}(\text{Inl}(y))), \%y. \text{Inr}(\text{Inr}(y)), z)) \\ & : \text{bij}((A+B)+C, A+(B+C)) \end{aligned}$$

 $\langle \text{proof} \rangle$

lemma *sum-assoc-ord-iso*:

$$\begin{aligned} & (\text{lam } z: (A+B)+C. \text{case}(\text{case}(\text{Inl}, \%y. \text{Inr}(\text{Inl}(y))), \%y. \text{Inr}(\text{Inr}(y)), z)) \\ & : \text{ord-iso}((A+B)+C, \text{radd}(A+B, \text{radd}(A, r, B, s), C, t), \\ & \quad A+(B+C), \text{radd}(A, r, B+C, \text{radd}(B, s, C, t))) \end{aligned}$$

 $\langle \text{proof} \rangle$

19.2 Multiplication of Relations – Lexicographic Product

19.2.1 Rewrite rule. Can be used to obtain introduction rules

lemma *rmult-iff* [*iff*]:

$$\begin{aligned} & \langle \langle a', b' \rangle, \langle a, b \rangle \rangle : \text{rmult}(A, r, B, s) \iff \\ & \quad (\langle a', a \rangle : r \ \& \ a': A \ \& \ a: A \ \& \ b': B \ \& \ b: B) \mid \\ & \quad (\langle b', b \rangle : s \ \& \ a'=a \ \& \ a: A \ \& \ b': B \ \& \ b: B) \end{aligned}$$

$\langle \text{proof} \rangle$

lemma *rmultE*:

$$\begin{aligned} & \llbracket \langle \langle a', b' \rangle, \langle a, b \rangle \rangle : \text{rmult}(A, r, B, s); \\ & \quad \llbracket \langle a', a \rangle : r; \quad a': A; \quad a: A; \quad b': B; \quad b: B \rrbracket \implies Q; \\ & \quad \llbracket \langle b', b \rangle : s; \quad a: A; \quad a'=a; \quad b': B; \quad b: B \rrbracket \implies Q \end{aligned}$$

 $\llbracket \implies Q$
 $\langle \text{proof} \rangle$

19.2.2 Type checking

lemma *rmult-type*: $rmult(A, r, B, s) \leq (A * B) * (A * B)$
 $\langle proof \rangle$

lemmas *field-rmult* = *rmult-type* [THEN *field-rel-subset*]

19.2.3 Linearity

lemma *linear-rmult*:
 $[[linear(A, r); linear(B, s)]] \implies linear(A * B, rmult(A, r, B, s))$
 $\langle proof \rangle$

19.2.4 Well-foundedness

lemma *wf-on-rmult*: $[[wf[A](r); wf[B](s)]] \implies wf[A * B](rmult(A, r, B, s))$
 $\langle proof \rangle$

lemma *wf-rmult*: $[[wf(r); wf(s)]] \implies wf(rmult(field(r), r, field(s), s))$
 $\langle proof \rangle$

lemma *well-ord-rmult*:
 $[[well-ord(A, r); well-ord(B, s)]] \implies well-ord(A * B, rmult(A, r, B, s))$
 $\langle proof \rangle$

19.2.5 An ord-iso congruence law

lemma *prod-bij*:
 $[[f: bij(A, C); g: bij(B, D)]]$
 $\implies (lam <x, y>: A * B. <f'x, g'y>) : bij(A * B, C * D)$
 $\langle proof \rangle$

lemma *prod-ord-iso-cong*:
 $[[f: ord-iso(A, r, A', r'); g: ord-iso(B, s, B', s')]]$
 $\implies (lam <x, y>: A * B. <f'x, g'y>)$
 $: ord-iso(A * B, rmult(A, r, B, s), A' * B', rmult(A', r', B', s'))$
 $\langle proof \rangle$

lemma *singleton-prod-bij*: $(lam z: A. <x, z>) : bij(A, \{x\} * A)$
 $\langle proof \rangle$

lemma *singleton-prod-ord-iso*:
 $well-ord(\{x\}, xr) \implies$
 $(lam z: A. <x, z>) : ord-iso(A, r, \{x\} * A, rmult(\{x\}, xr, A, r))$
 $\langle proof \rangle$

lemma *prod-sum-singleton-bij*:

$a \sim : C ==>$
 $(\text{lam } x : C * B + D. \text{ case } (\%x. x, \%y. <a, y>, x))$
 $: \text{bij}(C * B + D, C * B \text{ Un } \{a\} * D)$
 $\langle \text{proof} \rangle$

lemma *prod-sum-singleton-ord-iso*:

$[| a : A; \text{ well-ord}(A, r) |] ==>$
 $(\text{lam } x : \text{pred}(A, a, r) * B + \text{pred}(B, b, s). \text{ case } (\%x. x, \%y. <a, y>, x))$
 $: \text{ord-iso}(\text{pred}(A, a, r) * B + \text{pred}(B, b, s),$
 $\text{radd}(A * B, \text{rmult}(A, r, B, s), B, s),$
 $\text{pred}(A, a, r) * B \text{ Un } \{a\} * \text{pred}(B, b, s), \text{rmult}(A, r, B, s))$
 $\langle \text{proof} \rangle$

19.2.6 Distributive law

lemma *sum-prod-distrib-bij*:

$(\text{lam } <x, z> : (A + B) * C. \text{ case } (\%y. \text{Inl}(<y, z>), \%y. \text{Inr}(<y, z>), x))$
 $: \text{bij}((A + B) * C, (A * C) + (B * C))$
 $\langle \text{proof} \rangle$

lemma *sum-prod-distrib-ord-iso*:

$(\text{lam } <x, z> : (A + B) * C. \text{ case } (\%y. \text{Inl}(<y, z>), \%y. \text{Inr}(<y, z>), x))$
 $: \text{ord-iso}((A + B) * C, \text{rmult}(A + B, \text{radd}(A, r, B, s), C, t),$
 $(A * C) + (B * C), \text{radd}(A * C, \text{rmult}(A, r, C, t), B * C, \text{rmult}(B, s, C, t)))$
 $\langle \text{proof} \rangle$

19.2.7 Associativity

lemma *prod-assoc-bij*:

$(\text{lam } <<x, y>, z> : (A * B) * C. <x, <y, z>>) : \text{bij}((A * B) * C, A * (B * C))$
 $\langle \text{proof} \rangle$

lemma *prod-assoc-ord-iso*:

$(\text{lam } <<x, y>, z> : (A * B) * C. <x, <y, z>>)$
 $: \text{ord-iso}((A * B) * C, \text{rmult}(A * B, \text{rmult}(A, r, B, s), C, t),$
 $A * (B * C), \text{rmult}(A, r, B * C, \text{rmult}(B, s, C, t)))$
 $\langle \text{proof} \rangle$

19.3 Inverse Image of a Relation

19.3.1 Rewrite rule

lemma *rvimage-iff*: $<a, b> : \text{rvimage}(A, f, r) <-> <f'a, f'b> : r \ \& \ a : A \ \& \ b : A$
 $\langle \text{proof} \rangle$

19.3.2 Type checking

lemma *rvimage-type*: $\text{rvimage}(A, f, r) <= A * A$
 $\langle \text{proof} \rangle$

lemmas *field-rvimage* = *rvimage-type* [THEN *field-rel-subset*]

lemma *rvimage-converse*: $rvimage(A, f, converse(r)) = converse(rvimage(A, f, r))$
 $\langle proof \rangle$

19.3.3 Partial Ordering Properties

lemma *irrefl-rvimage*:

$\llbracket f: inj(A, B); irrefl(B, r) \rrbracket ==> irrefl(A, rvimage(A, f, r))$
 $\langle proof \rangle$

lemma *trans-on-rvimage*:

$\llbracket f: inj(A, B); trans[B](r) \rrbracket ==> trans[A](rvimage(A, f, r))$
 $\langle proof \rangle$

lemma *part-ord-rvimage*:

$\llbracket f: inj(A, B); part-ord(B, r) \rrbracket ==> part-ord(A, rvimage(A, f, r))$
 $\langle proof \rangle$

19.3.4 Linearity

lemma *linear-rvimage*:

$\llbracket f: inj(A, B); linear(B, r) \rrbracket ==> linear(A, rvimage(A, f, r))$
 $\langle proof \rangle$

lemma *tot-ord-rvimage*:

$\llbracket f: inj(A, B); tot-ord(B, r) \rrbracket ==> tot-ord(A, rvimage(A, f, r))$
 $\langle proof \rangle$

19.3.5 Well-foundedness

lemma *wf-rvimage* [intro!]: $wf(r) ==> wf(rvimage(A, f, r))$
 $\langle proof \rangle$

But note that the combination of *wf-imp-wf-on* and *wf-rvimage* gives $wf(r) \implies wf[C](rvimage(A, f, r))$

lemma *wf-on-rvimage*: $\llbracket f: A \multimap B; wf[B](r) \rrbracket ==> wf[A](rvimage(A, f, r))$
 $\langle proof \rangle$

lemma *well-ord-rvimage*:

$\llbracket f: inj(A, B); well-ord(B, r) \rrbracket ==> well-ord(A, rvimage(A, f, r))$
 $\langle proof \rangle$

lemma *ord-iso-rvimage*:

$f: bij(A, B) ==> f: ord-iso(A, rvimage(A, f, s), B, s)$
 $\langle proof \rangle$

lemma *ord-iso-rvimage-eq*:

$f: ord-iso(A, r, B, s) ==> rvimage(A, f, s) = r Int A * A$

$\langle proof \rangle$

19.4 Every well-founded relation is a subset of some inverse image of an ordinal

lemma *wf-rvimage-Ord*: $Ord(i) \implies wf(rvimage(A, f, Memrel(i)))$
 $\langle proof \rangle$

definition

$wfrank :: [i, i] \implies i$ **where**
 $wfrank(r, a) == wfrec(r, a, \%x f. \bigcup y \in r - \{\{x\}. succ(f'y))$

definition

$wftype :: i \implies i$ **where**
 $wftype(r) == \bigcup y \in range(r). succ(wfrank(r, y))$

lemma *wfrank*: $wf(r) \implies wfrank(r, a) = (\bigcup y \in r - \{\{a\}. succ(wfrank(r, y)))$
 $\langle proof \rangle$

lemma *Ord-wfrank*: $wf(r) \implies Ord(wfrank(r, a))$
 $\langle proof \rangle$

lemma *wfrank-lt*: $[|wf(r); \langle a, b \rangle \in r|] \implies wfrank(r, a) < wfrank(r, b)$
 $\langle proof \rangle$

lemma *Ord-wftype*: $wf(r) \implies Ord(wftype(r))$
 $\langle proof \rangle$

lemma *wftypeI*: $[|wf(r); x \in field(r)|] \implies wfrank(r, x) \in wftype(r)$
 $\langle proof \rangle$

lemma *wf-imp-subset-rvimage*:

$[|wf(r); r \subseteq A * A|] \implies \exists i f. Ord(i) \ \& \ r \leq rvimage(A, f, Memrel(i))$
 $\langle proof \rangle$

theorem *wf-iff-subset-rvimage*:

$relation(r) \implies wf(r) \iff (\exists i f A. Ord(i) \ \& \ r \leq rvimage(A, f, Memrel(i)))$
 $\langle proof \rangle$

19.5 Other Results

lemma *wf-times*: $A \ Int \ B = 0 \implies wf(A * B)$
 $\langle proof \rangle$

Could also be used to prove *wf-radd*

lemma *wf-Un*:

$[| range(r) \ Int \ domain(s) = 0; wf(r); wf(s) |] \implies wf(r \ Un \ s)$

$\langle proof \rangle$

19.5.1 The Empty Relation

lemma *wf0*: $wf(0)$

$\langle proof \rangle$

lemma *linear0*: $linear(0,0)$

$\langle proof \rangle$

lemma *well-ord0*: $well-ord(0,0)$

$\langle proof \rangle$

19.5.2 The "measure" relation is useful with wfrec

lemma *measure-eq-rvimage-Memrel*:

$measure(A,f) = rvimage(A, Lambda(A,f), Memrel(Collect(RepFun(A,f), Ord)))$

$\langle proof \rangle$

lemma *wf-measure [iff]*: $wf(measure(A,f))$

$\langle proof \rangle$

lemma *measure-iff [iff]*: $\langle x,y \rangle : measure(A,f) \longleftrightarrow x:A \ \& \ y:A \ \& \ f(x) < f(y)$

$\langle proof \rangle$

lemma *linear-measure*:

assumes *Ord**f*: $!!x. x \in A \implies Ord(f(x))$

and *inj*: $!!x \ y. [|x \in A; y \in A; f(x) = f(y)|] \implies x=y$

shows $linear(A, measure(A,f))$

$\langle proof \rangle$

lemma *wf-on-measure*: $wf[B](measure(A,f))$

$\langle proof \rangle$

lemma *well-ord-measure*:

assumes *Ord**f*: $!!x. x \in A \implies Ord(f(x))$

and *inj*: $!!x \ y. [|x \in A; y \in A; f(x) = f(y)|] \implies x=y$

shows $well-ord(A, measure(A,f))$

$\langle proof \rangle$

lemma *measure-type*: $measure(A,f) \leq A * A$

$\langle proof \rangle$

19.5.3 Well-foundedness of Unions

lemma *wf-on-Union*:

assumes *wfA*: $wf[A](r)$

and *wfB*: $!!a. a \in A \implies wf[B(a)](s)$

and *ok*: $!!a \ u \ v. [|<u,v> \in s; v \in B(a); a \in A|]$

$\implies (\exists a' \in A. <a',a> \in r \ \& \ u \in B(a')) \mid u \in B(a)$

shows $wf[\bigcup a \in A. B(a)](s)$
 $\langle proof \rangle$

19.5.4 Bijections involving Powersets

lemma *Pow-sum-bij*:

$(\lambda Z \in Pow(A+B). <\{x \in A. Inl(x) \in Z\}, \{y \in B. Inr(y) \in Z\}>)$
 $\in bij(Pow(A+B), Pow(A)*Pow(B))$
 $\langle proof \rangle$

As a special case, we have $bij(Pow(A \times B), A \rightarrow Pow(B))$

lemma *Pow-Sigma-bij*:

$(\lambda r \in Pow(Sigma(A,B)). \lambda x \in A. r''\{x\})$
 $\in bij(Pow(Sigma(A,B)), \Pi x \in A. Pow(B(x)))$
 $\langle proof \rangle$

end

20 OrderType: Order Types and Ordinal Arithmetic

theory *OrderType* **imports** *OrderArith OrdQuant Nat-ZF* **begin**

The order type of a well-ordering is the least ordinal isomorphic to it. Ordinal arithmetic is traditionally defined in terms of order types, as it is here. But a definition by transfinite recursion would be much simpler!

definition

ordermap $:: [i,i] \Rightarrow i$ **where**
ordermap(A,r) $== lam\ x:A. wfrec[A](r, x, \%x\ f. f\ \text{``}\ pred(A,x,r))$

definition

ordertype $:: [i,i] \Rightarrow i$ **where**
ordertype(A,r) $== ordermap(A,r)\ \text{``}\ A$

definition

Ord-alt $:: i \Rightarrow o$ **where**
Ord-alt(X) $== well-ord(X, Memrel(X)) \ \& \ (ALL\ u:X. u=pred(X, u, Memrel(X)))$

definition

ordify $:: i \Rightarrow i$ **where**
ordify(x) $== if\ Ord(x)\ then\ x\ else\ 0$

definition

omult :: $[i,i] \Rightarrow i$ (**infixl** ** 70) **where**
 $i ** j == ordertype(j*i, rmult(j, Memrel(j), i, Memrel(i)))$

definition

raw-oadd :: $[i,i] \Rightarrow i$ **where**
 $raw-oadd(i,j) == ordertype(i+j, radd(i, Memrel(i), j, Memrel(j)))$

definition

oadd :: $[i,i] \Rightarrow i$ (**infixl** ++ 65) **where**
 $i ++ j == raw-oadd(ordify(i), ordify(j))$

definition

odiff :: $[i,i] \Rightarrow i$ (**infixl** -- 65) **where**
 $i -- j == ordertype(i-j, Memrel(i))$

notation (*xsymbols*)

omult (**infixl** $\times \times$ 70)

notation (*HTML output*)

omult (**infixl** $\times \times$ 70)

20.1 Proofs needing the combination of Ordinal.thy and Order.thy

lemma *le-well-ord-Memrel*: $j \leq i \Rightarrow well_ord(j, Memrel(i))$
 $\langle proof \rangle$

lemmas *well-ord-Memrel* = *le-refl* [THEN *le-well-ord-Memrel*]

lemma *lt-pred-Memrel*:

$j < i \Rightarrow pred(i, j, Memrel(i)) = j$
 $\langle proof \rangle$

lemma *pred-Memrel*:

$x:A \Rightarrow pred(A, x, Memrel(A)) = A \text{ Int } x$
 $\langle proof \rangle$

lemma *Ord-iso-implies-eq-lemma*:

$[| j < i; f: ord_iso(i, Memrel(i), j, Memrel(j)) |] \Rightarrow R$
 $\langle proof \rangle$

lemma *Ord-iso-implies-eq*:

$[| Ord(i); Ord(j); f: ord_iso(i, Memrel(i), j, Memrel(j)) |]$

$\implies i=j$
 $\langle \text{proof} \rangle$

20.2 Ordermap and ordertype

lemma *ordermap-type*:
 $\text{ordermap}(A,r) : A \rightarrow \text{ordertype}(A,r)$
 $\langle \text{proof} \rangle$

20.2.1 Unfolding of ordermap

lemma *ordermap-eq-image*:
 $[[\text{wf}[A](r); x:A]] \implies \text{ordermap}(A,r) \text{ ' } x = \text{ordermap}(A,r) \text{ ' ' } \text{pred}(A,x,r)$
 $\langle \text{proof} \rangle$

lemma *ordermap-pred-unfold*:
 $[[\text{wf}[A](r); x:A]] \implies \text{ordermap}(A,r) \text{ ' } x = \{ \text{ordermap}(A,r) \text{ ' } y \mid y : \text{pred}(A,x,r) \}$
 $\langle \text{proof} \rangle$

lemmas *ordermap-unfold* = *ordermap-pred-unfold* [*simplified pred-def*]

20.2.2 Showing that ordermap, ordertype yield ordinals

lemma *Ord-ordermap*:
 $[[\text{well-ord}(A,r); x:A]] \implies \text{Ord}(\text{ordermap}(A,r) \text{ ' } x)$
 $\langle \text{proof} \rangle$

lemma *Ord-ordertype*:
 $\text{well-ord}(A,r) \implies \text{Ord}(\text{ordertype}(A,r))$
 $\langle \text{proof} \rangle$

20.2.3 ordermap preserves the orderings in both directions

lemma *ordermap-mono*:
 $[[<w,x>: r; \text{wf}[A](r); w:A; x:A]] \implies \text{ordermap}(A,r) \text{ ' } w : \text{ordermap}(A,r) \text{ ' } x$
 $\langle \text{proof} \rangle$

lemma *converse-ordermap-mono*:
 $[[\text{ordermap}(A,r) \text{ ' } w : \text{ordermap}(A,r) \text{ ' } x; \text{well-ord}(A,r); w:A; x:A]] \implies <w,x>: r$
 $\langle \text{proof} \rangle$

lemmas *ordermap-surj* =
 ordermap-type [*THEN surj-image, unfolded ordertype-def* [*symmetric*]]

lemma *ordermap-bij*:

$well-ord(A,r) ==> ordermap(A,r) : bij(A, ordertype(A,r))$
 $\langle proof \rangle$

20.2.4 Isomorphisms involving ordertype

lemma *ordertype-ord-iso*:

$well-ord(A,r)$
 $==> ordermap(A,r) : ord-iso(A,r, ordertype(A,r), Memrel(ordertype(A,r)))$
 $\langle proof \rangle$

lemma *ordertype-eq*:

$[| f : ord-iso(A,r,B,s); well-ord(B,s) |]$
 $==> ordertype(A,r) = ordertype(B,s)$
 $\langle proof \rangle$

lemma *ordertype-eq-imp-ord-iso*:

$[| ordertype(A,r) = ordertype(B,s); well-ord(A,r); well-ord(B,s) |]$
 $==> EX f. f : ord-iso(A,r,B,s)$
 $\langle proof \rangle$

20.2.5 Basic equalities for ordertype

lemma *le-ordertype-Memrel*: $j \leq i ==> ordertype(j, Memrel(i)) = j$
 $\langle proof \rangle$

lemmas *ordertype-Memrel* = *le-reft* [THEN *le-ordertype-Memrel*]

lemma *ordertype-0* [*simp*]: $ordertype(0,r) = 0$
 $\langle proof \rangle$

lemmas *bij-ordertype-vimage* = *ord-iso-rvimage* [THEN *ordertype-eq*]

20.2.6 A fundamental unfolding law for ordertype.

lemma *ordermap-pred-eq-ordermap*:

$[| well-ord(A,r); y:A; z: pred(A,y,r) |]$
 $==> ordermap(pred(A,y,r), r) ' z = ordermap(A, r) ' z$
 $\langle proof \rangle$

lemma *ordertype-unfold*:

$ordertype(A,r) = \{ ordermap(A,r) ' y . y : A \}$
 $\langle proof \rangle$

Theorems by Krzysztof Grabczewski; proofs simplified by lcp

lemma *ordertype-pred-subset*: $[| well-ord(A,r); x:A |] ==>$
 $ordertype(pred(A,x,r),r) <= ordertype(A,r)$

$\langle proof \rangle$

lemma *ordertype-pred-lt*:

$[| \text{well-ord}(A, r); x:A |]$
 $\implies \text{ordertype}(\text{pred}(A, x, r), r) < \text{ordertype}(A, r)$

$\langle proof \rangle$

lemma *ordertype-pred-unfold*:

$\text{well-ord}(A, r)$
 $\implies \text{ordertype}(A, r) = \{ \text{ordertype}(\text{pred}(A, x, r), r). x:A \}$

$\langle proof \rangle$

20.3 Alternative definition of ordinal

lemma *Ord-is-Ord-alt*: $\text{Ord}(i) \implies \text{Ord-alt}(i)$

$\langle proof \rangle$

lemma *Ord-alt-is-Ord*:

$\text{Ord-alt}(i) \implies \text{Ord}(i)$

$\langle proof \rangle$

20.4 Ordinal Addition

20.4.1 Order Type calculations for radd

Addition with 0

lemma *bij-sum-0*: $(\text{lam } z:A+0. \text{case}(\%x. x, \%y. y, z)) : \text{bij}(A+0, A)$

$\langle proof \rangle$

lemma *ordertype-sum-0-eq*:

$\text{well-ord}(A, r) \implies \text{ordertype}(A+0, \text{radd}(A, r, 0, s)) = \text{ordertype}(A, r)$

$\langle proof \rangle$

lemma *bij-0-sum*: $(\text{lam } z:0+A. \text{case}(\%x. x, \%y. y, z)) : \text{bij}(0+A, A)$

$\langle proof \rangle$

lemma *ordertype-0-sum-eq*:

$\text{well-ord}(A, r) \implies \text{ordertype}(0+A, \text{radd}(0, s, A, r)) = \text{ordertype}(A, r)$

$\langle proof \rangle$

Initial segments of radd. Statements by Grabczewski

lemma *pred-Inl-bij*:

$a:A \implies (\text{lam } x:\text{pred}(A, a, r). \text{Inl}(x))$
 $: \text{bij}(\text{pred}(A, a, r), \text{pred}(A+B, \text{Inl}(a), \text{radd}(A, r, B, s)))$

$\langle proof \rangle$

lemma *ordertype-pred-Inl-eq*:

$$\begin{aligned} & [| a:A; \text{well-ord}(A,r) |] \\ & \implies \text{ordertype}(\text{pred}(A+B, \text{Inl}(a), \text{radd}(A,r,B,s)), \text{radd}(A,r,B,s)) = \\ & \quad \text{ordertype}(\text{pred}(A,a,r), r) \end{aligned}$$
 $\langle \text{proof} \rangle$

lemma *pred-Inr-bij*:

$$\begin{aligned} & b:B \implies \\ & \quad \text{id}(A+\text{pred}(B,b,s)) \\ & : \text{bij}(A+\text{pred}(B,b,s), \text{pred}(A+B, \text{Inr}(b), \text{radd}(A,r,B,s))) \end{aligned}$$
 $\langle \text{proof} \rangle$

lemma *ordertype-pred-Inr-eq*:

$$\begin{aligned} & [| b:B; \text{well-ord}(A,r); \text{well-ord}(B,s) |] \\ & \implies \text{ordertype}(\text{pred}(A+B, \text{Inr}(b), \text{radd}(A,r,B,s)), \text{radd}(A,r,B,s)) = \\ & \quad \text{ordertype}(A+\text{pred}(B,b,s), \text{radd}(A,r,\text{pred}(B,b,s),s)) \end{aligned}$$
 $\langle \text{proof} \rangle$

20.4.2 ordify: trivial coercion to an ordinal

lemma *Ord-ordify* [*iff*, *TC*]: $\text{Ord}(\text{ordify}(x))$

$\langle \text{proof} \rangle$

lemma *ordify-idem* [*simp*]: $\text{ordify}(\text{ordify}(x)) = \text{ordify}(x)$

$\langle \text{proof} \rangle$

20.4.3 Basic laws for ordinal addition

lemma *Ord-raw-oadd*: $[|\text{Ord}(i); \text{Ord}(j)|] \implies \text{Ord}(\text{raw-oadd}(i,j))$

$\langle \text{proof} \rangle$

lemma *Ord-oadd* [*iff*, *TC*]: $\text{Ord}(i++j)$

$\langle \text{proof} \rangle$

Ordinal addition with zero

lemma *raw-oadd-0*: $\text{Ord}(i) \implies \text{raw-oadd}(i,0) = i$

$\langle \text{proof} \rangle$

lemma *oadd-0* [*simp*]: $\text{Ord}(i) \implies i++0 = i$

$\langle \text{proof} \rangle$

lemma *raw-oadd-0-left*: $\text{Ord}(i) \implies \text{raw-oadd}(0,i) = i$

$\langle \text{proof} \rangle$

lemma *oadd-0-left* [*simp*]: $\text{Ord}(i) \implies 0++i = i$

$\langle \text{proof} \rangle$

lemma *oadd-eq-if-raw-oadd*:

$$i++j = (\text{if } \text{Ord}(i) \text{ then } (\text{if } \text{Ord}(j) \text{ then } \text{raw-oadd}(i,j) \text{ else } i)$$

else (if Ord(j) then j else 0))

<proof>

lemma *raw-oadd-eq-oadd*: $[[Ord(i); Ord(j)]] ==> raw-oadd(i,j) = i++j$

<proof>

lemma *lt-oadd1*: $k < i ==> k < i++j$

<proof>

lemma *oadd-le-self*: $Ord(i) ==> i \leq i++j$

<proof>

Various other results

lemma *id-ord-iso-Memrel*: $A \leq B ==> id(A) : ord-iso(A, Memrel(A), A, Memrel(B))$

<proof>

lemma *subset-ord-iso-Memrel*:

$[[f : ord-iso(A, Memrel(B), C, r); A \leq B]] ==> f : ord-iso(A, Memrel(A), C, r)$

<proof>

lemma *restrict-ord-iso*:

$[[f \in ord-iso(i, Memrel(i), Order.pred(A, a, r), r); a \in A; j < i;$
 $trans[A](r)]]$
 $==> restrict(f, j) \in ord-iso(j, Memrel(j), Order.pred(A, f'j, r), r)$

<proof>

lemma *restrict-ord-iso2*:

$[[f \in ord-iso(Order.pred(A, a, r), r, i, Memrel(i)); a \in A;$
 $j < i; trans[A](r)]]$
 $==> converse(restrict(converse(f), j))$
 $\in ord-iso(Order.pred(A, converse(f)'j, r), r, j, Memrel(j))$

<proof>

lemma *ordertype-sum-Memrel*:

$[[well-ord(A, r); k < j]]$
 $==> ordertype(A+k, radd(A, r, k, Memrel(j))) =$
 $ordertype(A+k, radd(A, r, k, Memrel(k)))$

<proof>

lemma *oadd-lt-mono2*: $k < j ==> i++k < i++j$

<proof>

lemma *oadd-lt-cancel2*: $[[i++j < i++k; Ord(j)]] ==> j < k$

<proof>

lemma *oadd-lt-iff2*: $\text{Ord}(j) \implies i++j < i++k \iff j < k$
 $\langle \text{proof} \rangle$

lemma *oadd-inject*: $[\mid i++j = i++k; \text{Ord}(j); \text{Ord}(k) \mid] \implies j=k$
 $\langle \text{proof} \rangle$

lemma *lt-oadd-disj*: $k < i++j \implies k < i \mid (\exists l. j. k = i++l)$
 $\langle \text{proof} \rangle$

20.4.4 Ordinal addition with successor – via associativity!

lemma *oadd-assoc*: $(i++j)++k = i++(j++k)$
 $\langle \text{proof} \rangle$

lemma *oadd-unfold*: $[\mid \text{Ord}(i); \text{Ord}(j) \mid] \implies i++j = i \text{ Un } (\bigcup_{k \in j. \{i++k\}})$
 $\langle \text{proof} \rangle$

lemma *oadd-1*: $\text{Ord}(i) \implies i++1 = \text{succ}(i)$
 $\langle \text{proof} \rangle$

lemma *oadd-succ* [*simp*]: $\text{Ord}(j) \implies i++\text{succ}(j) = \text{succ}(i++j)$
 $\langle \text{proof} \rangle$

Ordinal addition with limit ordinals

lemma *oadd-UN*:
 $[\mid \forall x. x:A \implies \text{Ord}(j(x)); a:A \mid]$
 $\implies i++(\bigcup_{x \in A. j(x)}) = (\bigcup_{x \in A. i++j(x)})$
 $\langle \text{proof} \rangle$

lemma *oadd-Limit*: $\text{Limit}(j) \implies i++j = (\bigcup_{k \in j. i++k})$
 $\langle \text{proof} \rangle$

lemma *oadd-eq-0-iff*: $[\mid \text{Ord}(i); \text{Ord}(j) \mid] \implies (i++j) = 0 \iff i=0 \ \& \ j=0$
 $\langle \text{proof} \rangle$

lemma *oadd-eq-lt-iff*: $[\mid \text{Ord}(i); \text{Ord}(j) \mid] \implies 0 < (i++j) \iff 0 < i \mid 0 < j$
 $\langle \text{proof} \rangle$

lemma *oadd-LimitI*: $[\mid \text{Ord}(i); \text{Limit}(j) \mid] \implies \text{Limit}(i++j)$
 $\langle \text{proof} \rangle$

Order/monotonicity properties of ordinal addition

lemma *oadd-le-self2*: $\text{Ord}(i) \implies i \text{ le } j++i$
 $\langle \text{proof} \rangle$

lemma *oadd-le-mono1*: $k \text{ le } j \implies k++i \text{ le } j++i$
 $\langle \text{proof} \rangle$

lemma *oadd-lt-mono*: $[[i' \text{ le } i; j' < j]] ==> i'++j' < i++j$
 $\langle \text{proof} \rangle$

lemma *oadd-le-mono*: $[[i' \text{ le } i; j' \text{ le } j]] ==> i'++j' \text{ le } i++j$
 $\langle \text{proof} \rangle$

lemma *oadd-le-iff2*: $[[\text{Ord}(j); \text{Ord}(k)]] ==> i++j \text{ le } i++k <-> j \text{ le } k$
 $\langle \text{proof} \rangle$

lemma *oadd-lt-self*: $[[\text{Ord}(i); 0 < j]] ==> i < i++j$
 $\langle \text{proof} \rangle$

Every ordinal is exceeded by some limit ordinal.

lemma *Ord-imp-greater-Limit*: $\text{Ord}(i) ==> \exists k. i < k \ \& \ \text{Limit}(k)$
 $\langle \text{proof} \rangle$

lemma *Ord2-imp-greater-Limit*: $[[\text{Ord}(i); \text{Ord}(j)]] ==> \exists k. i < k \ \& \ j < k \ \& \ \text{Limit}(k)$
 $\langle \text{proof} \rangle$

20.5 Ordinal Subtraction

The difference is $\text{ordertype}(j - i, \text{Memrel}(j))$. It's probably simpler to define the difference recursively!

lemma *bij-sum-Diff*:
 $A <= B ==> (\text{lam } y:B. \text{ if } (y:A, \text{Inl}(y), \text{Inr}(y))) : \text{bij}(B, A+(B-A))$
 $\langle \text{proof} \rangle$

lemma *ordertype-sum-Diff*:
 $i \text{ le } j ==>$
 $\text{ordertype}(i+(j-i), \text{radd}(i, \text{Memrel}(j), j-i, \text{Memrel}(j))) =$
 $\text{ordertype}(j, \text{Memrel}(j))$
 $\langle \text{proof} \rangle$

lemma *Ord-odiff* $[\text{simp}, \text{TC}]$:
 $[[\text{Ord}(i); \text{Ord}(j)]] ==> \text{Ord}(i--j)$
 $\langle \text{proof} \rangle$

lemma *raw-oadd-ordertype-Diff*:
 $i \text{ le } j$
 $==> \text{raw-oadd}(i, j--i) = \text{ordertype}(i+(j-i), \text{radd}(i, \text{Memrel}(j), j-i, \text{Memrel}(j)))$
 $\langle \text{proof} \rangle$

lemma *oadd-odiff-inverse*: $i \text{ le } j ==> i ++ (j--i) = j$
 $\langle \text{proof} \rangle$

lemma *odiff-oadd-inverse*: $[[\text{Ord}(i); \text{Ord}(j)]] ==> (i++j) -- i = j$

$\langle proof \rangle$

lemma *odiff-lt-mono2*: $[i < j; k \leq i] \implies i - k < j - k$
 $\langle proof \rangle$

20.6 Ordinal Multiplication

lemma *Ord-omult* [*simp*, *TC*]:
 $[Ord(i); Ord(j)] \implies Ord(i ** j)$
 $\langle proof \rangle$

20.6.1 A useful unfolding law

lemma *pred-Pair-eq*:
 $[a:A; b:B] \implies pred(A*B, \langle a, b \rangle, rmult(A, r, B, s)) =$
 $pred(A, a, r) * B \text{ Un } (\{a\} * pred(B, b, s))$
 $\langle proof \rangle$

lemma *ordertype-pred-Pair-eq*:
 $[a:A; b:B; well-ord(A, r); well-ord(B, s)] \implies$
 $ordertype(pred(A*B, \langle a, b \rangle, rmult(A, r, B, s)), rmult(A, r, B, s)) =$
 $ordertype(pred(A, a, r) * B + pred(B, b, s),$
 $radd(A*B, rmult(A, r, B, s), B, s))$
 $\langle proof \rangle$

lemma *ordertype-pred-Pair-lemma*:
 $[i' < i; j' < j] \implies ordertype(pred(i*j, \langle i', j' \rangle, rmult(i, Memrel(i), j, Memrel(j))),$
 $rmult(i, Memrel(i), j, Memrel(j))) =$
 $raw-oadd(j ** i', j')$
 $\langle proof \rangle$

lemma *lt-omult*:
 $[Ord(i); Ord(j); k < j ** i] \implies EX j' i'. k = j ** i' ++ j' \ \& \ j' < j \ \& \ i' < i$
 $\langle proof \rangle$

lemma *omult-oadd-lt*:
 $[j' < j; i' < i] \implies j ** i' ++ j' < j ** i$
 $\langle proof \rangle$

lemma *omult-unfold*:
 $[Ord(i); Ord(j)] \implies j ** i = (\bigcup j' \in j. \bigcup i' \in i. \{j ** i' ++ j'\})$
 $\langle proof \rangle$

20.6.2 Basic laws for ordinal multiplication

Ordinal multiplication by zero

lemma *omult-0* [*simp*]: $i ** 0 = 0$

$\langle proof \rangle$

lemma *omult-0-left* [simp]: $0 ** i = 0$

$\langle proof \rangle$

Ordinal multiplication by 1

lemma *omult-1* [simp]: $Ord(i) ==> i ** 1 = i$

$\langle proof \rangle$

lemma *omult-1-left* [simp]: $Ord(i) ==> 1 ** i = i$

$\langle proof \rangle$

Distributive law for ordinal multiplication and addition

lemma *oadd-omult-distrib*:

$[| Ord(i); Ord(j); Ord(k) |] ==> i ** (j ++ k) = (i ** j) ++ (i ** k)$

$\langle proof \rangle$

lemma *omult-succ*: $[| Ord(i); Ord(j) |] ==> i ** succ(j) = (i ** j) ++ i$

$\langle proof \rangle$

Associative law

lemma *omult-assoc*:

$[| Ord(i); Ord(j); Ord(k) |] ==> (i ** j) ** k = i ** (j ** k)$

$\langle proof \rangle$

Ordinal multiplication with limit ordinals

lemma *omult-UN*:

$[| Ord(i); !!x. x:A ==> Ord(j(x)) |]$
 $==> i ** (\bigcup x \in A. j(x)) = (\bigcup x \in A. i ** j(x))$

$\langle proof \rangle$

lemma *omult-Limit*: $[| Ord(i); Limit(j) |] ==> i ** j = (\bigcup k \in j. i ** k)$

$\langle proof \rangle$

20.6.3 Ordering/monotonicity properties of ordinal multiplication

lemma *lt-omult1*: $[| k < i; 0 < j |] ==> k < i ** j$

$\langle proof \rangle$

lemma *omult-le-self*: $[| Ord(i); 0 < j |] ==> i \leq i ** j$

$\langle proof \rangle$

lemma *omult-le-mono1*: $[| k \leq j; Ord(i) |] ==> k ** i \leq j ** i$

$\langle proof \rangle$

lemma *omult-lt-mono2*: $[| k < j; 0 < i |] ==> i ** k < i ** j$

$\langle proof \rangle$

lemma *omult-le-mono2*: $[[k \leq j; \text{Ord}(i)]] \implies i ** k \leq i ** j$
 $\langle \text{proof} \rangle$

lemma *omult-le-mono*: $[[i' \leq i; j' \leq j]] \implies i' ** j' \leq i ** j$
 $\langle \text{proof} \rangle$

lemma *omult-lt-mono*: $[[i' \leq i; j' < j; 0 < i]] \implies i' ** j' < i ** j$
 $\langle \text{proof} \rangle$

lemma *omult-le-self2*: $[[\text{Ord}(i); 0 < j]] \implies i \leq j ** i$
 $\langle \text{proof} \rangle$

Further properties of ordinal multiplication

lemma *omult-inject*: $[[i ** j = i ** k; 0 < i; \text{Ord}(j); \text{Ord}(k)]] \implies j = k$
 $\langle \text{proof} \rangle$

20.7 The Relation Lt

lemma *wf-Lt*: $\text{wf}(Lt)$
 $\langle \text{proof} \rangle$

lemma *irrefl-Lt*: $\text{irrefl}(A, Lt)$
 $\langle \text{proof} \rangle$

lemma *trans-Lt*: $\text{trans}[A](Lt)$
 $\langle \text{proof} \rangle$

lemma *part-ord-Lt*: $\text{part-ord}(A, Lt)$
 $\langle \text{proof} \rangle$

lemma *linear-Lt*: $\text{linear}(\text{nat}, Lt)$
 $\langle \text{proof} \rangle$

lemma *tot-ord-Lt*: $\text{tot-ord}(\text{nat}, Lt)$
 $\langle \text{proof} \rangle$

lemma *well-ord-Lt*: $\text{well-ord}(\text{nat}, Lt)$
 $\langle \text{proof} \rangle$

end

21 Finite: Finite Powerset Operator and Finite Function Space

theory *Finite* **imports** *Inductive-ZF Epsilon Nat-ZF* **begin**

```

rep-datatype
  elimination    natE
  induction      nat-induct
  case-eqns      nat-case-0 nat-case-succ
  recursor-eqns  recursor-0 recursor-succ

```

```

consts
  Fin      ::  $i \Rightarrow i$ 
  FiniteFun ::  $[i, i] \Rightarrow i$        $((- \text{ -- } ||> / -) [61, 60] 60)$ 

```

```

inductive
  domains    Fin(A) <= Pow(A)
  intros
    emptyI: 0 : Fin(A)
    consI:   $[[ a : A; b : Fin(A) ]] \Rightarrow cons(a, b) : Fin(A)$ 
  type-intros empty-subsetI cons-subsetI PowI
  type-elim   PowD [THEN revcut-rl]

```

```

inductive
  domains    FiniteFun(A, B) <= Fin(A*B)
  intros
    emptyI: 0 :  $A \text{ -- } ||> B$ 
    consI:   $[[ a : A; b : B; h : A \text{ -- } ||> B; a \sim : domain(h) ]] \Rightarrow cons(<a, b>, h) : A \text{ -- } ||> B$ 
  type-intros Fin.intros

```

21.1 Finite Powerset Operator

```

lemma Fin-mono:  $A \leq B \Rightarrow Fin(A) \leq Fin(B)$ 
<proof>

```

```

lemmas FinD = Fin.dom-subset [THEN subsetD, THEN PowD, standard]

```

```

lemma Fin-induct [case-names 0 cons, induct set: Fin]:
   $[[ b : Fin(A);$ 
     $P(0);$ 
     $!!x y. [[ x : A; y : Fin(A); x \sim y; P(y) ]] \Rightarrow P(cons(x, y))$ 
   $]] \Rightarrow P(b)$ 
<proof>

```

```

declare Fin.intros [simp]

```

lemma *Fin-0*: $Fin(0) = \{0\}$

$\langle proof \rangle$

lemma *Fin-UnI* [*simp*]: $[| b: Fin(A); c: Fin(A) |] ==> b \text{ Un } c : Fin(A)$

$\langle proof \rangle$

lemma *Fin-UnionI*: $C : Fin(Fin(A)) ==> Union(C) : Fin(A)$

$\langle proof \rangle$

lemma *Fin-subset-lemma* [*rule-format*]: $b: Fin(A) ==> \forall z. z \leq b \rightarrow z: Fin(A)$

$\langle proof \rangle$

lemma *Fin-subset*: $[| c \leq b; b: Fin(A) |] ==> c: Fin(A)$

$\langle proof \rangle$

lemma *Fin-IntI1* [*intro,simp*]: $b: Fin(A) ==> b \text{ Int } c : Fin(A)$

$\langle proof \rangle$

lemma *Fin-IntI2* [*intro,simp*]: $c: Fin(A) ==> b \text{ Int } c : Fin(A)$

$\langle proof \rangle$

lemma *Fin-0-induct-lemma* [*rule-format*]:

$[| c: Fin(A); b: Fin(A); P(b);$
 $!!x y. [| x: A; y: Fin(A); x:y; P(y) |] ==> P(y-\{x\})$
 $|] ==> c \leq b \rightarrow P(b-c)$

$\langle proof \rangle$

lemma *Fin-0-induct*:

$[| b: Fin(A);$
 $P(b);$
 $!!x y. [| x: A; y: Fin(A); x:y; P(y) |] ==> P(y-\{x\})$
 $|] ==> P(0)$

$\langle proof \rangle$

lemma *nat-fun-subset-Fin*: $n: nat ==> n \rightarrow A \leq Fin(nat * A)$

$\langle proof \rangle$

21.2 Finite Function Space

lemma *FiniteFun-mono*:

$[| A \leq C; B \leq D |] ==> A \multimap B \leq C \multimap D$

$\langle proof \rangle$

lemma *FiniteFun-mono1*: $A \leq B \implies A -||> A \leq B -||> B$
 $\langle \text{proof} \rangle$

lemma *FiniteFun-is-fun*: $h: A -||> B \implies h: \text{domain}(h) \rightarrow B$
 $\langle \text{proof} \rangle$

lemma *FiniteFun-domain-Fin*: $h: A -||> B \implies \text{domain}(h) : \text{Fin}(A)$
 $\langle \text{proof} \rangle$

lemmas *FiniteFun-apply-type* = *FiniteFun-is-fun* [THEN *apply-type*, *standard*]

lemma *FiniteFun-subset-lemma* [rule-format]:
 $b: A -||> B \implies \text{ALL } z. z \leq b \implies z: A -||> B$
 $\langle \text{proof} \rangle$

lemma *FiniteFun-subset*: $[c \leq b; b: A -||> B] \implies c: A -||> B$
 $\langle \text{proof} \rangle$

lemma *fun-FiniteFunI* [rule-format]: $A: \text{Fin}(X) \implies \text{ALL } f. f: A \rightarrow B \implies f: A -||> B$
 $\langle \text{proof} \rangle$

lemma *lam-FiniteFun*: $A: \text{Fin}(X) \implies (\text{lam } x:A. b(x)) : A -||> \{b(x). x:A\}$
 $\langle \text{proof} \rangle$

lemma *FiniteFun-Collect-iff*:
 $f : \text{FiniteFun}(A, \{y:B. P(y)\})$
 $\iff f : \text{FiniteFun}(A, B) \ \& \ (\text{ALL } x:\text{domain}(f). P(f'x))$
 $\langle \text{proof} \rangle$

21.3 The Contents of a Singleton Set

definition

$\text{contents} :: i \Rightarrow i$ **where**
 $\text{contents}(X) == \text{THE } x. X = \{x\}$

lemma *contents-eq* [simp]: $\text{contents } (\{x\}) = x$
 $\langle \text{proof} \rangle$

end

22 Cardinal: Cardinal Numbers Without the Axiom of Choice

theory *Cardinal* **imports** *OrderType Finite Nat-ZF Sum* **begin**

definition

Least :: $(i \Rightarrow o) \Rightarrow i$ (**binder** *LEAST* 10) **where**
Least(*P*) == *THE* *i*. *Ord*(*i*) & *P*(*i*) & (*ALL* *j*. $j < i \Rightarrow \sim P(j)$)

definition

eqpoll :: $[i, i] \Rightarrow o$ (**infixl** *eqpoll* 50) **where**
A eqpoll B == *EX* *f*. *f*: *bij*(*A*, *B*)

definition

lepoll :: $[i, i] \Rightarrow o$ (**infixl** *lepoll* 50) **where**
A lepoll B == *EX* *f*. *f*: *inj*(*A*, *B*)

definition

lesspoll :: $[i, i] \Rightarrow o$ (**infixl** *lesspoll* 50) **where**
A lesspoll B == *A lepoll B* & $\sim(A \text{ eqpoll } B)$

definition

cardinal :: $i \Rightarrow i$ (**|**-) **where**
 $|A|$ == *LEAST* *i*. *i eqpoll A*

definition

Finite :: $i \Rightarrow o$ **where**
Finite(*A*) == *EX* *n*:*nat*. *A eqpoll n*

definition

Card :: $i \Rightarrow o$ **where**
Card(*i*) == (*i* = $|i|$)

notation (*xsymbols*)

eqpoll (**infixl** \approx 50) **and**
lepoll (**infixl** \lesssim 50) **and**
lesspoll (**infixl** \prec 50) **and**
Least (**binder** μ 10)

notation (*HTML output*)

eqpoll (**infixl** \approx 50) **and**
Least (**binder** μ 10)

22.1 The Schroeder-Bernstein Theorem

See Davey and Priestly, page 106

lemma *decomp-bnd-mono*: *bnd-mono*(*X*, $\%W$. $X - g^{''}(Y - f^{''}W)$)
 $\langle proof \rangle$

lemma *Banach-last-equation*:

$g: Y \rightarrow X$
 $\Rightarrow g^{''}(Y - f^{''} \text{ lfp}(X, \%W. X - g^{''}(Y - f^{''}W))) =$

$X = \text{lfp}(X, \% W. X = g^{''}(Y = f^{''}W))$
 $\langle \text{proof} \rangle$

lemma *decomposition*:

$[| f: X \rightarrow Y; g: Y \rightarrow X |] ==>$
 $EX\ XA\ XB\ YA\ YB. (XA\ Int\ XB = 0) \ \& \ (XA\ Un\ XB = X) \ \&$
 $(YA\ Int\ YB = 0) \ \& \ (YA\ Un\ YB = Y) \ \&$
 $f^{''}XA = YA \ \& \ g^{''}YB = XB$

$\langle \text{proof} \rangle$

lemma *schroeder-bernstein*:

$[| f: inj(X, Y); g: inj(Y, X) |] ==> EX\ h. h: bij(X, Y)$
 $\langle \text{proof} \rangle$

lemma *bij-imp-epoll*: $f: bij(A, B) ==> A \approx B$
 $\langle \text{proof} \rangle$

lemmas *epoll-refl* = *id-bij* [*THEN* *bij-imp-epoll*, *standard*, *simp*]

lemma *epoll-sym*: $X \approx Y ==> Y \approx X$
 $\langle \text{proof} \rangle$

lemma *epoll-trans*:

$[| X \approx Y; Y \approx Z |] ==> X \approx Z$
 $\langle \text{proof} \rangle$

lemma *subset-imp-lepoll*: $X \leq Y ==> X \lesssim Y$
 $\langle \text{proof} \rangle$

lemmas *lepoll-refl* = *subset-refl* [*THEN* *subset-imp-lepoll*, *standard*, *simp*]

lemmas *le-imp-lepoll* = *le-imp-subset* [*THEN* *subset-imp-lepoll*, *standard*]

lemma *epoll-imp-lepoll*: $X \approx Y ==> X \lesssim Y$
 $\langle \text{proof} \rangle$

lemma *lepoll-trans*: $[| X \lesssim Y; Y \lesssim Z |] ==> X \lesssim Z$
 $\langle \text{proof} \rangle$

lemma *epollIII*: $[| X \lesssim Y; Y \lesssim X |] ==> X \approx Y$
 $\langle \text{proof} \rangle$

lemma *eqpollE*:

$\llbracket X \approx Y; \llbracket X \lesssim Y; Y \lesssim X \rrbracket \implies P \rrbracket \implies P$
 $\langle proof \rangle$

lemma *eqpoll-iff*: $X \approx Y \iff X \lesssim Y \ \& \ Y \lesssim X$

$\langle proof \rangle$

lemma *lepoll-0-is-0*: $A \lesssim 0 \implies A = 0$

$\langle proof \rangle$

lemmas *empty-lepollI* = *empty-subsetI* [*THEN subset-imp-lepoll, standard*]

lemma *lepoll-0-iff*: $A \lesssim 0 \iff A = 0$

$\langle proof \rangle$

lemma *Un-lepoll-Un*:

$\llbracket A \lesssim B; C \lesssim D; B \text{ Int } D = 0 \rrbracket \implies A \text{ Un } C \lesssim B \text{ Un } D$
 $\langle proof \rangle$

lemmas *eqpoll-0-is-0* = *eqpoll-imp-lepoll* [*THEN lepoll-0-is-0, standard*]

lemma *eqpoll-0-iff*: $A \approx 0 \iff A = 0$

$\langle proof \rangle$

lemma *eqpoll-disjoint-Un*:

$\llbracket A \approx B; C \approx D; A \text{ Int } C = 0; B \text{ Int } D = 0 \rrbracket \implies A \text{ Un } C \approx B \text{ Un } D$
 $\langle proof \rangle$

22.2 lesspoll: contributions by Krzysztof Grabczewski

lemma *lesspoll-not-refl*: $\sim (i \prec i)$

$\langle proof \rangle$

lemma *lesspoll-irrefl* [*elim!*]: $i \prec i \implies P$

$\langle proof \rangle$

lemma *lesspoll-imp-lepoll*: $A \prec B \implies A \lesssim B$

$\langle proof \rangle$

lemma *lepoll-well-ord*: $\llbracket A \lesssim B; \text{well-ord}(B, r) \rrbracket \implies \exists X \text{ s. } \text{well-ord}(A, s)$

$\langle proof \rangle$

lemma *lepoll-iff-leqpoll*: $A \lesssim B \iff A \prec B \mid A \approx B$

$\langle proof \rangle$

lemma *inj-not-surj-succ*:

$\llbracket f : inj(A, succ(m)); f \sim: surj(A, succ(m)) \rrbracket ==> EX f. f:inj(A,m)$
 $\langle proof \rangle$

lemma *lesspoll-trans*:
 $\llbracket X \prec Y; Y \prec Z \rrbracket ==> X \prec Z$
 $\langle proof \rangle$

lemma *lesspoll-trans1*:
 $\llbracket X \lesssim Y; Y \prec Z \rrbracket ==> X \prec Z$
 $\langle proof \rangle$

lemma *lesspoll-trans2*:
 $\llbracket X \prec Y; Y \lesssim Z \rrbracket ==> X \prec Z$
 $\langle proof \rangle$

lemma *Least-equality*:
 $\llbracket P(i); Ord(i); !!x. x < i ==> \sim P(x) \rrbracket ==> (LEAST x. P(x)) = i$
 $\langle proof \rangle$

lemma *LeastI*: $\llbracket P(i); Ord(i) \rrbracket ==> P(LEAST x. P(x))$
 $\langle proof \rangle$

lemma *Least-le*: $\llbracket P(i); Ord(i) \rrbracket ==> (LEAST x. P(x)) le i$
 $\langle proof \rangle$

lemma *less-LeastE*: $\llbracket P(i); i < (LEAST x. P(x)) \rrbracket ==> Q$
 $\langle proof \rangle$

lemma *LeastI2*:
 $\llbracket P(i); Ord(i); !!j. P(j) ==> Q(j) \rrbracket ==> Q(LEAST j. P(j))$
 $\langle proof \rangle$

lemma *Least-0*:
 $\llbracket \sim (EX i. Ord(i) \ \& \ P(i)) \rrbracket ==> (LEAST x. P(x)) = 0$
 $\langle proof \rangle$

lemma *Ord-Least* *[intro,simp,TC]*: $Ord(LEAST x. P(x))$
 $\langle proof \rangle$

lemma *Least-cong*:

$(\lambda y. P(y) \leftrightarrow Q(y)) \implies (\text{LEAST } x. P(x)) = (\text{LEAST } x. Q(x))$
 $\langle \text{proof} \rangle$

lemma *cardinal-cong*: $X \approx Y \implies |X| = |Y|$

$\langle \text{proof} \rangle$

lemma *well-ord-cardinal-epoll*:

$\text{well-ord}(A, r) \implies |A| \approx A$
 $\langle \text{proof} \rangle$

lemmas *Ord-cardinal-epoll = well-ord-Memrel* [*THEN well-ord-cardinal-epoll*]

lemma *well-ord-cardinal-eqE*:

$[\text{well-ord}(X, r); \text{well-ord}(Y, s); |X| = |Y|] \implies X \approx Y$
 $\langle \text{proof} \rangle$

lemma *well-ord-cardinal-epoll-iff*:

$[\text{well-ord}(X, r); \text{well-ord}(Y, s)] \implies |X| = |Y| \leftrightarrow X \approx Y$
 $\langle \text{proof} \rangle$

lemma *Ord-cardinal-le*: $\text{Ord}(i) \implies |i| \text{ le } i$

$\langle \text{proof} \rangle$

lemma *Card-cardinal-eq*: $\text{Card}(K) \implies |K| = K$

$\langle \text{proof} \rangle$

lemma *CardI*: $[\text{Ord}(i); \lambda j. j < i \implies \sim(j \approx i)] \implies \text{Card}(i)$

$\langle \text{proof} \rangle$

lemma *Card-is-Ord*: $\text{Card}(i) \implies \text{Ord}(i)$

$\langle \text{proof} \rangle$

lemma *Card-cardinal-le*: $\text{Card}(K) \implies K \text{ le } |K|$

$\langle \text{proof} \rangle$

lemma *Ord-cardinal* [*simp,intro!*]: $\text{Ord}(|A|)$

$\langle \text{proof} \rangle$

lemma *Card-iff-initial*: $\text{Card}(K) <-> \text{Ord}(K) \ \& \ (\text{ALL } j. j < K \longrightarrow \sim j \approx K)$
 $\langle \text{proof} \rangle$

lemma *lt-Card-imp-lesspoll*: $[| \text{Card}(a); i < a |] \implies i \prec a$
 $\langle \text{proof} \rangle$

lemma *Card-0*: $\text{Card}(0)$
 $\langle \text{proof} \rangle$

lemma *Card-Un*: $[| \text{Card}(K); \text{Card}(L) |] \implies \text{Card}(K \text{ Un } L)$
 $\langle \text{proof} \rangle$

lemma *Card-cardinal*: $\text{Card}(|A|)$
 $\langle \text{proof} \rangle$

lemma *cardinal-eq-lemma*: $[| |i| \text{ le } j; j \text{ le } i |] \implies |j| = |i|$
 $\langle \text{proof} \rangle$

lemma *cardinal-mono*: $i \text{ le } j \implies |i| \text{ le } |j|$
 $\langle \text{proof} \rangle$

lemma *cardinal-lt-imp-lt*: $[| |i| < |j|; \text{Ord}(i); \text{Ord}(j) |] \implies i < j$
 $\langle \text{proof} \rangle$

lemma *Card-lt-imp-lt*: $[| |i| < K; \text{Ord}(i); \text{Card}(K) |] \implies i < K$
 $\langle \text{proof} \rangle$

lemma *Card-lt-iff*: $[| \text{Ord}(i); \text{Card}(K) |] \implies (|i| < K) <-> (i < K)$
 $\langle \text{proof} \rangle$

lemma *Card-le-iff*: $[| \text{Ord}(i); \text{Card}(K) |] \implies (K \text{ le } |i|) <-> (K \text{ le } i)$
 $\langle \text{proof} \rangle$

lemma *well-ord-lepoll-imp-Card-le*:
 $[| \text{well-ord}(B, r); A \lesssim B |] \implies |A| \text{ le } |B|$
 $\langle \text{proof} \rangle$

lemma *lepoll-cardinal-le*: $[| A \lesssim i; \text{Ord}(i) |] \implies |A| \text{ le } i$
 $\langle \text{proof} \rangle$

lemma *lepoll-Ord-imp-eqpoll*: $[| A \lesssim i; \text{Ord}(i) |] \implies |A| \approx A$
 $\langle \text{proof} \rangle$

lemma *lesspoll-imp-epoll*: $[| A \prec i; \text{Ord}(i) |] \implies |A| \approx A$
 $\langle \text{proof} \rangle$

lemma *cardinal-subset-Ord*: $[| A \leq i; \text{Ord}(i) |] \implies |A| \leq i$
 $\langle \text{proof} \rangle$

22.3 The finite cardinals

lemma *cons-lepoll-consD*:
 $[| \text{cons}(u,A) \lesssim \text{cons}(v,B); u \sim A; v \sim B |] \implies A \lesssim B$
 $\langle \text{proof} \rangle$

lemma *cons-epoll-consD*: $[| \text{cons}(u,A) \approx \text{cons}(v,B); u \sim A; v \sim B |] \implies A \approx B$
 $\langle \text{proof} \rangle$

lemma *succ-lepoll-succD*: $\text{succ}(m) \lesssim \text{succ}(n) \implies m \lesssim n$
 $\langle \text{proof} \rangle$

lemma *nat-lepoll-imp-le* *[rule-format]*:
 $m:\text{nat} \implies \text{ALL } n:\text{nat}. m \lesssim n \dashv\vdash m \text{ le } n$
 $\langle \text{proof} \rangle$

lemma *nat-epoll-iff*: $[| m:\text{nat}; n:\text{nat} |] \implies m \approx n \iff m = n$
 $\langle \text{proof} \rangle$

lemma *nat-into-Card*:
 $n:\text{nat} \implies \text{Card}(n)$
 $\langle \text{proof} \rangle$

lemmas *cardinal-0* = *nat-0I* *[THEN nat-into-Card, THEN Card-cardinal-eq, iff]*
lemmas *cardinal-1* = *nat-1I* *[THEN nat-into-Card, THEN Card-cardinal-eq, iff]*

lemma *succ-lepoll-natE*: $[| \text{succ}(n) \lesssim n; n:\text{nat} |] \implies P$
 $\langle \text{proof} \rangle$

lemma *n-lesspoll-nat*: $n \in \text{nat} \implies n \prec \text{nat}$
 $\langle \text{proof} \rangle$

lemma *nat-lepoll-imp-ex-epoll-n*:
 $[| n \in \text{nat}; \text{nat} \lesssim X |] \implies \exists Y. Y \subseteq X \ \& \ n \approx Y$
 $\langle \text{proof} \rangle$

lemma *lepoll-imp-lesspoll-succ*:

$\llbracket A \lesssim m; m:\text{nat} \rrbracket \implies A \prec \text{succ}(m)$
 $\langle \text{proof} \rangle$

lemma *lesspoll-succ-imp-lepoll*:

$\llbracket A \prec \text{succ}(m); m:\text{nat} \rrbracket \implies A \lesssim m$
 $\langle \text{proof} \rangle$

lemma *lesspoll-succ-iff*: $m:\text{nat} \implies A \prec \text{succ}(m) \iff A \lesssim m$

$\langle \text{proof} \rangle$

lemma *lepoll-succ-disj*: $\llbracket A \lesssim \text{succ}(m); m:\text{nat} \rrbracket \implies A \lesssim m \mid A \approx \text{succ}(m)$

$\langle \text{proof} \rangle$

lemma *lesspoll-cardinal-lt*: $\llbracket A \prec i; \text{Ord}(i) \rrbracket \implies |A| < i$

$\langle \text{proof} \rangle$

22.4 The first infinite cardinal: Omega, or nat

lemma *lt-not-lepoll*: $\llbracket n < i; n:\text{nat} \rrbracket \implies \sim i \lesssim n$

$\langle \text{proof} \rangle$

lemma *Ord-nat-eqpoll-iff*: $\llbracket \text{Ord}(i); n:\text{nat} \rrbracket \implies i \approx n \iff i = n$

$\langle \text{proof} \rangle$

lemma *Card-nat*: $\text{Card}(\text{nat})$

$\langle \text{proof} \rangle$

lemma *nat-le-cardinal*: $\text{nat} \text{ le } i \implies \text{nat} \text{ le } |i|$

$\langle \text{proof} \rangle$

22.5 Towards Cardinal Arithmetic

lemma *cons-lepoll-cong*:

$\llbracket A \lesssim B; b \sim: B \rrbracket \implies \text{cons}(a, A) \lesssim \text{cons}(b, B)$
 $\langle \text{proof} \rangle$

lemma *cons-eqpoll-cong*:

$\llbracket A \approx B; a \sim: A; b \sim: B \rrbracket \implies \text{cons}(a, A) \approx \text{cons}(b, B)$
 $\langle \text{proof} \rangle$

lemma *cons-lepoll-cons-iff*:

$\llbracket a \sim: A; b \sim: B \rrbracket \implies \text{cons}(a, A) \lesssim \text{cons}(b, B) \iff A \lesssim B$
 $\langle \text{proof} \rangle$

lemma *cons-eqpoll-cons-iff*:

$\llbracket a \sim: A; b \sim: B \rrbracket \implies \text{cons}(a, A) \approx \text{cons}(b, B) \iff A \approx B$
 $\langle \text{proof} \rangle$

lemma *singleton-epoll-1*: $\{a\} \approx 1$

$\langle proof \rangle$

lemma *cardinal-singleton*: $|\{a\}| = 1$

$\langle proof \rangle$

lemma *not-0-is-lepoll-1*: $A \sim 0 \implies 1 \lesssim A$

$\langle proof \rangle$

lemma *succ-epoll-cong*: $A \approx B \implies succ(A) \approx succ(B)$

$\langle proof \rangle$

lemma *sum-epoll-cong*: $[| A \approx C; B \approx D |] \implies A+B \approx C+D$

$\langle proof \rangle$

lemma *prod-epoll-cong*:

$[| A \approx C; B \approx D |] \implies A*B \approx C*D$

$\langle proof \rangle$

lemma *inj-disjoint-epoll*:

$[| f: inj(A,B); A \text{ Int } B = 0 |] \implies A \text{ Un } (B - range(f)) \approx B$

$\langle proof \rangle$

22.6 Lemmas by Krzysztof Grabczewski

lemma *Diff-sing-lepoll*:

$[| a:A; A \lesssim succ(n) |] \implies A - \{a\} \lesssim n$

$\langle proof \rangle$

lemma *lepoll-Diff-sing*:

$[| succ(n) \lesssim A |] \implies n \lesssim A - \{a\}$

$\langle proof \rangle$

lemma *Diff-sing-epoll*: $[| a:A; A \approx succ(n) |] \implies A - \{a\} \approx n$

$\langle proof \rangle$

lemma *lepoll-1-is-sing*: $[| A \lesssim 1; a:A |] \implies A = \{a\}$

$\langle proof \rangle$

lemma *Un-lepoll-sum*: $A \text{ Un } B \lesssim A+B$

$\langle proof \rangle$

lemma *well-ord-Un*:

$[| well-ord(X,R); well-ord(Y,S) |] \implies \exists X \ T. well-ord(X \text{ Un } Y, T)$

$\langle proof \rangle$

lemma *disj-Un-eqpoll-sum*: $A \text{ Int } B = 0 \implies A \text{ Un } B \approx A + B$
 $\langle proof \rangle$

22.7 Finite and infinite sets

lemma *Finite-0* [*simp*]: $Finite(0)$
 $\langle proof \rangle$

lemma *lepoll-nat-imp-Finite*: $[| A \lesssim n; n:nat |] \implies Finite(A)$
 $\langle proof \rangle$

lemma *lesspoll-nat-is-Finite*:
 $A \prec nat \implies Finite(A)$
 $\langle proof \rangle$

lemma *lepoll-Finite*:
 $[| Y \lesssim X; Finite(X) |] \implies Finite(Y)$
 $\langle proof \rangle$

lemmas *subset-Finite* = *subset-imp-lepoll* [*THEN lepoll-Finite, standard*]

lemma *Finite-Int*: $Finite(A) \mid Finite(B) \implies Finite(A \text{ Int } B)$
 $\langle proof \rangle$

lemmas *Finite-Diff* = *Diff-subset* [*THEN subset-Finite, standard*]

lemma *Finite-cons*: $Finite(x) \implies Finite(cons(y,x))$
 $\langle proof \rangle$

lemma *Finite-succ*: $Finite(x) \implies Finite(succ(x))$
 $\langle proof \rangle$

lemma *Finite-cons-iff* [*iff*]: $Finite(cons(y,x)) \iff Finite(x)$
 $\langle proof \rangle$

lemma *Finite-succ-iff* [*iff*]: $Finite(succ(x)) \iff Finite(x)$
 $\langle proof \rangle$

lemma *nat-le-infinite-Ord*:
 $[| Ord(i); \sim Finite(i) |] \implies nat \text{ le } i$
 $\langle proof \rangle$

lemma *Finite-imp-well-ord*:
 $Finite(A) \implies \exists r. \text{ well-ord}(A,r)$
 $\langle proof \rangle$

lemma *succ-lepoll-imp-not-empty*: $\text{succ}(x) \lesssim y \implies y \neq 0$
 $\langle \text{proof} \rangle$

lemma *eqpoll-succ-imp-not-empty*: $x \approx \text{succ}(n) \implies x \neq 0$
 $\langle \text{proof} \rangle$

lemma *Finite-Fin-lemma* [rule-format]:
 $n \in \text{nat} \implies \forall A. (A \approx n \ \& \ A \subseteq X) \dashrightarrow A \in \text{Fin}(X)$
 $\langle \text{proof} \rangle$

lemma *Finite-Fin*: $[| \text{Finite}(A); A \subseteq X |] \implies A \in \text{Fin}(X)$
 $\langle \text{proof} \rangle$

lemma *eqpoll-imp-Finite-iff*: $A \approx B \implies \text{Finite}(A) <-> \text{Finite}(B)$
 $\langle \text{proof} \rangle$

lemma *Fin-lemma* [rule-format]: $n: \text{nat} \implies \text{ALL } A. A \approx n \dashrightarrow A : \text{Fin}(A)$
 $\langle \text{proof} \rangle$

lemma *Finite-into-Fin*: $\text{Finite}(A) \implies A : \text{Fin}(A)$
 $\langle \text{proof} \rangle$

lemma *Fin-into-Finite*: $A : \text{Fin}(U) \implies \text{Finite}(A)$
 $\langle \text{proof} \rangle$

lemma *Finite-Fin-iff*: $\text{Finite}(A) <-> A : \text{Fin}(A)$
 $\langle \text{proof} \rangle$

lemma *Finite-Un*: $[| \text{Finite}(A); \text{Finite}(B) |] \implies \text{Finite}(A \text{ Un } B)$
 $\langle \text{proof} \rangle$

lemma *Finite-Un-iff* [simp]: $\text{Finite}(A \text{ Un } B) <-> (\text{Finite}(A) \ \& \ \text{Finite}(B))$
 $\langle \text{proof} \rangle$

The converse must hold too.

lemma *Finite-Union*: $[| \text{ALL } y:X. \text{Finite}(y); \text{Finite}(X) |] \implies \text{Finite}(\text{Union}(X))$
 $\langle \text{proof} \rangle$

lemma *Finite-induct* [case-names 0 cons, induct set: Finite]:
 $[| \text{Finite}(A); P(0);$
 $\quad !! x B. \quad [| \text{Finite}(B); x \sim: B; P(B) |] \implies P(\text{cons}(x, B)) |]$
 $\implies P(A)$
 $\langle \text{proof} \rangle$

lemma *Diff-sing-Finite*: $\text{Finite}(A - \{a\}) \implies \text{Finite}(A)$
 $\langle \text{proof} \rangle$

lemma *Diff-Finite* [rule-format]: $Finite(B) ==> Finite(A-B) --> Finite(A)$
 <proof>

lemma *Finite-RepFun*: $Finite(A) ==> Finite(RepFun(A,f))$
 <proof>

lemma *Finite-RepFun-iff-lemma* [rule-format]:
 $[|Finite(x); !!x y. f(x)=f(y) ==> x=y|]$
 $==> \forall A. x = RepFun(A,f) --> Finite(A)$
 <proof>

I don't know why, but if the premise is expressed using meta-connectives then the simplifier cannot prove it automatically in conditional rewriting.

lemma *Finite-RepFun-iff*:
 $(\forall x y. f(x)=f(y) --> x=y) ==> Finite(RepFun(A,f)) <-> Finite(A)$
 <proof>

lemma *Finite-Pow*: $Finite(A) ==> Finite(Pow(A))$
 <proof>

lemma *Finite-Pow-imp-Finite*: $Finite(Pow(A)) ==> Finite(A)$
 <proof>

lemma *Finite-Pow-iff* [iff]: $Finite(Pow(A)) <-> Finite(A)$
 <proof>

lemma *nat-wf-on-converse-Memrel*: $n:nat ==> wf[n](converse(Memrel(n)))$
 <proof>

lemma *nat-well-ord-converse-Memrel*: $n:nat ==> well-ord(n, converse(Memrel(n)))$
 <proof>

lemma *well-ord-converse*:
 $[|well-ord(A,r);$
 $well-ord(ordertype(A,r), converse(Memrel(ordertype(A, r))))|]$
 $==> well-ord(A, converse(r))$
 <proof>

lemma *ordertype-eq-n*:
 $[|well-ord(A,r); A \approx n; n:nat|] ==> ordertype(A,r)=n$
 <proof>

lemma *Finite-well-ord-converse*:
 $[|Finite(A); well-ord(A,r)|] ==> well-ord(A, converse(r))$

$\langle proof \rangle$

lemma *nat-into-Finite*: $n:nat ==> Finite(n)$
 $\langle proof \rangle$

lemma *nat-not-Finite*: $\sim Finite(nat)$
 $\langle proof \rangle$

$\langle ML \rangle$

end

23 Univ: The Cumulative Hierarchy and a Small Universe for Recursive Types

theory *Univ* **imports** *Epsilon Cardinal* **begin**

definition

$Vfrom :: [i,i] => i$ **where**
 $Vfrom(A,i) == transrec(i, \%x f. A \ Un \ (\bigcup y \in x. Pow(f'y)))$

abbreviation

$Vset :: i => i$ **where**
 $Vset(x) == Vfrom(0,x)$

definition

$Vrec :: [i, [i,i] => i] => i$ **where**
 $Vrec(a,H) == transrec(rank(a), \%x g. lam z: Vset(succ(x)).$
 $H(z, lam w: Vset(x). g'rank(w)'w)) ' a$

definition

$Vrecursor :: [[i,i] => i, i] => i$ **where**
 $Vrecursor(H,a) == transrec(rank(a), \%x g. lam z: Vset(succ(x)).$
 $H(lam w: Vset(x). g'rank(w)'w, z)) ' a$

definition

$univ :: i => i$ **where**
 $univ(A) == Vfrom(A,nat)$

23.1 Immediate Consequences of the Definition of $Vfrom(A, i)$

NOT SUITABLE FOR REWRITING – RECURSIVE!

lemma *Vfrom*: $Vfrom(A,i) = A \ Un \ (\bigcup j \in i. Pow(Vfrom(A,j)))$
 $\langle proof \rangle$

23.1.1 Monotonicity

lemma *Vfrom-mono* [rule-format]:

$$A \leq B \implies \forall j. i \leq j \longrightarrow Vfrom(A, i) \leq Vfrom(B, j)$$

<proof>

lemma *VfromI*: $[[a \in Vfrom(A, j); j < i]] \implies a \in Vfrom(A, i)$

<proof>

23.1.2 A fundamental equality: Vfrom does not require ordinals!

lemma *Vfrom-rank-subset1*: $Vfrom(A, x) \leq Vfrom(A, rank(x))$

<proof>

lemma *Vfrom-rank-subset2*: $Vfrom(A, rank(x)) \leq Vfrom(A, x)$

<proof>

lemma *Vfrom-rank-eq*: $Vfrom(A, rank(x)) = Vfrom(A, x)$

<proof>

23.2 Basic Closure Properties

lemma *zero-in-Vfrom*: $y : x \implies 0 \in Vfrom(A, x)$

<proof>

lemma *i-subset-Vfrom*: $i \leq Vfrom(A, i)$

<proof>

lemma *A-subset-Vfrom*: $A \leq Vfrom(A, i)$

<proof>

lemmas *A-into-Vfrom = A-subset-Vfrom* [THEN subsetD]

lemma *subset-mem-Vfrom*: $a \leq Vfrom(A, i) \implies a \in Vfrom(A, succ(i))$

<proof>

23.2.1 Finite sets and ordered pairs

lemma *singleton-in-Vfrom*: $a \in Vfrom(A, i) \implies \{a\} \in Vfrom(A, succ(i))$

<proof>

lemma *doubleton-in-Vfrom*:

$$[[a \in Vfrom(A, i); b \in Vfrom(A, i)]] \implies \{a, b\} \in Vfrom(A, succ(i))$$

<proof>

lemma *Pair-in-Vfrom*:

$$[[a \in Vfrom(A, i); b \in Vfrom(A, i)]] \implies \langle a, b \rangle \in Vfrom(A, succ(succ(i)))$$

<proof>

lemma *succ-in-Vfrom*: $a \leq Vfrom(A, i) \implies succ(a) \in Vfrom(A, succ(succ(i)))$

$\langle proof \rangle$

23.3 0, Successor and Limit Equations for $Vfrom$

lemma *Vfrom-0*: $Vfrom(A, 0) = A$

$\langle proof \rangle$

lemma *Vfrom-succ-lemma*: $Ord(i) ==> Vfrom(A, succ(i)) = A \text{ Un } Pow(Vfrom(A, i))$

$\langle proof \rangle$

lemma *Vfrom-succ*: $Vfrom(A, succ(i)) = A \text{ Un } Pow(Vfrom(A, i))$

$\langle proof \rangle$

lemma *Vfrom-Union*: $y:X ==> Vfrom(A, Union(X)) = (\bigcup y \in X. Vfrom(A, y))$

$\langle proof \rangle$

23.4 $Vfrom$ applied to Limit Ordinals

lemma *Limit-Vfrom-eq*:

$Limit(i) ==> Vfrom(A, i) = (\bigcup y \in i. Vfrom(A, y))$

$\langle proof \rangle$

lemma *Limit-VfromE*:

$[\![a \in Vfrom(A, i); \sim R ==> Limit(i);$
 $!!x. [\![x < i; a \in Vfrom(A, x)]\!] ==> R$
 $\!]\!] ==> R$

$\langle proof \rangle$

lemma *singleton-in-VLimit*:

$[\![a \in Vfrom(A, i); Limit(i)]\!] ==> \{a\} \in Vfrom(A, i)$

$\langle proof \rangle$

lemmas *Vfrom-UnI1* =

Un-upper1 [THEN subset-refl [THEN Vfrom-mono, THEN subsetD], standard]

lemmas *Vfrom-UnI2* =

Un-upper2 [THEN subset-refl [THEN Vfrom-mono, THEN subsetD], standard]

Hard work is finding a single $j:i$ such that $a, b_i = Vfrom(A, j)$

lemma *doubleton-in-VLimit*:

$[\![a \in Vfrom(A, i); b \in Vfrom(A, i); Limit(i)]\!] ==> \{a, b\} \in Vfrom(A, i)$

$\langle proof \rangle$

lemma *Pair-in-VLimit*:

$[\![a \in Vfrom(A, i); b \in Vfrom(A, i); Limit(i)]\!] ==> \langle a, b \rangle \in Vfrom(A, i) \langle proof \rangle$

lemma *product-VLimit*: $Limit(i) ==> Vfrom(A, i) * Vfrom(A, i) \leq Vfrom(A, i)$

$\langle proof \rangle$

lemmas *Sigma-subset-VLimit* =
subset-trans [*OF Sigma-mono product-VLimit*]

lemmas *nat-subset-VLimit* =
subset-trans [*OF nat-le-Limit* [*THEN le-imp-subset*] *i-subset-Vfrom*]

lemma *nat-into-VLimit*: [$n: \text{nat}; \text{Limit}(i)$] $\implies n \in \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

23.4.1 Closure under Disjoint Union

lemmas *zero-in-VLimit* = *Limit-has-0* [*THEN ltD*, *THEN zero-in-Vfrom*, *standard*]

lemma *one-in-VLimit*: $\text{Limit}(i) \implies 1 \in \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemma *Inl-in-VLimit*:
 $[a \in \text{Vfrom}(A, i); \text{Limit}(i)] \implies \text{Inl}(a) \in \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemma *Inr-in-VLimit*:
 $[b \in \text{Vfrom}(A, i); \text{Limit}(i)] \implies \text{Inr}(b) \in \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemma *sum-VLimit*: $\text{Limit}(i) \implies \text{Vfrom}(C, i) + \text{Vfrom}(C, i) \leq \text{Vfrom}(C, i)$
 $\langle \text{proof} \rangle$

lemmas *sum-subset-VLimit* = *subset-trans* [*OF sum-mono sum-VLimit*]

23.5 Properties assuming *Transset*(*A*)

lemma *Transset-Vfrom*: $\text{Transset}(A) \implies \text{Transset}(\text{Vfrom}(A, i))$
 $\langle \text{proof} \rangle$

lemma *Transset-Vfrom-succ*:
 $\text{Transset}(A) \implies \text{Vfrom}(A, \text{succ}(i)) = \text{Pow}(\text{Vfrom}(A, i))$
 $\langle \text{proof} \rangle$

lemma *Transset-Pair-subset*: [$\langle a, b \rangle \leq C; \text{Transset}(C)$] $\implies a: C \ \& \ b: C$
 $\langle \text{proof} \rangle$

lemma *Transset-Pair-subset-VLimit*:
 $[\langle a, b \rangle \leq \text{Vfrom}(A, i); \text{Transset}(A); \text{Limit}(i)]$
 $\implies \langle a, b \rangle \in \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemma *Union-in-Vfrom*:
 $[X \in \text{Vfrom}(A, j); \text{Transset}(A)] \implies \text{Union}(X) \in \text{Vfrom}(A, \text{succ}(j))$
 $\langle \text{proof} \rangle$

lemma *Union-in-VLimit:*

$[[X \in Vfrom(A,i); \text{Limit}(i); \text{Transset}(A)]] \implies Union(X) \in Vfrom(A,i)$
 $\langle proof \rangle$

General theorem for membership in $Vfrom(A,i)$ when i is a limit ordinal

lemma *in-VLimit:*

$[[a \in Vfrom(A,i); b \in Vfrom(A,i); \text{Limit}(i);$
 $!!x y j. [[j < i; 1:j; x \in Vfrom(A,j); y \in Vfrom(A,j)]]$
 $\implies EX k. h(x,y) \in Vfrom(A,k) \ \& \ k < i]]$
 $\implies h(a,b) \in Vfrom(A,i) \langle proof \rangle$

23.5.1 Products

lemma *prod-in-Vfrom:*

$[[a \in Vfrom(A,j); b \in Vfrom(A,j); \text{Transset}(A)]]$
 $\implies a*b \in Vfrom(A, succ(succ(succ(j))))$
 $\langle proof \rangle$

lemma *prod-in-VLimit:*

$[[a \in Vfrom(A,i); b \in Vfrom(A,i); \text{Limit}(i); \text{Transset}(A)]]$
 $\implies a*b \in Vfrom(A,i)$
 $\langle proof \rangle$

23.5.2 Disjoint Sums, or Quine Ordered Pairs

lemma *sum-in-Vfrom:*

$[[a \in Vfrom(A,j); b \in Vfrom(A,j); \text{Transset}(A); 1:j]]$
 $\implies a+b \in Vfrom(A, succ(succ(succ(j))))$
 $\langle proof \rangle$

lemma *sum-in-VLimit:*

$[[a \in Vfrom(A,i); b \in Vfrom(A,i); \text{Limit}(i); \text{Transset}(A)]]$
 $\implies a+b \in Vfrom(A,i)$
 $\langle proof \rangle$

23.5.3 Function Space!

lemma *fun-in-Vfrom:*

$[[a \in Vfrom(A,j); b \in Vfrom(A,j); \text{Transset}(A)]] \implies$
 $a \multimap b \in Vfrom(A, succ(succ(succ(succ(j)))))$
 $\langle proof \rangle$

lemma *fun-in-VLimit:*

$[[a \in Vfrom(A,i); b \in Vfrom(A,i); \text{Limit}(i); \text{Transset}(A)]]$
 $\implies a \multimap b \in Vfrom(A,i)$
 $\langle proof \rangle$

lemma *Pow-in-Vfrom:*

$[[a \in Vfrom(A,j); \text{Transset}(A)]] \implies Pow(a) \in Vfrom(A, succ(succ(j)))$

<proof>

lemma *Pow-in-VLimit*:

$[| a \in Vfrom(A,i); Limit(i); Transset(A) |] ==> Pow(a) \in Vfrom(A,i)$
<proof>

23.6 The Set $Vset(i)$

lemma *Vset*: $Vset(i) = (\bigcup_{j \in i}. Pow(Vset(j)))$
<proof>

lemmas *Vset-succ* = *Transset-0* [*THEN Transset-Vfrom-succ, standard*]

lemmas *Transset-Vset* = *Transset-0* [*THEN Transset-Vfrom, standard*]

23.6.1 Characterisation of the elements of $Vset(i)$

lemma *VsetD* [*rule-format*]: $Ord(i) ==> \forall b. b \in Vset(i) --> rank(b) < i$
<proof>

lemma *VsetI-lemma* [*rule-format*]:
 $Ord(i) ==> \forall b. rank(b) \in i --> b \in Vset(i)$
<proof>

lemma *VsetI*: $rank(x) < i ==> x \in Vset(i)$
<proof>

Merely a lemma for the next result

lemma *Vset-Ord-rank-iff*: $Ord(i) ==> b \in Vset(i) <-> rank(b) < i$
<proof>

lemma *Vset-rank-iff* [*simp*]: $b \in Vset(a) <-> rank(b) < rank(a)$
<proof>

This is $rank(rank(a)) = rank(a)$

declare *Ord-rank* [*THEN rank-of-Ord, simp*]

lemma *rank-Vset*: $Ord(i) ==> rank(Vset(i)) = i$
<proof>

lemma *Finite-Vset*: $i \in nat ==> Finite(Vset(i))$
<proof>

23.6.2 Reasoning about Sets in Terms of Their Elements' Ranks

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

lemma *Int-Vset-subset*:
 $[| !!i. Ord(i) ==> a \text{ Int } Vset(i) \leq b |] ==> a \leq b$
<proof>

23.6.3 Set Up an Environment for Simplification

lemma *rank-Inl*: $\text{rank}(a) < \text{rank}(\text{Inl}(a))$
<proof>

lemma *rank-Inr*: $\text{rank}(a) < \text{rank}(\text{Inr}(a))$
<proof>

lemmas *rank-rls* = *rank-Inl rank-Inr rank-pair1 rank-pair2*

23.6.4 Recursion over Vset Levels!

NOT SUITABLE FOR REWRITING: recursive!

lemma *Vrec*: $\text{Vrec}(a, H) = H(a, \text{lam } x: \text{Vset}(\text{rank}(a)). \text{Vrec}(x, H))$
<proof>

This form avoids giant explosions in proofs. NOTE USE OF ==

lemma *def-Vrec*:
 $[[\text{!!}x. h(x) == \text{Vrec}(x, H)]] ==>$
 $h(a) = H(a, \text{lam } x: \text{Vset}(\text{rank}(a)). h(x))$
<proof>

NOT SUITABLE FOR REWRITING: recursive!

lemma *Vrecursor*:
 $\text{Vrecursor}(H, a) = H(\text{lam } x: \text{Vset}(\text{rank}(a)). \text{Vrecursor}(H, x), a)$
<proof>

This form avoids giant explosions in proofs. NOTE USE OF ==

lemma *def-Vrecursor*:
 $h == \text{Vrecursor}(H) ==> h(a) = H(\text{lam } x: \text{Vset}(\text{rank}(a)). h(x), a)$
<proof>

23.7 The Datatype Universe: *univ*(A)

lemma *univ-mono*: $A \leq B ==> \text{univ}(A) \leq \text{univ}(B)$
<proof>

lemma *Transset-univ*: $\text{Transset}(A) ==> \text{Transset}(\text{univ}(A))$
<proof>

23.7.1 The Set *univ*(A) as a Limit

lemma *univ-eq-UN*: $\text{univ}(A) = (\bigcup i \in \text{nat}. \text{Vfrom}(A, i))$
<proof>

lemma *subset-univ-eq-Int*: $c \leq \text{univ}(A) ==> c = (\bigcup i \in \text{nat}. c \text{ Int } \text{Vfrom}(A, i))$
<proof>

lemma *univ-Int-Vfrom-subset*:

$$\begin{aligned} & [| a \leq \text{univ}(X); \\ & \quad !!i. i:\text{nat} ==> a \text{ Int } V\text{from}(X,i) \leq b |] \\ & ==> a \leq b \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *univ-Int-Vfrom-eq*:

$$\begin{aligned} & [| a \leq \text{univ}(X); \quad b \leq \text{univ}(X); \\ & \quad !!i. i:\text{nat} ==> a \text{ Int } V\text{from}(X,i) = b \text{ Int } V\text{from}(X,i) \\ & |] ==> a = b \\ & \langle \text{proof} \rangle \end{aligned}$$

23.8 Closure Properties for $\text{univ}(A)$

lemma *zero-in-univ*: $0 \in \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemma *zero-subset-univ*: $\{0\} \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemma *A-subset-univ*: $A \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemmas *A-into-univ* = *A-subset-univ* [*THEN subsetD, standard*]

23.8.1 Closure under Unordered and Ordered Pairs

lemma *singleton-in-univ*: $a: \text{univ}(A) ==> \{a\} \in \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemma *doubleton-in-univ*:

$$[| a: \text{univ}(A); \quad b: \text{univ}(A) |] ==> \{a,b\} \in \text{univ}(A)$$
 $\langle \text{proof} \rangle$

lemma *Pair-in-univ*:

$$[| a: \text{univ}(A); \quad b: \text{univ}(A) |] ==> \langle a,b \rangle \in \text{univ}(A)$$
 $\langle \text{proof} \rangle$

lemma *Union-in-univ*:

$$[| X: \text{univ}(A); \quad \text{Transset}(A) |] ==> \text{Union}(X) \in \text{univ}(A)$$
 $\langle \text{proof} \rangle$

lemma *product-univ*: $\text{univ}(A) * \text{univ}(A) \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

23.8.2 The Natural Numbers

lemma *nat-subset-univ*: $\text{nat} \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

$\text{n:nat} ==_i \text{n:univ}(A)$

lemmas *nat-into-univ* = *nat-subset-univ* [*THEN subsetD, standard*]

23.8.3 Instances for 1 and 2

lemma *one-in-univ*: $1 \in \text{univ}(A)$
 $\langle \text{proof} \rangle$

unused!

lemma *two-in-univ*: $2 \in \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemma *bool-subset-univ*: $\text{bool} \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemmas *bool-into-univ* = *bool-subset-univ* [*THEN subsetD, standard*]

23.8.4 Closure under Disjoint Union

lemma *Inl-in-univ*: $a: \text{univ}(A) \implies \text{Inl}(a) \in \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemma *Inr-in-univ*: $b: \text{univ}(A) \implies \text{Inr}(b) \in \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemma *sum-univ*: $\text{univ}(C) + \text{univ}(C) \leq \text{univ}(C)$
 $\langle \text{proof} \rangle$

lemmas *sum-subset-univ* = *subset-trans* [*OF sum-mono sum-univ*]

lemma *Sigma-subset-univ*:
 $[[A \subseteq \text{univ}(D); \bigwedge x. x \in A \implies B(x) \subseteq \text{univ}(D)]] \implies \text{Sigma}(A, B) \subseteq \text{univ}(D)$
 $\langle \text{proof} \rangle$

23.9 Finite Branching Closure Properties

23.9.1 Closure under Finite Powerset

lemma *Fin-Vfrom-lemma*:
 $[[b: \text{Fin}(\text{Vfrom}(A, i)); \text{Limit}(i)]] \implies \exists j. b \leq \text{Vfrom}(A, j) \ \& \ j < i$
 $\langle \text{proof} \rangle$

lemma *Fin-VLimit*: $\text{Limit}(i) \implies \text{Fin}(\text{Vfrom}(A, i)) \leq \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemmas *Fin-subset-VLimit* = *subset-trans* [*OF Fin-mono Fin-VLimit*]

lemma *Fin-univ*: $\text{Fin}(\text{univ}(A)) \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

23.9.2 Closure under Finite Powers: Functions from a Natural Number

lemma *nat-fun-VLimit*:

$[[n: \text{nat}; \text{Limit}(i)]] \implies n \rightarrow \text{Vfrom}(A, i) \leq \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemmas *nat-fun-subset-VLimit* = *subset-trans* [OF *Pi-mono nat-fun-VLimit*]

lemma *nat-fun-univ*: $n: \text{nat} \implies n \rightarrow \text{univ}(A) \leq \text{univ}(A)$

$\langle \text{proof} \rangle$

23.9.3 Closure under Finite Function Space

General but seldom-used version; normally the domain is fixed

lemma *FiniteFun-VLimit1*:

$\text{Limit}(i) \implies \text{Vfrom}(A, i) -||> \text{Vfrom}(A, i) \leq \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemma *FiniteFun-univ1*: $\text{univ}(A) -||> \text{univ}(A) \leq \text{univ}(A)$

$\langle \text{proof} \rangle$

Version for a fixed domain

lemma *FiniteFun-VLimit*:

$[[W \leq \text{Vfrom}(A, i); \text{Limit}(i)]] \implies W -||> \text{Vfrom}(A, i) \leq \text{Vfrom}(A, i)$
 $\langle \text{proof} \rangle$

lemma *FiniteFun-univ*:

$W \leq \text{univ}(A) \implies W -||> \text{univ}(A) \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemma *FiniteFun-in-univ*:

$[[f: W -||> \text{univ}(A); W \leq \text{univ}(A)]] \implies f \in \text{univ}(A)$
 $\langle \text{proof} \rangle$

Remove $\text{!} =$ from the rule above

lemmas *FiniteFun-in-univ'* = *FiniteFun-in-univ* [OF - *subsetI*]

23.10 * For QUniv. Properties of Vfrom analogous to the "take-lemma" *

Intersecting $a*b$ with $\text{Vfrom}...$

This version says a, b exist one level down, in the smaller set $\text{Vfrom}(X, i)$

lemma *doubleton-in-Vfrom-D*:

$[[\{a, b\} \in \text{Vfrom}(X, \text{succ}(i)); \text{Transset}(X)]] \implies a \in \text{Vfrom}(X, i) \ \& \ b \in \text{Vfrom}(X, i)$
 $\langle \text{proof} \rangle$

This weaker version says a, b exist at the same level

lemmas *Vfrom-doubleton-D = Transset-Vfrom [THEN Transset-doubleton-D, standard]*

lemma *Pair-in-Vfrom-D:*

$$[| <a,b> \in Vfrom(X, succ(i)); Transset(X) |]$$

$$\implies a \in Vfrom(X, i) \ \& \ b \in Vfrom(X, i)$$

$$\langle proof \rangle$$

lemma *product-Int-Vfrom-subset:*

$$Transset(X) \implies$$

$$(a*b) \text{ Int } Vfrom(X, succ(i)) \leq (a \text{ Int } Vfrom(X, i)) * (b \text{ Int } Vfrom(X, i))$$

$$\langle proof \rangle$$

$\langle ML \rangle$

end

24 QUniv: A Small Universe for Lazy Recursive Types

theory *QUniv imports Univ QPair begin*

rep-datatype

elimination *sumE*
induction *TrueI*
case-eqns *case-Inl case-Inr*

rep-datatype

elimination *qsumE*
induction *TrueI*
case-eqns *qcase-QInl qcase-QInr*

definition

quniv :: *i* => *i* **where**
quniv(*A*) == *Pow*(*univ*(*eclose*(*A*)))

24.1 Properties involving Transset and Sum

lemma *Transset-includes-summands:*

$$[| Transset(C); A+B \leq C |] \implies A \leq C \ \& \ B \leq C$$

$$\langle proof \rangle$$

lemma *Transset-sum-Int-subset*:

$\text{Transset}(C) \implies (A+B) \text{ Int } C \leq (A \text{ Int } C) + (B \text{ Int } C)$
 $\langle \text{proof} \rangle$

24.2 Introduction and Elimination Rules

lemma *qunivI*: $X \leq \text{univ}(\text{eclose}(A)) \implies X : \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemma *qunivD*: $X : \text{quniv}(A) \implies X \leq \text{univ}(\text{eclose}(A))$
 $\langle \text{proof} \rangle$

lemma *quniv-mono*: $A \leq B \implies \text{quniv}(A) \leq \text{quniv}(B)$
 $\langle \text{proof} \rangle$

24.3 Closure Properties

lemma *univ-eclose-subset-quniv*: $\text{univ}(\text{eclose}(A)) \leq \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemma *univ-subset-quniv*: $\text{univ}(A) \leq \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemmas *univ-into-quniv* = *univ-subset-quniv* [THEN subsetD, standard]

lemma *Pow-univ-subset-quniv*: $\text{Pow}(\text{univ}(A)) \leq \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemmas *univ-subset-into-quniv* =
PowI [THEN *Pow-univ-subset-quniv* [THEN subsetD], standard]

lemmas *zero-in-quniv* = *zero-in-univ* [THEN *univ-into-quniv*, standard]

lemmas *one-in-quniv* = *one-in-univ* [THEN *univ-into-quniv*, standard]

lemmas *two-in-quniv* = *two-in-univ* [THEN *univ-into-quniv*, standard]

lemmas *A-subset-quniv* = *subset-trans* [OF *A-subset-univ univ-subset-quniv*]

lemmas *A-into-quniv* = *A-subset-quniv* [THEN subsetD, standard]

lemma *QPair-subset-univ*:

$[| a \leq \text{univ}(A); b \leq \text{univ}(A) |] \implies \langle a; b \rangle \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

24.4 Quine Disjoint Sum

lemma *QInl-subset-univ*: $a \leq \text{univ}(A) \implies \text{QInl}(a) \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

lemmas *naturals-subset-nat* =
Ord-nat [*THEN Ord-is-Transset, unfolded Transset-def, THEN bspec, standard*]

lemmas *naturals-subset-univ* =
subset-trans [*OF naturals-subset-nat nat-subset-univ*]

lemma *QInr-subset-univ*: $a \leq \text{univ}(A) \implies \text{QInr}(a) \leq \text{univ}(A)$
 $\langle \text{proof} \rangle$

24.5 Closure for Quine-Inspired Products and Sums

lemma *QPair-in-quniv*:
 $[a : \text{quniv}(A); b : \text{quniv}(A)] \implies \langle a; b \rangle : \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemma *QSigma-quniv*: $\text{quniv}(A) \lt * \text{quniv}(A) \leq \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemmas *QSigma-subset-quniv* = *subset-trans* [*OF QSigma-mono QSigma-quniv*]

lemma *quniv-QPair-D*:
 $\langle a; b \rangle : \text{quniv}(A) \implies a : \text{quniv}(A) \ \& \ b : \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemmas *quniv-QPair-E* = *quniv-QPair-D* [*THEN conjE, standard*]

lemma *quniv-QPair-iff*: $\langle a; b \rangle : \text{quniv}(A) \iff a : \text{quniv}(A) \ \& \ b : \text{quniv}(A)$
 $\langle \text{proof} \rangle$

24.6 Quine Disjoint Sum

lemma *QInl-in-quniv*: $a : \text{quniv}(A) \implies \text{QInl}(a) : \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemma *QInr-in-quniv*: $b : \text{quniv}(A) \implies \text{QInr}(b) : \text{quniv}(A)$
 $\langle \text{proof} \rangle$

lemma *qsum-quniv*: $\text{quniv}(C) \lt + \text{quniv}(C) \leq \text{quniv}(C)$
 $\langle \text{proof} \rangle$

lemmas *qsum-subset-quniv* = *subset-trans* [*OF qsum-mono qsum-quniv*]

24.7 The Natural Numbers

lemmas *nat-subset-quniv* = *subset-trans* [*OF nat-subset-univ univ-subset-quniv*]

lemmas *nat-into-quniv* = *nat-subset-quniv* [*THEN subsetD, standard*]

lemmas *bool-subset-quniv* = *subset-trans* [*OF bool-subset-univ univ-subset-quniv*]

lemmas *bool-into-quniv* = *bool-subset-quniv* [*THEN subsetD, standard*]

lemma *QPair-Int-Vfrom-succ-subset*:

Transset(*X*) ==>
 $\langle a; b \rangle \text{ Int } V\text{from}(X, \text{succ}(i)) \leq \langle a \text{ Int } V\text{from}(X, i); b \text{ Int } V\text{from}(X, i) \rangle$
 <proof>

24.8 "Take-Lemma" Rules

lemma *QPair-Int-Vfrom-subset*:

Transset(*X*) ==>
 $\langle a; b \rangle \text{ Int } V\text{from}(X, i) \leq \langle a \text{ Int } V\text{from}(X, i); b \text{ Int } V\text{from}(X, i) \rangle$
 <proof>

lemmas *QPair-Int-Vset-subset-trans* =

subset-trans [*OF Transset-0* [*THEN QPair-Int-Vfrom-subset*] *QPair-mono*]

lemma *QPair-Int-Vset-subset-UN*:

Ord(*i*) ==> $\langle a; b \rangle \text{ Int } V\text{set}(i) \leq (\bigcup_{j \in i}. \langle a \text{ Int } V\text{set}(j); b \text{ Int } V\text{set}(j) \rangle)$
 <proof>

end

25 Datatype-ZF: Datatype and CoDatatype Definitions

theory *Datatype-ZF*

imports *Inductive-ZF Univ QUniv*

uses *Tools/datatype-package.ML*

begin

<ML>

end

definition

raw-mod :: $[i, i] \Rightarrow i$ **where**
raw-mod (*m*, *n*) ==
transrec(*m*, %*j* *f*. if *j* < *n* | *n* = 0 then *j* else *f* (*j* # - *n*))

definition

div :: $[i, i] \Rightarrow i$ (**infixl** *div* 70) **where**
m div n == *raw-div* (*natify*(*m*), *natify*(*n*))

definition

mod :: $[i, i] \Rightarrow i$ (**infixl** *mod* 70) **where**
m mod n == *raw-mod* (*natify*(*m*), *natify*(*n*))

notation (*xsymbols*)

mult (**infixr** # × 70)

notation (*HTML output*)

mult (**infixr** # × 70)

declare *rec-type* [*simp*]

nat-0-le [*simp*]

lemma *zero-lt-lemma*: $[0 < k; k \in \text{nat}] \Rightarrow \exists j \in \text{nat}. k = \text{succ}(j)$
 <proof>

lemmas *zero-lt-natE* = *zero-lt-lemma* [*THEN* *bexE*, *standard*]

26.1 natify, the Coercion to nat

lemma *pred-succ-eq* [*simp*]: *pred*(*succ*(*y*)) = *y*
 <proof>

lemma *natify-succ*: *natify*(*succ*(*x*)) = *succ*(*natify*(*x*))
 <proof>

lemma *natify-0* [*simp*]: *natify*(0) = 0
 <proof>

lemma *natify-non-succ*: $\forall z. x \sim = \text{succ}(z) \Rightarrow \text{natify}(x) = 0$
 <proof>

lemma *natify-in-nat* [*iff*, *TC*]: *natify*(*x*) ∈ *nat*
 <proof>

lemma *natify-ident* [*simp*]: *n* ∈ *nat* $\Rightarrow \text{natify}(n) = n$
 <proof>

lemma *natify-eqE*: $[|natify(x) = y; x \in nat|] ==> x=y$
 $\langle proof \rangle$

lemma *natify-idem* [simp]: $natify(natify(x)) = natify(x)$
 $\langle proof \rangle$

lemma *add-natify1* [simp]: $natify(m) \# + n = m \# + n$
 $\langle proof \rangle$

lemma *add-natify2* [simp]: $m \# + natify(n) = m \# + n$
 $\langle proof \rangle$

lemma *mult-natify1* [simp]: $natify(m) \# * n = m \# * n$
 $\langle proof \rangle$

lemma *mult-natify2* [simp]: $m \# * natify(n) = m \# * n$
 $\langle proof \rangle$

lemma *diff-natify1* [simp]: $natify(m) \# - n = m \# - n$
 $\langle proof \rangle$

lemma *diff-natify2* [simp]: $m \# - natify(n) = m \# - n$
 $\langle proof \rangle$

lemma *mod-natify1* [simp]: $natify(m) \bmod n = m \bmod n$
 $\langle proof \rangle$

lemma *mod-natify2* [simp]: $m \bmod natify(n) = m \bmod n$
 $\langle proof \rangle$

lemma *div-natify1* [simp]: $natify(m) \bmod n = m \bmod n$
 $\langle proof \rangle$

lemma *div-natify2* [simp]: $m \bmod natify(n) = m \bmod n$

$\langle proof \rangle$

26.2 Typing rules

lemma *raw-add-type*: $[| m \in nat; n \in nat |] ==> raw-add (m, n) \in nat$
 $\langle proof \rangle$

lemma *add-type* [*iff*, *TC*]: $m \# + n \in nat$
 $\langle proof \rangle$

lemma *raw-mult-type*: $[| m \in nat; n \in nat |] ==> raw-mult (m, n) \in nat$
 $\langle proof \rangle$

lemma *mult-type* [*iff*, *TC*]: $m \# * n \in nat$
 $\langle proof \rangle$

lemma *raw-diff-type*: $[| m \in nat; n \in nat |] ==> raw-diff (m, n) \in nat$
 $\langle proof \rangle$

lemma *diff-type* [*iff*, *TC*]: $m \# - n \in nat$
 $\langle proof \rangle$

lemma *diff-0-eq-0* [*simp*]: $0 \# - n = 0$
 $\langle proof \rangle$

lemma *diff-succ-succ* [*simp*]: $succ(m) \# - succ(n) = m \# - n$
 $\langle proof \rangle$

declare *raw-diff-succ* [*simp del*]

lemma *diff-0* [*simp*]: $m \# - 0 = natify(m)$
 $\langle proof \rangle$

lemma *diff-le-self*: $m \in nat ==> (m \# - n) \leq m$
 $\langle proof \rangle$

26.3 Addition

lemma *add-0-natify* [*simp*]: $0 \# + m = natify(m)$
 $\langle proof \rangle$

lemma *add-succ* [*simp*]: $succ(m) \# + n = succ(m \# + n)$

$\langle proof \rangle$

lemma *add-0*: $m \in nat \implies 0 \# + m = m$
 $\langle proof \rangle$

lemma *add-assoc*: $(m \# + n) \# + k = m \# + (n \# + k)$
 $\langle proof \rangle$

lemma *add-0-right-natify* [*simp*]: $m \# + 0 = natify(m)$
 $\langle proof \rangle$

lemma *add-succ-right* [*simp*]: $m \# + succ(n) = succ(m \# + n)$
 $\langle proof \rangle$

lemma *add-0-right*: $m \in nat \implies m \# + 0 = m$
 $\langle proof \rangle$

lemma *add-commute*: $m \# + n = n \# + m$
 $\langle proof \rangle$

lemma *add-left-commute*: $m \# + (n \# + k) = n \# + (m \# + k)$
 $\langle proof \rangle$

lemmas *add-ac* = *add-assoc add-commute add-left-commute*

lemma *raw-add-left-cancel*:
[$raw-add(k, m) = raw-add(k, n); k \in nat$] $\implies m = n$
 $\langle proof \rangle$

lemma *add-left-cancel-natify*: $k \# + m = k \# + n \implies natify(m) = natify(n)$
 $\langle proof \rangle$

lemma *add-left-cancel*:
[$i = j; i \# + m = j \# + n; m \in nat; n \in nat$] $\implies m = n$
 $\langle proof \rangle$

lemma *add-le-elim1-natify*: $k \# + m \leq k \# + n \implies natify(m) \leq natify(n)$
 $\langle proof \rangle$

lemma *add-le-elim1*: [$k \# + m \leq k \# + n; m \in nat; n \in nat$] $\implies m \leq n$
 $\langle proof \rangle$

lemma *add-lt-elim1-natify*: $k\# + m < k\# + n \implies \text{natify}(m) < \text{natify}(n)$
 $\langle \text{proof} \rangle$

lemma *add-lt-elim1*: $[k\# + m < k\# + n; m \in \text{nat}; n \in \text{nat}] \implies m < n$
 $\langle \text{proof} \rangle$

lemma *zero-less-add*: $[n \in \text{nat}; m \in \text{nat}] \implies 0 < m \# + n \iff (0 < m \mid 0 < n)$
 $\langle \text{proof} \rangle$

26.4 Monotonicity of Addition

lemma *add-lt-mono1*: $[i < j; j \in \text{nat}] \implies i\# + k < j\# + k$
 $\langle \text{proof} \rangle$

strict, in second argument

lemma *add-lt-mono2*: $[i < j; j \in \text{nat}] \implies k\# + i < k\# + j$
 $\langle \text{proof} \rangle$

A [clumsy] way of lifting $\#$ monotonicity to \leq monotonicity

lemma *Ord-lt-mono-imp-le-mono*:
assumes *lt-mono*: $\forall i j. [i < j; j \in \text{nat}] \implies f(i) < f(j)$
and ford: $\forall i. i \in \text{nat} \implies \text{Ord}(f(i))$
and leij: $i \leq j$
and jink: $j \in \text{nat}$
shows $f(i) \leq f(j)$
 $\langle \text{proof} \rangle$

\leq monotonicity, 1st argument

lemma *add-le-mono1*: $[i \leq j; j \in \text{nat}] \implies i\# + k \leq j\# + k$
 $\langle \text{proof} \rangle$

\leq monotonicity, both arguments

lemma *add-le-mono*: $[i \leq j; k \leq l; j \in \text{nat}; l \in \text{nat}] \implies i\# + k \leq j\# + l$
 $\langle \text{proof} \rangle$

Combinations of less-than and less-than-or-equals

lemma *add-lt-le-mono*: $[i < j; k \leq l; j \in \text{nat}; l \in \text{nat}] \implies i\# + k < j\# + l$
 $\langle \text{proof} \rangle$

lemma *add-le-lt-mono*: $[i \leq j; k < l; j \in \text{nat}; l \in \text{nat}] \implies i\# + k < j\# + l$
 $\langle \text{proof} \rangle$

Less-than: in other words, strict in both arguments

lemma *add-lt-mono*: $[i < j; k < l; j \in \text{nat}; l \in \text{nat}] \implies i\# + k < j\# + l$
 $\langle \text{proof} \rangle$

lemma *diff-add-inverse*: $(n \# + m) \# - n = \text{natify}(m)$
 $\langle \text{proof} \rangle$

lemma *diff-add-inverse2*: $(m \# + n) \# - n = \text{natify}(m)$
 $\langle \text{proof} \rangle$

lemma *diff-cancel*: $(k \# + m) \# - (k \# + n) = m \# - n$
 $\langle \text{proof} \rangle$

lemma *diff-cancel2*: $(m \# + k) \# - (n \# + k) = m \# - n$
 $\langle \text{proof} \rangle$

lemma *diff-add-0*: $n \# - (n \# + m) = 0$
 $\langle \text{proof} \rangle$

lemma *pred-0* [*simp*]: $\text{pred}(0) = 0$
 $\langle \text{proof} \rangle$

lemma *eq-succ-imp-eq-m1*: $[[i = \text{succ}(j); i \in \text{nat}]] \implies j = i \# - 1 \ \& \ j \in \text{nat}$
 $\langle \text{proof} \rangle$

lemma *pred-Un-distrib*:
 $[[i \in \text{nat}; j \in \text{nat}]] \implies \text{pred}(i \text{ Un } j) = \text{pred}(i) \text{ Un } \text{pred}(j)$
 $\langle \text{proof} \rangle$

lemma *pred-type* [*TC, simp*]:
 $i \in \text{nat} \implies \text{pred}(i) \in \text{nat}$
 $\langle \text{proof} \rangle$

lemma *nat-diff-pred*: $[[i \in \text{nat}; j \in \text{nat}]] \implies i \# - \text{succ}(j) = \text{pred}(i \# - j)$
 $\langle \text{proof} \rangle$

lemma *diff-succ-eq-pred*: $i \# - \text{succ}(j) = \text{pred}(i \# - j)$
 $\langle \text{proof} \rangle$

lemma *nat-diff-Un-distrib*:
 $[[i \in \text{nat}; j \in \text{nat}; k \in \text{nat}]] \implies (i \text{ Un } j) \# - k = (i \# - k) \text{ Un } (j \# - k)$
 $\langle \text{proof} \rangle$

lemma *diff-Un-distrib*:
 $[[i \in \text{nat}; j \in \text{nat}]] \implies (i \text{ Un } j) \# - k = (i \# - k) \text{ Un } (j \# - k)$
 $\langle \text{proof} \rangle$

We actually prove $i \# - j \# - k = i \# - (j \# + k)$

lemma *diff-diff-left* [*simplified*]:
 $\text{natify}(i) \# - \text{natify}(j) \# - k = \text{natify}(i) \# - (\text{natify}(j) \# + k)$
 $\langle \text{proof} \rangle$

lemma *eq-add-iff*: $(u \# + m = u \# + n) <-> (0 \# + m = \text{nativify}(n))$
 $\langle \text{proof} \rangle$

lemma *less-add-iff*: $(u \# + m < u \# + n) <-> (0 \# + m < \text{nativify}(n))$
 $\langle \text{proof} \rangle$

lemma *diff-add-eq*: $((u \# + m) \# - (u \# + n)) = ((0 \# + m) \# - n)$
 $\langle \text{proof} \rangle$

lemma *eq-cong2*: $u = u' ==> (t == u) == (t == u')$
 $\langle \text{proof} \rangle$

lemma *iff-cong2*: $u <-> u' ==> (t == u) == (t == u')$
 $\langle \text{proof} \rangle$

26.5 Multiplication

lemma *mult-0* [*simp*]: $0 \# * m = 0$
 $\langle \text{proof} \rangle$

lemma *mult-succ* [*simp*]: $\text{succ}(m) \# * n = n \# + (m \# * n)$
 $\langle \text{proof} \rangle$

lemma *mult-0-right* [*simp*]: $m \# * 0 = 0$
 $\langle \text{proof} \rangle$

lemma *mult-succ-right* [*simp*]: $m \# * \text{succ}(n) = m \# + (m \# * n)$
 $\langle \text{proof} \rangle$

lemma *mult-1-nativify* [*simp*]: $1 \# * n = \text{nativify}(n)$
 $\langle \text{proof} \rangle$

lemma *mult-1-right-nativify* [*simp*]: $n \# * 1 = \text{nativify}(n)$
 $\langle \text{proof} \rangle$

lemma *mult-1*: $n \in \text{nat} ==> 1 \# * n = n$
 $\langle \text{proof} \rangle$

lemma *mult-1-right*: $n \in \text{nat} ==> n \# * 1 = n$
 $\langle \text{proof} \rangle$

lemma *mult-commute*: $m \# * n = n \# * m$

$\langle proof \rangle$

lemma *add-mult-distrib*: $(m \# + n) \# * k = (m \# * k) \# + (n \# * k)$
 $\langle proof \rangle$

lemma *add-mult-distrib-left*: $k \# * (m \# + n) = (k \# * m) \# + (k \# * n)$
 $\langle proof \rangle$

lemma *mult-assoc*: $(m \# * n) \# * k = m \# * (n \# * k)$
 $\langle proof \rangle$

lemma *mult-left-commute*: $m \# * (n \# * k) = n \# * (m \# * k)$
 $\langle proof \rangle$

lemmas *mult-ac = mult-assoc mult-commute mult-left-commute*

lemma *lt-succ-eq-0-disj*:
[[$m \in nat$; $n \in nat$]]
==> $(m < succ(n)) <-> (m = 0 \mid (\exists j \in nat. m = succ(j) \ \& \ j < n))$
 $\langle proof \rangle$

lemma *less-diff-conv* [rule-format]:
[[$j \in nat$; $k \in nat$]] ==> $\forall i \in nat. (i < j \# - k) <-> (i \# + k < j)$
 $\langle proof \rangle$

lemmas *nat-typechecks = rec-type nat-0I nat-1I nat-succI Ord-nat*

end

27 ArithSimp: Arithmetic with simplification

theory *ArithSimp*
imports *Arith*
uses $\sim \sim /src/Provers/Arith/cancel-numerals.ML$
 $\sim \sim /src/Provers/Arith/combine-numerals.ML$
arith-data.ML
begin

27.1 Difference

lemma *diff-self-eq-0* [simp]: $m \# - m = 0$
 $\langle proof \rangle$

lemma *add-diff-inverse*: $[| n \text{ le } m; m:\text{nat} |] ==> n \# + (m \# - n) = m$
 $\langle \text{proof} \rangle$

lemma *add-diff-inverse2*: $[| n \text{ le } m; m:\text{nat} |] ==> (m \# - n) \# + n = m$
 $\langle \text{proof} \rangle$

lemma *diff-succ*: $[| n \text{ le } m; m:\text{nat} |] ==> \text{succ}(m) \# - n = \text{succ}(m \# - n)$
 $\langle \text{proof} \rangle$

lemma *zero-less-diff* [*simp*]:
 $[| m:\text{nat}; n:\text{nat} |] ==> 0 < (n \# - m) \quad <-> \quad m < n$
 $\langle \text{proof} \rangle$

lemma *diff-mult-distrib*: $(m \# - n) \# * k = (m \# * k) \# - (n \# * k)$
 $\langle \text{proof} \rangle$

lemma *diff-mult-distrib2*: $k \# * (m \# - n) = (k \# * m) \# - (k \# * n)$
 $\langle \text{proof} \rangle$

27.2 Remainder

lemma *div-termination*: $[| 0 < n; n \text{ le } m; m:\text{nat} |] ==> m \# - n < m$
 $\langle \text{proof} \rangle$

lemmas *div-rls* =
nat-typechecks *Ord-transrec-type* *apply-funtype*
div-termination [*THEN ltD*]
nat-into-Ord *not-lt-iff-le* [*THEN iffD1*]

lemma *raw-mod-type*: $[| m:\text{nat}; n:\text{nat} |] ==> \text{raw-mod } (m, n) : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *mod-type* [*TC,iff*]: $m \text{ mod } n : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *DIVISION-BY-ZERO-DIV*: $a \text{ div } 0 = 0$
 $\langle \text{proof} \rangle$

lemma *DIVISION-BY-ZERO-MOD*: $a \text{ mod } 0 = \text{nativify}(a)$
 $\langle \text{proof} \rangle$

lemma *raw-mod-less*: $m < n \implies \text{raw-mod } (m, n) = m$
 $\langle \text{proof} \rangle$

lemma *mod-less* [simp]: $[| m < n; n : \text{nat} |] \implies m \text{ mod } n = m$
 $\langle \text{proof} \rangle$

lemma *raw-mod-geq*:
 $[| 0 < n; n \leq m; m : \text{nat} |] \implies \text{raw-mod } (m, n) = \text{raw-mod } (m \# -n, n)$
 $\langle \text{proof} \rangle$

lemma *mod-geq*: $[| n \leq m; m : \text{nat} |] \implies m \text{ mod } n = (m \# -n) \text{ mod } n$
 $\langle \text{proof} \rangle$

27.3 Division

lemma *raw-div-type*: $[| m : \text{nat}; n : \text{nat} |] \implies \text{raw-div } (m, n) : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *div-type* [TC, iff]: $m \text{ div } n : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *raw-div-less*: $m < n \implies \text{raw-div } (m, n) = 0$
 $\langle \text{proof} \rangle$

lemma *div-less* [simp]: $[| m < n; n : \text{nat} |] \implies m \text{ div } n = 0$
 $\langle \text{proof} \rangle$

lemma *raw-div-geq*: $[| 0 < n; n \leq m; m : \text{nat} |] \implies \text{raw-div}(m, n) = \text{succ}(\text{raw-div}(m \# -n, n))$
 $\langle \text{proof} \rangle$

lemma *div-geq* [simp]:
 $[| 0 < n; n \leq m; m : \text{nat} |] \implies m \text{ div } n = \text{succ } ((m \# -n) \text{ div } n)$
 $\langle \text{proof} \rangle$

declare *div-less* [simp] *div-geq* [simp]

lemma *mod-div-lemma*: $[| m : \text{nat}; n : \text{nat} |] \implies (m \text{ div } n) \# * n \# + m \text{ mod } n = m$
 $\langle \text{proof} \rangle$

lemma *mod-div-equality-nativify*: $(m \text{ div } n) \# * n \# + m \text{ mod } n = \text{nativify}(m)$
 $\langle \text{proof} \rangle$

lemma *mod-div-equality*: $m: \text{nat} \implies (m \text{ div } n) \# * n \# + m \text{ mod } n = m$
 $\langle \text{proof} \rangle$

27.4 Further Facts about Remainder

(mainly for mutilated chess board)

lemma *mod-succ-lemma*:
 $[[\ 0 < n; \ m: \text{nat}; \ n: \text{nat} \]]$
 $\implies \text{succ}(m) \text{ mod } n = (\text{if } \text{succ}(m \text{ mod } n) = n \text{ then } 0 \text{ else } \text{succ}(m \text{ mod } n))$
 $\langle \text{proof} \rangle$

lemma *mod-succ*:
 $n: \text{nat} \implies \text{succ}(m) \text{ mod } n = (\text{if } \text{succ}(m \text{ mod } n) = n \text{ then } 0 \text{ else } \text{succ}(m \text{ mod } n))$
 $\langle \text{proof} \rangle$

lemma *mod-less-divisor*: $[[\ 0 < n; \ n: \text{nat} \]]$ $\implies m \text{ mod } n < n$
 $\langle \text{proof} \rangle$

lemma *mod-1-eq* [simp]: $m \text{ mod } 1 = 0$
 $\langle \text{proof} \rangle$

lemma *mod2-cases*: $b < 2 \implies k \text{ mod } 2 = b \mid k \text{ mod } 2 = (\text{if } b=1 \text{ then } 0 \text{ else } 1)$
 $\langle \text{proof} \rangle$

lemma *mod2-succ-succ* [simp]: $\text{succ}(\text{succ}(m)) \text{ mod } 2 = m \text{ mod } 2$
 $\langle \text{proof} \rangle$

lemma *mod2-add-more* [simp]: $(m \# + m \# + n) \text{ mod } 2 = n \text{ mod } 2$
 $\langle \text{proof} \rangle$

lemma *mod2-add-self* [simp]: $(m \# + m) \text{ mod } 2 = 0$
 $\langle \text{proof} \rangle$

27.5 Additional theorems about \leq

lemma *add-le-self*: $m: \text{nat} \implies m \text{ le } (m \# + n)$
 $\langle \text{proof} \rangle$

lemma *add-le-self2*: $m: \text{nat} \implies m \text{ le } (n \# + m)$
 $\langle \text{proof} \rangle$

lemma *mult-le-mono1*: $[[\ i \text{ le } j; \ j: \text{nat} \]]$ $\implies (i \# * k) \text{ le } (j \# * k)$
 $\langle \text{proof} \rangle$

lemma *mult-le-mono*: $[[\ i \text{ le } j; \ k \text{ le } l; \ j: \text{nat}; \ l: \text{nat} \]]$ $\implies i \# * k \text{ le } j \# * l$

$\langle proof \rangle$

lemma *mult-lt-mono2*: $[| i < j; 0 < k; j : nat; k : nat |] ==> k \#* i < k \#* j$
 $\langle proof \rangle$

lemma *mult-lt-mono1*: $[| i < j; 0 < k; j : nat; k : nat |] ==> i \#* k < j \#* k$
 $\langle proof \rangle$

lemma *add-eq-0-iff* [iff]: $m \# + n = 0 <-> natify(m)=0 \ \& \ natify(n)=0$
 $\langle proof \rangle$

lemma *zero-lt-mult-iff* [iff]: $0 < m \#* n <-> 0 < natify(m) \ \& \ 0 < natify(n)$
 $\langle proof \rangle$

lemma *mult-eq-1-iff* [iff]: $m \#* n = 1 <-> natify(m)=1 \ \& \ natify(n)=1$
 $\langle proof \rangle$

lemma *mult-is-zero*: $[| m : nat; n : nat |] ==> (m \#* n = 0) <-> (m = 0 \mid n = 0)$
 $\langle proof \rangle$

lemma *mult-is-zero-natify* [iff]:
 $(m \#* n = 0) <-> (natify(m) = 0 \mid natify(n) = 0)$
 $\langle proof \rangle$

27.6 Cancellation Laws for Common Factors in Comparisons

lemma *mult-less-cancel-lemma*:
 $[| k : nat; m : nat; n : nat |] ==> (m \#* k < n \#* k) <-> (0 < k \ \& \ m < n)$
 $\langle proof \rangle$

lemma *mult-less-cancel2* [simp]:
 $(m \#* k < n \#* k) <-> (0 < natify(k) \ \& \ natify(m) < natify(n))$
 $\langle proof \rangle$

lemma *mult-less-cancel1* [simp]:
 $(k \#* m < k \#* n) <-> (0 < natify(k) \ \& \ natify(m) < natify(n))$
 $\langle proof \rangle$

lemma *mult-le-cancel2* [simp]: $(m \#* k \leq n \#* k) <-> (0 < natify(k) \ \longrightarrow \ natify(m) \leq natify(n))$
 $\langle proof \rangle$

lemma *mult-le-cancel1* [simp]: $(k \#* m \leq k \#* n) <-> (0 < natify(k) \ \longrightarrow \ natify(m) \leq natify(n))$
 $\langle proof \rangle$

lemma *mult-le-cancel-le1*: $k : \text{nat} \implies k \#* m \text{ le } k \longleftrightarrow (0 < k \longrightarrow \text{nativify}(m) \text{ le } 1)$
 $\langle \text{proof} \rangle$

lemma *Ord-eq-iff-le*: $[| \text{Ord}(m); \text{Ord}(n) |] \implies m=n \longleftrightarrow (m \text{ le } n \ \& \ n \text{ le } m)$
 $\langle \text{proof} \rangle$

lemma *mult-cancel2-lemma*:
 $[| k : \text{nat}; m : \text{nat}; n : \text{nat} |] \implies (m \#* k = n \#* k) \longleftrightarrow (m=n \mid k=0)$
 $\langle \text{proof} \rangle$

lemma *mult-cancel2* [simp]:
 $(m \#* k = n \#* k) \longleftrightarrow (\text{nativify}(m) = \text{nativify}(n) \mid \text{nativify}(k) = 0)$
 $\langle \text{proof} \rangle$

lemma *mult-cancel1* [simp]:
 $(k \#* m = k \#* n) \longleftrightarrow (\text{nativify}(m) = \text{nativify}(n) \mid \text{nativify}(k) = 0)$
 $\langle \text{proof} \rangle$

lemma *div-cancel-raw*:
 $[| 0 < n; 0 < k; k : \text{nat}; m : \text{nat}; n : \text{nat} |] \implies (k \#* m) \text{ div } (k \#* n) = m \text{ div } n$
 $\langle \text{proof} \rangle$

lemma *div-cancel*:
 $[| 0 < \text{nativify}(n); 0 < \text{nativify}(k) |] \implies (k \#* m) \text{ div } (k \#* n) = m \text{ div } n$
 $\langle \text{proof} \rangle$

27.7 More Lemmas about Remainder

lemma *mult-mod-distrib-raw*:
 $[| k : \text{nat}; m : \text{nat}; n : \text{nat} |] \implies (k \#* m) \text{ mod } (k \#* n) = k \#* (m \text{ mod } n)$
 $\langle \text{proof} \rangle$

lemma *mod-mult-distrib2*: $k \#* (m \text{ mod } n) = (k \#* m) \text{ mod } (k \#* n)$
 $\langle \text{proof} \rangle$

lemma *mult-mod-distrib*: $(m \text{ mod } n) \#* k = (m \#* k) \text{ mod } (n \#* k)$
 $\langle \text{proof} \rangle$

lemma *mod-add-self2-raw*: $n \in \text{nat} \implies (m \#+ n) \text{ mod } n = m \text{ mod } n$
 $\langle \text{proof} \rangle$

lemma *mod-add-self2* [simp]: $(m \#+ n) \text{ mod } n = m \text{ mod } n$
 $\langle \text{proof} \rangle$

lemma *mod-add-self1* [simp]: $(n \#+ m) \text{ mod } n = m \text{ mod } n$

$\langle proof \rangle$

lemma *mod-mult-self1-raw*: $k \in nat \implies (m \# + k \# * n) \bmod n = m \bmod n$
 $\langle proof \rangle$

lemma *mod-mult-self1* [simp]: $(m \# + k \# * n) \bmod n = m \bmod n$
 $\langle proof \rangle$

lemma *mod-mult-self2* [simp]: $(m \# + n \# * k) \bmod n = m \bmod n$
 $\langle proof \rangle$

lemma *mult-eq-self-implies-10*: $m = m \# * n \implies \text{natify}(n) = 1 \mid m = 0$
 $\langle proof \rangle$

lemma *less-imp-succ-add* [rule-format]:
 $\llbracket m < n; n: nat \rrbracket \implies \exists k: nat. n = \text{succ}(m \# + k)$
 $\langle proof \rangle$

lemma *less-iff-succ-add*:
 $\llbracket m: nat; n: nat \rrbracket \implies (m < n) \iff (\exists k: nat. n = \text{succ}(m \# + k))$
 $\langle proof \rangle$

lemma *add-lt-elim2*:
 $\llbracket a \# + d = b \# + c; a < b; b \in nat; c \in nat; d \in nat \rrbracket \implies c < d$
 $\langle proof \rangle$

lemma *add-le-elim2*:
 $\llbracket a \# + d = b \# + c; a \leq b; b \in nat; c \in nat; d \in nat \rrbracket \implies c \leq d$
 $\langle proof \rangle$

27.7.1 More Lemmas About Difference

lemma *diff-is-0-lemma*:
 $\llbracket m: nat; n: nat \rrbracket \implies m \# - n = 0 \iff m \leq n$
 $\langle proof \rangle$

lemma *diff-is-0-iff*: $m \# - n = 0 \iff \text{natify}(m) \leq \text{natify}(n)$
 $\langle proof \rangle$

lemma *nat-lt-imp-diff-eq-0*:
 $\llbracket a: nat; b: nat; a < b \rrbracket \implies a \# - b = 0$
 $\langle proof \rangle$

lemma *raw-nat-diff-split*:
 $\llbracket a: nat; b: nat \rrbracket \implies$
 $(P(a \# - b)) \iff ((a < b \implies P(0)) \ \& \ (\forall d: nat. a = b \# + d \implies P(d)))$
 $\langle proof \rangle$

```

lemma nat-diff-split:
  (P(a #- b)) <->
    (natify(a) < natify(b) --> P(0)) & (ALL d:nat. natify(a) = b #+ d -->
P(d))
<proof>

Difference and less-than

lemma diff-lt-imp-lt: [(k#-i) < (k#-j); i∈nat; j∈nat; k∈nat] ==> j<i
<proof>

lemma lt-imp-diff-lt: [j<i; i≤k; k∈nat] ==> (k#-i) < (k#-j)
<proof>

lemma diff-lt-iff-lt: [i≤k; j∈nat; k∈nat] ==> (k#-i) < (k#-j) <-> j<i
<proof>

end

```

28 List-ZF: Lists in Zermelo-Fraenkel Set Theory

```

theory List-ZF imports Datatype-ZF ArithSimp begin

```

```

consts

```

```

  list      :: i=>i

```

```

datatype

```

```

  list(A) = Nil | Cons (a:A, l: list(A))

```

```

syntax

```

```

[]          :: i                               ([])
@List      :: is => i                          ([(-)])

```

```

translations

```

```

[x, xs]    == Cons(x, [xs])
[x]         == Cons(x, [])
[]          == Nil

```

```

consts

```

```

  length :: i=>i
  hd     :: i=>i
  tl     :: i=>i

```

```

primrec

```

```

  length([]) = 0

```

$length(Cons(a,l)) = succ(length(l))$

primrec

$hd([]) = 0$
 $hd(Cons(a,l)) = a$

primrec

$tl([]) = []$
 $tl(Cons(a,l)) = l$

consts

$map \quad :: [i=>i, i] => i$
 $set-of-list \quad :: i=>i$
 $app \quad :: [i,i] => i \quad \text{(infixr @ 60)}$

primrec

$map(f,[]) = []$
 $map(f,Cons(a,l)) = Cons(f(a), map(f,l))$

primrec

$set-of-list([]) = 0$
 $set-of-list(Cons(a,l)) = cons(a, set-of-list(l))$

primrec

$app-Nil: [] @ ys = ys$
 $app-Cons: (Cons(a,l)) @ ys = Cons(a, l @ ys)$

consts

$rev \quad :: i=>i$
 $flat \quad :: i=>i$
 $list-add \quad :: i=>i$

primrec

$rev([]) = []$
 $rev(Cons(a,l)) = rev(l) @ [a]$

primrec

$flat([]) = []$
 $flat(Cons(l,ls)) = l @ flat(ls)$

primrec

$list-add([]) = 0$
 $list-add(Cons(a,l)) = a \# + list-add(l)$

consts

$drop \quad :: [i,i] => i$

primrec

drop-0: $\text{drop}(0, l) = l$
drop-succ: $\text{drop}(\text{succ}(i), l) = \text{tl } (\text{drop}(i, l))$

definition

take :: $[i, i] \Rightarrow i$ **where**
take(*n*, *as*) == *list-rec*(*lam n:nat. []*,
 $\%a \ l \ r. \text{lam } n:\text{nat}. \text{nat-case}([], \%m. \text{Cons}(a, r' m), n), \text{as}) 'n$

definition

nth :: $[i, i] \Rightarrow i$ **where**
— returns the (n+1)th element of a list, or 0 if the list is too short.
nth(*n*, *as*) == *list-rec*(*lam n:nat. 0*,
 $\%a \ l \ r. \text{lam } n:\text{nat}. \text{nat-case}(a, \%m. r' m, n), \text{as}) 'n$

definition

list-update :: $[i, i, i] \Rightarrow i$ **where**
list-update(*xs*, *i*, *v*) == *list-rec*(*lam n:nat. Nil*,
 $\%u \ us \ vs. \text{lam } n:\text{nat}. \text{nat-case}(\text{Cons}(v, us), \%m. \text{Cons}(u, vs' m), n), xs) 'i$

consts

filter :: $[i \Rightarrow o, i] \Rightarrow i$
upt :: $[i, i] \Rightarrow i$

primrec

filter(*P*, *Nil*) = *Nil*
filter(*P*, *Cons*(*x*, *xs*)) =
 $(\text{if } P(x) \text{ then } \text{Cons}(x, \text{filter}(P, xs)) \text{ else } \text{filter}(P, xs))$

primrec

upt(*i*, 0) = *Nil*
upt(*i*, *succ*(*j*)) = $(\text{if } i \text{ le } j \text{ then } \text{upt}(i, j)@[j] \text{ else } \text{Nil})$

definition

min :: $[i, i] \Rightarrow i$ **where**
min(*x*, *y*) == $(\text{if } x \text{ le } y \text{ then } x \text{ else } y)$

definition

max :: $[i, i] \Rightarrow i$ **where**
max(*x*, *y*) == $(\text{if } x \text{ le } y \text{ then } y \text{ else } x)$

declare *list.intros* [*simp*, *TC*]

inductive-cases *ConsE*: $\text{Cons}(a,l) : \text{list}(A)$

lemma *Cons-type-iff* [*simp*]: $\text{Cons}(a,l) \in \text{list}(A) <-> a \in A \ \& \ l \in \text{list}(A)$
<proof>

lemma *Cons-iff*: $\text{Cons}(a,l) = \text{Cons}(a',l') <-> a = a' \ \& \ l = l'$
<proof>

lemma *Nil-Cons-iff*: $\sim \text{Nil} = \text{Cons}(a,l)$
<proof>

lemma *list-unfold*: $\text{list}(A) = \{0\} + (A * \text{list}(A))$
<proof>

lemma *list-mono*: $A \leq B ==> \text{list}(A) \leq \text{list}(B)$
<proof>

lemma *list-univ*: $\text{list}(\text{univ}(A)) \leq \text{univ}(A)$
<proof>

lemmas *list-subset-univ* = *subset-trans* [*OF list-mono list-univ*]

lemma *list-into-univ*: $[\mid l : \text{list}(A); \ A \leq \text{univ}(B) \mid] ==> l : \text{univ}(B)$
<proof>

lemma *list-case-type*:
 $[\mid l : \text{list}(A);$
 $c : C(\text{Nil});$
 $!!x \ y. [\mid x : A; \ y : \text{list}(A) \mid] ==> h(x,y) : C(\text{Cons}(x,y))$
 $\mid] ==> \text{list-case}(c,h,l) : C(l)$
<proof>

lemma *list-0-triv*: $\text{list}(0) = \{\text{Nil}\}$
<proof>

lemma *tl-type*: $l : \text{list}(A) ==> \text{tl}(l) : \text{list}(A)$
<proof>

lemma *drop-Nil* [*simp*]: $i:\text{nat} \implies \text{drop}(i, \text{Nil}) = \text{Nil}$
 $\langle \text{proof} \rangle$

lemma *drop-succ-Cons* [*simp*]: $i:\text{nat} \implies \text{drop}(\text{succ}(i), \text{Cons}(a,l)) = \text{drop}(i,l)$
 $\langle \text{proof} \rangle$

lemma *drop-type* [*simp*, *TC*]: $[i:\text{nat}; l:\text{list}(A)] \implies \text{drop}(i,l) : \text{list}(A)$
 $\langle \text{proof} \rangle$

declare *drop-succ* [*simp del*]

lemma *list-rec-type* [*TC*]:
 $[l:\text{list}(A);$
 $c:C(\text{Nil});$
 $!!x\ y\ r. [x:A; y:\text{list}(A); r:C(y)] \implies h(x,y,r):C(\text{Cons}(x,y))$
 $] \implies \text{list-rec}(c,h,l) : C(l)$
 $\langle \text{proof} \rangle$

lemma *map-type* [*TC*]:
 $[l:\text{list}(A); !!x. x:A \implies h(x):B] \implies \text{map}(h,l) : \text{list}(B)$
 $\langle \text{proof} \rangle$

lemma *map-type2* [*TC*]: $l:\text{list}(A) \implies \text{map}(h,l) : \text{list}(\{h(u). u:A\})$
 $\langle \text{proof} \rangle$

lemma *length-type* [*TC*]: $l:\text{list}(A) \implies \text{length}(l) : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *lt-length-in-nat*:
 $[x < \text{length}(xs); xs \in \text{list}(A)] \implies x \in \text{nat}$
 $\langle \text{proof} \rangle$

lemma *app-type* [*TC*]: $[xs:\text{list}(A); ys:\text{list}(A)] \implies xs@ys : \text{list}(A)$
 $\langle \text{proof} \rangle$

lemma *rev-type* [*TC*]: $xs:\text{list}(A) \implies \text{rev}(xs) : \text{list}(A)$

$\langle proof \rangle$

lemma *flat-type* [TC]: $ls: list(list(A)) \implies flat(ls) : list(A)$
 $\langle proof \rangle$

lemma *set-of-list-type* [TC]: $l: list(A) \implies set-of-list(l) : Pow(A)$
 $\langle proof \rangle$

lemma *set-of-list-append*:
 $xs: list(A) \implies set-of-list (xs@ys) = set-of-list(xs) \cup set-of-list(ys)$
 $\langle proof \rangle$

lemma *list-add-type* [TC]: $xs: list(nat) \implies list-add(xs) : nat$
 $\langle proof \rangle$

lemma *map-ident* [simp]: $l: list(A) \implies map(\%u. u, l) = l$
 $\langle proof \rangle$

lemma *map-compose*: $l: list(A) \implies map(h, map(j,l)) = map(\%u. h(j(u)), l)$
 $\langle proof \rangle$

lemma *map-app-distrib*: $xs: list(A) \implies map(h, xs@ys) = map(h,xs) @ map(h,ys)$
 $\langle proof \rangle$

lemma *map-flat*: $ls: list(list(A)) \implies map(h, flat(ls)) = flat(map(map(h),ls))$
 $\langle proof \rangle$

lemma *list-rec-map*:
 $l: list(A) \implies$
 $list-rec(c, d, map(h,l)) =$
 $list-rec(c, \%x xs r. d(h(x), map(h,xs), r), l)$
 $\langle proof \rangle$

lemmas *list-CollectD* = *Collect-subset* [THEN *list-mono*, THEN *subsetD*, stan-

dard]

lemma *map-list-Collect*: $l: \text{list}(\{x:A. h(x)=j(x)\}) \implies \text{map}(h,l) = \text{map}(j,l)$
 $\langle \text{proof} \rangle$

lemma *length-map* [*simp*]: $xs: \text{list}(A) \implies \text{length}(\text{map}(h,xs)) = \text{length}(xs)$
 $\langle \text{proof} \rangle$

lemma *length-app* [*simp*]:
 $[[\ xs: \text{list}(A); \ ys: \text{list}(A) \]]$
 $\implies \text{length}(xs@ys) = \text{length}(xs) \# + \text{length}(ys)$
 $\langle \text{proof} \rangle$

lemma *length-rev* [*simp*]: $xs: \text{list}(A) \implies \text{length}(\text{rev}(xs)) = \text{length}(xs)$
 $\langle \text{proof} \rangle$

lemma *length-flat*:
 $ls: \text{list}(\text{list}(A)) \implies \text{length}(\text{flat}(ls)) = \text{list-add}(\text{map}(\text{length},ls))$
 $\langle \text{proof} \rangle$

lemma *drop-length-Cons* [*rule-format*]:
 $xs: \text{list}(A) \implies$
 $\forall x. \ EX \ z \ zs. \ \text{drop}(\text{length}(xs), \text{Cons}(x,xs)) = \text{Cons}(z,zs)$
 $\langle \text{proof} \rangle$

lemma *drop-length* [*rule-format*]:
 $l: \text{list}(A) \implies \forall i \in \text{length}(l). \ (\EX \ z \ zs. \ \text{drop}(i,l) = \text{Cons}(z,zs))$
 $\langle \text{proof} \rangle$

lemma *app-right-Nil* [*simp*]: $xs: \text{list}(A) \implies xs@Nil=xs$
 $\langle \text{proof} \rangle$

lemma *app-assoc*: $xs: \text{list}(A) \implies (xs@ys)@zs = xs@(ys@zs)$
 $\langle \text{proof} \rangle$

lemma *flat-app-distrib*: $ls: \text{list}(\text{list}(A)) \implies \text{flat}(ls@ms) = \text{flat}(ls)@flat(ms)$
 $\langle \text{proof} \rangle$

lemma *rev-map-distrib*: $l: \text{list}(A) \implies \text{rev}(\text{map}(h,l)) = \text{map}(h,\text{rev}(l))$

$\langle proof \rangle$

lemma *rev-app-distrib*:

$\llbracket xs: list(A); ys: list(A) \rrbracket ==> rev(xs@ys) = rev(ys)@rev(xs)$
 $\langle proof \rangle$

lemma *rev-rev-ident* [simp]: $l: list(A) ==> rev(rev(l))=l$

$\langle proof \rangle$

lemma *rev-flat*: $ls: list(list(A)) ==> rev(flat(ls)) = flat(map(rev,rev(ls)))$

$\langle proof \rangle$

lemma *list-add-app*:

$\llbracket xs: list(nat); ys: list(nat) \rrbracket$
 $==> list-add(xs@ys) = list-add(ys) \# + list-add(xs)$
 $\langle proof \rangle$

lemma *list-add-rev*: $l: list(nat) ==> list-add(rev(l)) = list-add(l)$

$\langle proof \rangle$

lemma *list-add-flat*:

$ls: list(list(nat)) ==> list-add(flat(ls)) = list-add(map(list-add,ls))$
 $\langle proof \rangle$

lemma *list-append-induct* [case-names Nil snoc, consumes 1]:

$\llbracket l: list(A);$
 $P(Nil);$
 $!!x y. \llbracket x: A; y: list(A); P(y) \rrbracket ==> P(y @ [x])$
 $\rrbracket ==> P(l)$
 $\langle proof \rangle$

lemma *list-complete-induct-lemma* [rule-format]:

assumes *ih*:
 $\bigwedge l. \llbracket l \in list(A);$
 $\forall l' \in list(A). length(l') < length(l) --> P(l') \rrbracket$
 $==> P(l)$
shows $n \in nat ==> \forall l \in list(A). length(l) < n --> P(l)$
 $\langle proof \rangle$

theorem *list-complete-induct*:

$\llbracket l \in list(A);$
 $\bigwedge l. \llbracket l \in list(A);$
 $\forall l' \in list(A). length(l') < length(l) --> P(l') \rrbracket$

$$\begin{aligned} & \implies P(l) \\ \text{[]} & \implies P(l) \\ \langle \text{proof} \rangle & \end{aligned}$$

lemma *min-sym*: [$i:\text{nat}; j:\text{nat}$] $\implies \text{min}(i,j)=\text{min}(j,i)$
 $\langle \text{proof} \rangle$

lemma *min-type* [simp,TC]: [$i:\text{nat}; j:\text{nat}$] $\implies \text{min}(i,j):\text{nat}$
 $\langle \text{proof} \rangle$

lemma *min-0* [simp]: $i:\text{nat} \implies \text{min}(0,i) = 0$
 $\langle \text{proof} \rangle$

lemma *min-02* [simp]: $i:\text{nat} \implies \text{min}(i, 0) = 0$
 $\langle \text{proof} \rangle$

lemma *lt-min-iff*: [$i:\text{nat}; j:\text{nat}; k:\text{nat}$] $\implies i < \text{min}(j,k) \iff i < j \ \& \ i < k$
 $\langle \text{proof} \rangle$

lemma *min-succ-succ* [simp]:
[$i:\text{nat}; j:\text{nat}$] $\implies \text{min}(\text{succ}(i), \text{succ}(j)) = \text{succ}(\text{min}(i, j))$
 $\langle \text{proof} \rangle$

lemma *filter-append* [simp]:
 $xs:\text{list}(A) \implies \text{filter}(P, xs @ ys) = \text{filter}(P, xs) @ \text{filter}(P, ys)$
 $\langle \text{proof} \rangle$

lemma *filter-type* [simp,TC]: $xs:\text{list}(A) \implies \text{filter}(P, xs):\text{list}(A)$
 $\langle \text{proof} \rangle$

lemma *length-filter*: $xs:\text{list}(A) \implies \text{length}(\text{filter}(P, xs)) \leq \text{length}(xs)$
 $\langle \text{proof} \rangle$

lemma *filter-is-subset*: $xs:\text{list}(A) \implies \text{set-of-list}(\text{filter}(P, xs)) \leq \text{set-of-list}(xs)$
 $\langle \text{proof} \rangle$

lemma *filter-False* [simp]: $xs:\text{list}(A) \implies \text{filter}(\%p. \text{False}, xs) = \text{Nil}$
 $\langle \text{proof} \rangle$

lemma *filter-True* [simp]: $xs:\text{list}(A) \implies \text{filter}(\%p. \text{True}, xs) = xs$

$\langle proof \rangle$

lemma *length-is-0-iff* [simp]: $xs:list(A) ==> length(xs)=0 <-> xs=Nil$
 $\langle proof \rangle$

lemma *length-is-0-iff2* [simp]: $xs:list(A) ==> 0 = length(xs) <-> xs=Nil$
 $\langle proof \rangle$

lemma *length-tl* [simp]: $xs:list(A) ==> length(tl(xs)) = length(xs) \# - 1$
 $\langle proof \rangle$

lemma *length-greater-0-iff*: $xs:list(A) ==> 0 < length(xs) <-> xs \sim Nil$
 $\langle proof \rangle$

lemma *length-succ-iff*: $xs:list(A) ==> length(xs)=succ(n) <-> (EX y ys. xs=Cons(y, ys) \& length(ys)=n)$
 $\langle proof \rangle$

lemma *append-is-Nil-iff* [simp]:
 $xs:list(A) ==> (xs@ys = Nil) <-> (xs=Nil \& ys = Nil)$
 $\langle proof \rangle$

lemma *append-is-Nil-iff2* [simp]:
 $xs:list(A) ==> (Nil = xs@ys) <-> (xs=Nil \& ys = Nil)$
 $\langle proof \rangle$

lemma *append-left-is-self-iff* [simp]:
 $xs:list(A) ==> (xs@ys = xs) <-> (ys = Nil)$
 $\langle proof \rangle$

lemma *append-left-is-self-iff2* [simp]:
 $xs:list(A) ==> (xs = xs@ys) <-> (ys = Nil)$
 $\langle proof \rangle$

lemma *append-left-is-Nil-iff* [rule-format]:
 $[| xs:list(A); ys:list(A); zs:list(A) |] ==>$
 $length(ys)=length(zs) \dashv\dashv (xs@ys=zs <-> (xs=Nil \& ys=zs))$
 $\langle proof \rangle$

lemma *append-left-is-Nil-iff2* [rule-format]:
 $[| xs:list(A); ys:list(A); zs:list(A) |] ==>$
 $length(ys)=length(zs) \dashv\dashv (zs=ys@xs <-> (xs=Nil \& ys=zs))$
 $\langle proof \rangle$

lemma *append-eq-append-iff* [*rule-format,simp*]:
 $xs:list(A) ==> \forall ys \in list(A).$
 $length(xs)=length(ys) \dashv\dashv (xs@us = ys@vs) <-> (xs=ys \ \& \ us=vs)$
 $\langle proof \rangle$

lemma *append-eq-append* [*rule-format*]:
 $xs:list(A) ==>$
 $\forall ys \in list(A). \forall us \in list(A). \forall vs \in list(A).$
 $length(us) = length(vs) \dashv\dashv (xs@us = ys@vs) \dashv\dashv (xs=ys \ \& \ us=vs)$
 $\langle proof \rangle$

lemma *append-eq-append-iff2* [*simp*]:
 $[\![xs:list(A); ys:list(A); us:list(A); vs:list(A); length(us)=length(vs)]\!] ==>$
 $xs@us = ys@vs <-> (xs=ys \ \& \ us=vs)$
 $\langle proof \rangle$

lemma *append-self-iff* [*simp*]:
 $[\![xs:list(A); ys:list(A); zs:list(A)]\!] ==> xs@ys=xs@zs <-> ys=zs$
 $\langle proof \rangle$

lemma *append-self-iff2* [*simp*]:
 $[\![xs:list(A); ys:list(A); zs:list(A)]\!] ==> ys@xs=zs@xs <-> ys=zs$
 $\langle proof \rangle$

lemma *append1-eq-iff* [*rule-format,simp*]:
 $xs:list(A) ==> \forall ys \in list(A). xs@[x] = ys@[y] <-> (xs = ys \ \& \ x=y)$
 $\langle proof \rangle$

lemma *append-right-is-self-iff* [*simp*]:
 $[\![xs:list(A); ys:list(A)]\!] ==> (xs@ys = ys) <-> (xs=Nil)$
 $\langle proof \rangle$

lemma *append-right-is-self-iff2* [*simp*]:
 $[\![xs:list(A); ys:list(A)]\!] ==> (ys = xs@ys) <-> (xs=Nil)$
 $\langle proof \rangle$

lemma *hd-append* [*rule-format,simp*]:
 $xs:list(A) ==> xs \sim Nil \dashv\dashv hd(xs @ ys) = hd(xs)$
 $\langle proof \rangle$

lemma *tl-append* [*rule-format,simp*]:
 $xs:list(A) ==> xs \sim Nil \dashv\dashv tl(xs @ ys) = tl(xs)@ys$
 $\langle proof \rangle$

lemma *rev-is-Nil-iff* [*simp*]: $xs:list(A) ==> (rev(xs) = Nil <-> xs = Nil)$

$\langle proof \rangle$

lemma *Nil-is-rev-iff* [simp]: $xs: list(A) \implies (Nil = rev(xs) \iff xs = Nil)$
 $\langle proof \rangle$

lemma *rev-is-rev-iff* [rule-format,simp]:
 $xs: list(A) \implies \forall ys \in list(A). rev(xs) = rev(ys) \iff xs = ys$
 $\langle proof \rangle$

lemma *rev-list-elim* [rule-format]:
 $xs: list(A) \implies$
 $(xs = Nil \implies P) \implies (\forall ys \in list(A). \forall y \in A. xs = ys @ [y] \implies P) \implies P$
 $\langle proof \rangle$

lemma *length-drop* [rule-format,simp]:
 $n: nat \implies \forall xs \in list(A). length(drop(n, xs)) = length(xs) \# - n$
 $\langle proof \rangle$

lemma *drop-all* [rule-format,simp]:
 $n: nat \implies \forall xs \in list(A). length(xs) \leq n \implies drop(n, xs) = Nil$
 $\langle proof \rangle$

lemma *drop-append* [rule-format]:
 $n: nat \implies$
 $\forall xs \in list(A). drop(n, xs @ ys) = drop(n, xs) @ drop(n \# - length(xs), ys)$
 $\langle proof \rangle$

lemma *drop-drop*:
 $m: nat \implies \forall xs \in list(A). \forall n \in nat. drop(n, drop(m, xs)) = drop(n \# + m, xs)$
 $\langle proof \rangle$

lemma *take-0* [simp]: $xs: list(A) \implies take(0, xs) = Nil$
 $\langle proof \rangle$

lemma *take-succ-Cons* [simp]:
 $n: nat \implies take(succ(n), Cons(a, xs)) = Cons(a, take(n, xs))$
 $\langle proof \rangle$

lemma *take-Nil* [simp]: $n: nat \implies take(n, Nil) = Nil$
 $\langle proof \rangle$

lemma *take-all* [rule-format,simp]:

$n:\text{nat} \implies \forall xs \in \text{list}(A). \text{length}(xs) \leq n \implies \text{take}(n, xs) = xs$
 $\langle \text{proof} \rangle$

lemma *take-type* [rule-format,simp,TC]:
 $xs:\text{list}(A) \implies \forall n \in \text{nat}. \text{take}(n, xs):\text{list}(A)$
 $\langle \text{proof} \rangle$

lemma *take-append* [rule-format,simp]:
 $xs:\text{list}(A) \implies$
 $\forall ys \in \text{list}(A). \forall n \in \text{nat}. \text{take}(n, xs @ ys) =$
 $\text{take}(n, xs) @ \text{take}(n \# - \text{length}(xs), ys)$
 $\langle \text{proof} \rangle$

lemma *take-take* [rule-format]:
 $m : \text{nat} \implies$
 $\forall xs \in \text{list}(A). \forall n \in \text{nat}. \text{take}(n, \text{take}(m, xs)) = \text{take}(\min(n, m), xs)$
 $\langle \text{proof} \rangle$

lemma *nth-0* [simp]: $\text{nth}(0, \text{Cons}(a, l)) = a$
 $\langle \text{proof} \rangle$

lemma *nth-Cons* [simp]: $n:\text{nat} \implies \text{nth}(\text{succ}(n), \text{Cons}(a, l)) = \text{nth}(n, l)$
 $\langle \text{proof} \rangle$

lemma *nth-empty* [simp]: $\text{nth}(n, \text{Nil}) = 0$
 $\langle \text{proof} \rangle$

lemma *nth-type* [rule-format,simp,TC]:
 $xs:\text{list}(A) \implies \forall n. n < \text{length}(xs) \implies \text{nth}(n, xs) : A$
 $\langle \text{proof} \rangle$

lemma *nth-eq-0* [rule-format]:
 $xs:\text{list}(A) \implies \forall n \in \text{nat}. \text{length}(xs) \leq n \implies \text{nth}(n, xs) = 0$
 $\langle \text{proof} \rangle$

lemma *nth-append* [rule-format]:
 $xs:\text{list}(A) \implies$
 $\forall n \in \text{nat}. \text{nth}(n, xs @ ys) = (\text{if } n < \text{length}(xs) \text{ then } \text{nth}(n, xs)$
 $\text{else } \text{nth}(n \# - \text{length}(xs), ys))$
 $\langle \text{proof} \rangle$

lemma *set-of-list-conv-nth*:
 $xs:\text{list}(A)$
 $\implies \text{set-of-list}(xs) = \{x:A. \exists i:\text{nat}. i < \text{length}(xs) \ \& \ x = \text{nth}(i, xs)\}$
 $\langle \text{proof} \rangle$

lemma *nth-take-lemma* [rule-format]:

$k: \text{nat} ==>$
 $\forall xs \in \text{list}(A). (\forall ys \in \text{list}(A). k \text{ le } \text{length}(xs) \text{ --> } k \text{ le } \text{length}(ys) \text{ -->}$
 $(\forall i \in \text{nat}. i < k \text{ --> } \text{nth}(i, xs) = \text{nth}(i, ys)) \text{ --> } \text{take}(k, xs) = \text{take}(k, ys))$
 $\langle \text{proof} \rangle$

lemma *nth-equalityI* [rule-format]:

$[[xs: \text{list}(A); ys: \text{list}(A); \text{length}(xs) = \text{length}(ys);$
 $\forall i \in \text{nat}. i < \text{length}(xs) \text{ --> } \text{nth}(i, xs) = \text{nth}(i, ys)]]$
 $==> xs = ys$
 $\langle \text{proof} \rangle$

lemma *take-equalityI* [rule-format]:

$[[xs: \text{list}(A); ys: \text{list}(A); (\forall i \in \text{nat}. \text{take}(i, xs) = \text{take}(i, ys))]]$
 $==> xs = ys$
 $\langle \text{proof} \rangle$

lemma *nth-drop* [rule-format]:

$n: \text{nat} ==> \forall i \in \text{nat}. \forall xs \in \text{list}(A). \text{nth}(i, \text{drop}(n, xs)) = \text{nth}(n \# + i, xs)$
 $\langle \text{proof} \rangle$

lemma *take-succ* [rule-format]:

$xs \in \text{list}(A)$
 $==> \forall i. i < \text{length}(xs) \text{ --> } \text{take}(\text{succ}(i), xs) = \text{take}(i, xs) @ [\text{nth}(i, xs)]$
 $\langle \text{proof} \rangle$

lemma *take-add* [rule-format]:

$[[xs \in \text{list}(A); j \in \text{nat}]]$
 $==> \forall i \in \text{nat}. \text{take}(i \# + j, xs) = \text{take}(i, xs) @ \text{take}(j, \text{drop}(i, xs))$
 $\langle \text{proof} \rangle$

lemma *length-take*:

$l \in \text{list}(A) ==> \forall n \in \text{nat}. \text{length}(\text{take}(n, l)) = \min(n, \text{length}(l))$
 $\langle \text{proof} \rangle$

28.1 The function zip

Crafty definition to eliminate a type argument

consts

zip-aux :: $[i, i] ==> i$

primrec

$\text{zip-aux}(B, []) =$
 $(\lambda ys \in \text{list}(B). \text{list-case}([], \%y l. [], ys))$

$\text{zip-aux}(B, \text{Cons}(x, l)) =$

$(\lambda ys \in \text{list}(B).$
 $\text{list-case}(\text{Nil}, \%y \text{ } zs. \text{Cons}(<x,y>, \text{zip-aux}(B,l) 'zs), ys))$

definition

$\text{zip} :: [i, i] \Rightarrow i$ **where**
 $\text{zip}(xs, ys) == \text{zip-aux}(\text{set-of-list}(ys), xs) 'ys$

lemma *list-on-set-of-list*: $xs \in \text{list}(A) \Rightarrow xs \in \text{list}(\text{set-of-list}(xs))$
 $\langle \text{proof} \rangle$

lemma *zip-Nil* [*simp*]: $ys:\text{list}(A) \Rightarrow \text{zip}(\text{Nil}, ys) = \text{Nil}$
 $\langle \text{proof} \rangle$

lemma *zip-Nil2* [*simp*]: $xs:\text{list}(A) \Rightarrow \text{zip}(xs, \text{Nil}) = \text{Nil}$
 $\langle \text{proof} \rangle$

lemma *zip-aux-unique* [*rule-format*]:
 $[| B \leq C; xs \in \text{list}(A) |] \Rightarrow \forall ys \in \text{list}(B). \text{zip-aux}(C, xs) 'ys = \text{zip-aux}(B, xs) 'ys$
 $\langle \text{proof} \rangle$

lemma *zip-Cons-Cons* [*simp*]:
 $[| xs:\text{list}(A); ys:\text{list}(B); x:A; y:B |] \Rightarrow$
 $\text{zip}(\text{Cons}(x, xs), \text{Cons}(y, ys)) = \text{Cons}(<x,y>, \text{zip}(xs, ys))$
 $\langle \text{proof} \rangle$

lemma *zip-type* [*rule-format, simp, TC*]:
 $xs:\text{list}(A) \Rightarrow \forall ys \in \text{list}(B). \text{zip}(xs, ys):\text{list}(A*B)$
 $\langle \text{proof} \rangle$

lemma *length-zip* [*rule-format, simp*]:
 $xs:\text{list}(A) \Rightarrow \forall ys \in \text{list}(B). \text{length}(\text{zip}(xs, ys)) =$
 $\text{min}(\text{length}(xs), \text{length}(ys))$
 $\langle \text{proof} \rangle$

lemma *zip-append1* [*rule-format*]:
 $[| ys:\text{list}(A); zs:\text{list}(B) |] \Rightarrow$
 $\forall xs \in \text{list}(A). \text{zip}(xs @ ys, zs) =$
 $\text{zip}(xs, \text{take}(\text{length}(xs), zs)) @ \text{zip}(ys, \text{drop}(\text{length}(xs), zs))$
 $\langle \text{proof} \rangle$

lemma *zip-append2* [*rule-format*]:
 $[| xs:\text{list}(A); zs:\text{list}(B) |] \Rightarrow \forall ys \in \text{list}(B). \text{zip}(xs, ys @ zs) =$
 $\text{zip}(\text{take}(\text{length}(ys), xs), ys) @ \text{zip}(\text{drop}(\text{length}(ys), xs), zs)$
 $\langle \text{proof} \rangle$

lemma *zip-append* [*simp*]:

$$[[\text{length}(xs) = \text{length}(us); \text{length}(ys) = \text{length}(vs);$$

$$xs:\text{list}(A); us:\text{list}(B); ys:\text{list}(A); vs:\text{list}(B)]]$$

$$\implies \text{zip}(xs @ ys, us @ vs) = \text{zip}(xs, us) @ \text{zip}(ys, vs)$$

$$\langle \text{proof} \rangle$$

lemma *zip-rev* [*rule-format, simp*]:

$$ys:\text{list}(B) \implies \forall xs \in \text{list}(A).$$

$$\text{length}(xs) = \text{length}(ys) \dashrightarrow \text{zip}(\text{rev}(xs), \text{rev}(ys)) = \text{rev}(\text{zip}(xs, ys))$$

$$\langle \text{proof} \rangle$$

lemma *nth-zip* [*rule-format, simp*]:

$$ys:\text{list}(B) \implies \forall i \in \text{nat}. \forall xs \in \text{list}(A).$$

$$i < \text{length}(xs) \dashrightarrow i < \text{length}(ys) \dashrightarrow$$

$$\text{nth}(i, \text{zip}(xs, ys)) = \langle \text{nth}(i, xs), \text{nth}(i, ys) \rangle$$

$$\langle \text{proof} \rangle$$

lemma *set-of-list-zip* [*rule-format*]:

$$[[xs:\text{list}(A); ys:\text{list}(B); i:\text{nat}]]$$

$$\implies \text{set-of-list}(\text{zip}(xs, ys)) =$$

$$\{ \langle x, y \rangle : A * B. \text{EX } i:\text{nat}. i < \min(\text{length}(xs), \text{length}(ys))$$

$$\& x = \text{nth}(i, xs) \& y = \text{nth}(i, ys) \}$$

$$\langle \text{proof} \rangle$$

lemma *list-update-Nil* [*simp*]: $i:\text{nat} \implies \text{list-update}(\text{Nil}, i, v) = \text{Nil}$

$$\langle \text{proof} \rangle$$

lemma *list-update-Cons-0* [*simp*]: $\text{list-update}(\text{Cons}(x, xs), 0, v) = \text{Cons}(v, xs)$

$$\langle \text{proof} \rangle$$

lemma *list-update-Cons-succ* [*simp*]:

$$n:\text{nat} \implies$$

$$\text{list-update}(\text{Cons}(x, xs), \text{succ}(n), v) = \text{Cons}(x, \text{list-update}(xs, n, v))$$

$$\langle \text{proof} \rangle$$

lemma *list-update-type* [*rule-format, simp, TC*]:

$$[[xs:\text{list}(A); v:A]] \implies \forall n \in \text{nat}. \text{list-update}(xs, n, v) : \text{list}(A)$$

$$\langle \text{proof} \rangle$$

lemma *length-list-update* [*rule-format, simp*]:

$$xs:\text{list}(A) \implies \forall i \in \text{nat}. \text{length}(\text{list-update}(xs, i, v)) = \text{length}(xs)$$

$$\langle \text{proof} \rangle$$

lemma *nth-list-update* [*rule-format*]:

$$[[xs:\text{list}(A)]] \implies \forall i \in \text{nat}. \forall j \in \text{nat}. i < \text{length}(xs) \dashrightarrow$$

$nth(j, list-update(xs, i, x)) = (if\ i=j\ then\ x\ else\ nth(j, xs))$
 $\langle proof \rangle$

lemma *nth-list-update-eq* [simp]:
 $[[\ i < length(xs);\ xs:list(A)\]]\ ==>\ nth(i, list-update(xs, i, x)) = x$
 $\langle proof \rangle$

lemma *nth-list-update-neq* [rule-format, simp]:
 $xs:list(A) ==>$
 $\forall i \in nat. \forall j \in nat. i \sim j \dashv\rightarrow nth(j, list-update(xs, i, x)) = nth(j, xs)$
 $\langle proof \rangle$

lemma *list-update-overwrite* [rule-format, simp]:
 $xs:list(A) ==> \forall i \in nat. i < length(xs)$
 $\dashv\rightarrow list-update(list-update(xs, i, x), i, y) = list-update(xs, i, y)$
 $\langle proof \rangle$

lemma *list-update-same-conv* [rule-format]:
 $xs:list(A) ==>$
 $\forall i \in nat. i < length(xs) \dashv\rightarrow$
 $(list-update(xs, i, x) = xs) <-> (nth(i, xs) = x)$
 $\langle proof \rangle$

lemma *update-zip* [rule-format]:
 $ys:list(B) ==>$
 $\forall i \in nat. \forall xy \in A*B. \forall xs \in list(A).$
 $length(xs) = length(ys) \dashv\rightarrow$
 $list-update(zip(xs, ys), i, xy) = zip(list-update(xs, i, fst(xy)),$
 $list-update(ys, i, snd(xy)))$
 $\langle proof \rangle$

lemma *set-update-subset-cons* [rule-format]:
 $xs:list(A) ==>$
 $\forall i \in nat. set-of-list(list-update(xs, i, x)) \leq cons(x, set-of-list(xs))$
 $\langle proof \rangle$

lemma *set-of-list-update-subsetI*:
 $[[\ set-of-list(xs) \leq A;\ xs:list(A);\ x:A;\ i:nat\]]$
 $\impl set-of-list(list-update(xs, i, x)) \leq A$
 $\langle proof \rangle$

lemma *upt-rec*:
 $j:nat \impl upt(i, j) = (if\ i < j\ then\ Cons(i, upt(succ(i), j))\ else\ Nil)$
 $\langle proof \rangle$

lemma *upt-conv-Nil* [simp]: $[[\ j \leq i;\ j:nat\]]\impl upt(i, j) = Nil$

$\langle proof \rangle$

lemma *upt-succ-append*:

$\llbracket i \text{ le } j; j:\text{nat} \rrbracket \implies \text{upt}(i, \text{succ}(j)) = \text{upt}(i, j) @ [j]$
 $\langle proof \rangle$

lemma *upt-conv-Cons*:

$\llbracket i < j; j:\text{nat} \rrbracket \implies \text{upt}(i, j) = \text{Cons}(i, \text{upt}(\text{succ}(i), j))$
 $\langle proof \rangle$

lemma *upt-type* $[simp, TC]: j:\text{nat} \implies \text{upt}(i, j) : \text{list}(\text{nat})$

$\langle proof \rangle$

lemma *upt-add-eq-append*:

$\llbracket i \text{ le } j; j:\text{nat}; k:\text{nat} \rrbracket \implies \text{upt}(i, j \# + k) = \text{upt}(i, j) @ \text{upt}(j, j \# + k)$
 $\langle proof \rangle$

lemma *length-upt* $[simp]: \llbracket i:\text{nat}; j:\text{nat} \rrbracket \implies \text{length}(\text{upt}(i, j)) = j \# - i$

$\langle proof \rangle$

lemma *nth-upt* $[rule-format, simp]:$

$\llbracket i:\text{nat}; j:\text{nat}; k:\text{nat} \rrbracket \implies i \# + k < j \dashv\dashv \text{nth}(k, \text{upt}(i, j)) = i \# + k$
 $\langle proof \rangle$

lemma *take-upt* $[rule-format, simp]:$

$\llbracket m:\text{nat}; n:\text{nat} \rrbracket \implies$
 $\forall i \in \text{nat}. i \# + m \text{ le } n \dashv\dashv \text{take}(m, \text{upt}(i, n)) = \text{upt}(i, i \# + m)$
 $\langle proof \rangle$

lemma *map-succ-upt*:

$\llbracket m:\text{nat}; n:\text{nat} \rrbracket \implies \text{map}(\text{succ}, \text{upt}(m, n)) = \text{upt}(\text{succ}(m), \text{succ}(n))$
 $\langle proof \rangle$

lemma *nth-map* $[rule-format, simp]:$

$xs : \text{list}(A) \implies$
 $\forall n \in \text{nat}. n < \text{length}(xs) \dashv\dashv \text{nth}(n, \text{map}(f, xs)) = f(\text{nth}(n, xs))$
 $\langle proof \rangle$

lemma *nth-map-upt* $[rule-format]:$

$\llbracket m:\text{nat}; n:\text{nat} \rrbracket \implies$
 $\forall i \in \text{nat}. i < n \# - m \dashv\dashv \text{nth}(i, \text{map}(f, \text{upt}(m, n))) = f(m \# + i)$
 $\langle proof \rangle$

definition

sublist $:: [i, i] \implies i$ **where**

$sublist(xs, A) ==$
 $map(fst, (filter(\%p. snd(p): A, zip(xs, upt(0, length(xs)))))$

lemma *sublist-0* [simp]: $xs: list(A) ==> sublist(xs, 0) = Nil$
 $\langle proof \rangle$

lemma *sublist-Nil* [simp]: $sublist(Nil, A) = Nil$
 $\langle proof \rangle$

lemma *sublist-shift-lemma*:
 $[| xs: list(B); i: nat |] ==>$
 $map(fst, filter(\%p. snd(p): A, zip(xs, upt(i, i \# + length(xs))))) =$
 $map(fst, filter(\%p. snd(p): nat \& snd(p) \# + i: A, zip(xs, upt(0, length(xs)))))$
 $\langle proof \rangle$

lemma *sublist-type* [simp, TC]:
 $xs: list(B) ==> sublist(xs, A): list(B)$
 $\langle proof \rangle$

lemma *upt-add-eq-append2*:
 $[| i: nat; j: nat |] ==> upt(0, i \# + j) = upt(0, i) @ upt(i, i \# + j)$
 $\langle proof \rangle$

lemma *sublist-append*:
 $[| xs: list(B); ys: list(B) |] ==>$
 $sublist(xs @ ys, A) = sublist(xs, A) @ sublist(ys, \{j: nat. j \# + length(xs): A\})$
 $\langle proof \rangle$

lemma *sublist-Cons*:
 $[| xs: list(B); x: B |] ==>$
 $sublist(Cons(x, xs), A) =$
 $(if 0: A then [x] else []) @ sublist(xs, \{j: nat. succ(j) : A\})$
 $\langle proof \rangle$

lemma *sublist-singleton* [simp]:
 $sublist([x], A) = (if 0 : A then [x] else [])$
 $\langle proof \rangle$

lemma *sublist-upt-eq-take* [rule-format, simp]:
 $xs: list(A) ==> ALL n: nat. sublist(xs, n) = take(n, xs)$
 $\langle proof \rangle$

lemma *sublist-Int-eq*:
 $xs : list(B) ==> sublist(xs, A \cap nat) = sublist(xs, A)$
 $\langle proof \rangle$

Repetition of a List Element

consts *repeat* :: $[i, i] ==> i$

primrec

$repeat(a, 0) = []$

$repeat(a, succ(n)) = Cons(a, repeat(a, n))$

lemma *length-repeat*: $n \in nat \implies length(repeat(a, n)) = n$
 $\langle proof \rangle$

lemma *repeat-succ-app*: $n \in nat \implies repeat(a, succ(n)) = repeat(a, n) @ [a]$
 $\langle proof \rangle$

lemma *repeat-type* [TC]: $[a \in A; n \in nat] \implies repeat(a, n) \in list(A)$
 $\langle proof \rangle$

end

29 EquivClass: Equivalence Relations

theory *EquivClass* **imports** *Trancl Perm* **begin**

definition

quotient $:: [i, i] \implies i \quad (\text{infixl } '//' \ 90) \quad \text{where}$
 $A // r == \{r''\{x\} . x:A\}$

definition

congruent $:: [i, i \implies i] \implies o \quad \text{where}$
 $congruent(r, b) == ALL \ y \ z. <y, z>:r \ \longrightarrow \ b(y) = b(z)$

definition

congruent2 $:: [i, i, [i, i] \implies i] \implies o \quad \text{where}$
 $congruent2(r1, r2, b) == ALL \ y1 \ z1 \ y2 \ z2.$
 $<y1, z1>:r1 \ \longrightarrow \ <y2, z2>:r2 \ \longrightarrow \ b(y1, y2) = b(z1, z2)$

abbreviation

RESPECTS $:: [i \implies i, i] \implies o \quad (\text{infixr } respects \ 80) \quad \text{where}$
 $f \ respects \ r == congruent(r, f)$

abbreviation

RESPECTS2 $:: [i \implies i \implies i, i] \implies o \quad (\text{infixr } respects2 \ 80) \quad \text{where}$
 $f \ respects2 \ r == congruent2(r, r, f)$
 — Abbreviation for the common case where the relations are identical

29.1 Suppes, Theorem 70: r is an equiv relation iff $converse(r) \ O \ r = r$

lemma *sym-trans-comp-subset*:

$[sym(r); trans(r)] \implies converse(r) \ O \ r \leq r$
 $\langle proof \rangle$

lemma *refl-comp-subset*:

$\llbracket \text{refl}(A,r); r \leq A * A \rrbracket \implies r \leq \text{converse}(r) \text{ } O \text{ } r$
 $\langle \text{proof} \rangle$

lemma *equiv-comp-eq*:

$\text{equiv}(A,r) \implies \text{converse}(r) \text{ } O \text{ } r = r$
 $\langle \text{proof} \rangle$

lemma *comp-equivI*:

$\llbracket \text{converse}(r) \text{ } O \text{ } r = r; \text{ domain}(r) = A \rrbracket \implies \text{equiv}(A,r)$
 $\langle \text{proof} \rangle$

lemma *equiv-class-subset*:

$\llbracket \text{sym}(r); \text{ trans}(r); \langle a,b \rangle: r \rrbracket \implies r''\{a\} \leq r''\{b\}$
 $\langle \text{proof} \rangle$

lemma *equiv-class-eq*:

$\llbracket \text{equiv}(A,r); \langle a,b \rangle: r \rrbracket \implies r''\{a\} = r''\{b\}$
 $\langle \text{proof} \rangle$

lemma *equiv-class-self*:

$\llbracket \text{equiv}(A,r); a: A \rrbracket \implies a: r''\{a\}$
 $\langle \text{proof} \rangle$

lemma *subset-equiv-class*:

$\llbracket \text{equiv}(A,r); r''\{b\} \leq r''\{a\}; b: A \rrbracket \implies \langle a,b \rangle: r$
 $\langle \text{proof} \rangle$

lemma *eq-equiv-class*: $\llbracket r''\{a\} = r''\{b\}; \text{ equiv}(A,r); b: A \rrbracket \implies \langle a,b \rangle: r$
 $\langle \text{proof} \rangle$

lemma *equiv-class-nondisjoint*:

$\llbracket \text{equiv}(A,r); x: (r''\{a\} \text{ Int } r''\{b\}) \rrbracket \implies \langle a,b \rangle: r$
 $\langle \text{proof} \rangle$

lemma *equiv-type*: $\text{equiv}(A,r) \implies r \leq A * A$

$\langle \text{proof} \rangle$

lemma *equiv-class-eq-iff*:

$\text{equiv}(A,r) \implies \langle x,y \rangle: r \iff r''\{x\} = r''\{y\} \ \& \ x:A \ \& \ y:A$
 $\langle \text{proof} \rangle$

lemma *eq-equiv-class-iff*:

$\llbracket \text{equiv}(A,r); x:A; y:A \rrbracket \implies r''\{x\} = r''\{y\} \iff \langle x,y \rangle : r$
 $\langle \text{proof} \rangle$

lemma *quotientI* [TC]: $x:A \implies r''\{x\} : A//r$

$\langle \text{proof} \rangle$

lemma *quotientE*:

$\llbracket X : A//r; !!x. \llbracket X = r''\{x\}; x:A \rrbracket \implies P \rrbracket \implies P$
 $\langle \text{proof} \rangle$

lemma *Union-quotient*:

$\text{equiv}(A,r) \implies \text{Union}(A//r) = A$
 $\langle \text{proof} \rangle$

lemma *quotient-disj*:

$\llbracket \text{equiv}(A,r); X : A//r; Y : A//r \rrbracket \implies X=Y \mid (X \text{ Int } Y \leq 0)$
 $\langle \text{proof} \rangle$

29.2 Defining Unary Operations upon Equivalence Classes

lemma *UN-equiv-class*:

$\llbracket \text{equiv}(A,r); b \text{ respects } r; a:A \rrbracket \implies (\text{UN } x:r''\{a\}. b(x)) = b(a)$
 $\langle \text{proof} \rangle$

lemma *UN-equiv-class-type*:

$\llbracket \text{equiv}(A,r); b \text{ respects } r; X : A//r; !!x. x : A \rrbracket \implies b(x) : B$
 $\implies (\text{UN } x:X. b(x)) : B$
 $\langle \text{proof} \rangle$

lemma *UN-equiv-class-inject*:

$\llbracket \text{equiv}(A,r); b \text{ respects } r;$
 $(\text{UN } x:X. b(x)) = (\text{UN } y:Y. b(y)); X : A//r; Y : A//r;$
 $!!x y. \llbracket x:A; y:A; b(x)=b(y) \rrbracket \implies \langle x,y \rangle : r \rrbracket$
 $\implies X=Y$
 $\langle \text{proof} \rangle$

29.3 Defining Binary Operations upon Equivalence Classes

lemma *congruent2-implies-congruent*:

$\llbracket \text{equiv}(A,r1); \text{congruent2}(r1,r2,b); a:A \rrbracket \implies \text{congruent}(r2,b(a))$
 $\langle \text{proof} \rangle$

lemma *congruent2-implies-congruent-UN*:

$$[\text{equiv}(A1, r1); \text{equiv}(A2, r2); \text{congruent2}(r1, r2, b); a: A2] \implies$$

$$\text{congruent}(r1, \%x1. \bigcup x2 \in r2^{\text{``}\{a\}}. b(x1, x2))$$

$$\langle \text{proof} \rangle$$

lemma *UN-equiv-class2*:

$$[\text{equiv}(A1, r1); \text{equiv}(A2, r2); \text{congruent2}(r1, r2, b); a1: A1; a2: A2]$$

$$\implies (\bigcup x1 \in r1^{\text{``}\{a1\}}. \bigcup x2 \in r2^{\text{``}\{a2\}}. b(x1, x2)) = b(a1, a2)$$

$$\langle \text{proof} \rangle$$

lemma *UN-equiv-class-type2*:

$$[\text{equiv}(A, r); b \text{ respects2 } r;$$

$$X1: A//r; X2: A//r;$$

$$!!x1\ x2. [x1: A; x2: A] \implies b(x1, x2) : B$$

$$] \implies (UN\ x1:X1. UN\ x2:X2. b(x1, x2)) : B$$

$$\langle \text{proof} \rangle$$

lemma *congruent2I*:

$$[\text{equiv}(A1, r1); \text{equiv}(A2, r2);$$

$$!!\ y\ z\ w. [w \in A2; \langle y, z \rangle \in r1] \implies b(y, w) = b(z, w);$$

$$!!\ y\ z\ w. [w \in A1; \langle y, z \rangle \in r2] \implies b(w, y) = b(w, z)$$

$$] \implies \text{congruent2}(r1, r2, b)$$

$$\langle \text{proof} \rangle$$

lemma *congruent2-commuteI*:

assumes *equivA*: $\text{equiv}(A, r)$
and *commute*: $!!\ y\ z. [y: A; z: A] \implies b(y, z) = b(z, y)$
and *cong*: $!!\ y\ z\ w. [w: A; \langle y, z \rangle: r] \implies b(w, y) = b(w, z)$
shows *b respects2 r*

$$\langle \text{proof} \rangle$$

lemma *congruent-commuteI*:

$$[\text{equiv}(A, r); Z: A//r;$$

$$!!w. [w: A] \implies \text{congruent}(r, \%z. b(w, z));$$

$$!!x\ y. [x: A; y: A] \implies b(y, x) = b(x, y)$$

$$] \implies \text{congruent}(r, \%w. UN\ z: Z. b(w, z))$$

$$\langle \text{proof} \rangle$$

end

30 Int-ZF: The Integers as Equivalence Classes Over Pairs of Natural Numbers

theory *Int-ZF* **imports** *EquivClass ArithSimp* **begin**

definition

intrel :: *i* **where**
intrel == {*p* : (*nat***nat*)*(*nat***nat*).
 $\exists x1\ y1\ x2\ y2. p = \langle \langle x1, y1 \rangle, \langle x2, y2 \rangle \rangle \ \& \ x1 \# + y2 = x2 \# + y1$ }

definition

int :: *i* **where**
int == (*nat***nat*)//*intrel*

definition

int-of :: *i* => *i* — coercion from *nat* to *int* (*\$#* - [80] 80) **where**
\$# m == *intrel* “ {<*nativify*(*m*), 0>}

definition

intify :: *i* => *i* — coercion from ANYTHING to *int* **where**
intify(*m*) == if *m* : *int* then *m* else *\$#0*

definition

raw-zminus :: *i* => *i* **where**
raw-zminus(*z*) == $\bigcup \langle x, y \rangle \in z. \text{intrel} \text{“} \{ \langle y, x \rangle \}$

definition

zminus :: *i* => *i* (*\$-* - [80] 80) **where**
\$- z == *raw-zminus* (*intify*(*z*))

definition

znegative :: *i* => *o* **where**
znegative(*z*) == $\exists x\ y. x < y \ \& \ y \in \text{nat} \ \& \ \langle x, y \rangle \in z$

definition

iszero :: *i* => *o* **where**
iszero(*z*) == *z* = *\$# 0*

definition

raw-nat-of :: *i* => *i* **where**
raw-nat-of(*z*) == *nativify* ($\bigcup \langle x, y \rangle \in z. x \# - y$)

definition

nat-of :: *i* => *i* **where**
nat-of(*z*) == *raw-nat-of* (*intify*(*z*))

definition

zmagnitude :: *i* => *i* **where**
— could be replaced by an absolute value function from *int* to *int*?
zmagnitude(*z*) ==
THE *m*. *m* ∈ *nat* & (($\sim \text{znegative}(z)$ & *z* = *\$# m*) |
($\text{znegative}(z)$ & *\$- z* = *\$# m*))

definition

$raw_zmult \quad :: \quad [i,i] => i \quad \textbf{where}$

$raw_zmult(z1, z2) ==$
 $\bigcup p1 \in z1. \bigcup p2 \in z2. \quad split(\%x1 \ y1. \ split(\%x2 \ y2.$
 $\quad \quad \quad intrel''\{\langle x1 \#*x2 \ \# + \ y1 \#*y2, \ x1 \#*y2 \ \# + \ y1 \#*x2 \rangle\}, \ p2), \ p1)$

definition

$zmult \quad :: \quad [i,i] => i \quad (\textbf{infixl} \ \$* \ 70) \quad \textbf{where}$
 $z1 \ \$* \ z2 == raw_zmult \ (intify(z1), intify(z2))$

definition

$raw_zadd \quad :: \quad [i,i] => i \quad \textbf{where}$
 $raw_zadd \ (z1, \ z2) ==$
 $\bigcup z1 \in z1. \bigcup z2 \in z2. \quad \textit{let} \ \langle x1, y1 \rangle = z1; \ \langle x2, y2 \rangle = z2$
 $\quad \quad \quad \textit{in} \ intrel''\{\langle x1 \ \# + \ x2, \ y1 \ \# + \ y2 \rangle\}$

definition

$zadd \quad :: \quad [i,i] => i \quad (\textbf{infixl} \ \$+ \ 65) \quad \textbf{where}$
 $z1 \ \$+ \ z2 == raw_zadd \ (intify(z1), intify(z2))$

definition

$zdiff \quad :: \quad [i,i] => i \quad (\textbf{infixl} \ \$- \ 65) \quad \textbf{where}$
 $z1 \ \$- \ z2 == z1 \ \$+ \ zminus(z2)$

definition

$zless \quad :: \quad [i,i] => o \quad (\textbf{infixl} \ \$< \ 50) \quad \textbf{where}$
 $z1 \ \$< \ z2 == znegative(z1 \ \$- \ z2)$

definition

$zle \quad :: \quad [i,i] => o \quad (\textbf{infixl} \ \$\leq \ 50) \quad \textbf{where}$
 $z1 \ \$\leq \ z2 == z1 \ \$< \ z2 \mid intify(z1) = intify(z2)$

notation (*xsymbols*)

$zmult \ (\textbf{infixl} \ \$\times \ 70) \textbf{ and}$
 $zle \ (\textbf{infixl} \ \$\leq \ 50) \text{ --- less than or equals}$

notation (*HTML output*)

$zmult \ (\textbf{infixl} \ \$\times \ 70) \textbf{ and}$
 $zle \ (\textbf{infixl} \ \$\leq \ 50)$

declare *quotientE* [*elim!*]

30.1 Proving that *intrel* is an equivalence relation

lemma *intrel-iff* [*simp*]:

$\langle \langle x1, y1 \rangle, \langle x2, y2 \rangle \rangle : intrel \ \langle - \rangle$

$\langle proof \rangle$

30.2 Collapsing rules: to remove *intify* from arithmetic expressions

lemma *intify-idem* [simp]: $intify(intify(x)) = intify(x)$
 $\langle proof \rangle$

lemma *int-of-natify* [simp]: $\$ \# (natify(m)) = \$ \# m$
 $\langle proof \rangle$

lemma *zminus-intify* [simp]: $\$ - (intify(m)) = \$ - m$
 $\langle proof \rangle$

lemma *zadd-intify1* [simp]: $intify(x) \$ + y = x \$ + y$
 $\langle proof \rangle$

lemma *zadd-intify2* [simp]: $x \$ + intify(y) = x \$ + y$
 $\langle proof \rangle$

lemma *zdiff-intify1* [simp]: $intify(x) \$ - y = x \$ - y$
 $\langle proof \rangle$

lemma *zdiff-intify2* [simp]: $x \$ - intify(y) = x \$ - y$
 $\langle proof \rangle$

lemma *zmult-intify1* [simp]: $intify(x) \$ * y = x \$ * y$
 $\langle proof \rangle$

lemma *zmult-intify2* [simp]: $x \$ * intify(y) = x \$ * y$
 $\langle proof \rangle$

lemma *zless-intify1* [simp]: $intify(x) \$ < y \leftrightarrow x \$ < y$
 $\langle proof \rangle$

lemma *zless-intify2* [simp]: $x \$ < intify(y) \leftrightarrow x \$ < y$
 $\langle proof \rangle$

lemma *zle-intify1* [simp]: $intify(x) \$ \leq y \leftrightarrow x \$ \leq y$
 $\langle proof \rangle$

lemma *zle-intify2* [simp]: $x \leq \text{intify}(y) \leftrightarrow x \leq y$
 <proof>

30.3 *zminus*: unary negation on *int*

lemma *zminus-congruent*: $(\%<x,y>. \text{intrel} \{<y,x>\})$ respects *intrel*
 <proof>

lemma *raw-zminus-type*: $z : \text{int} \implies \text{raw-zminus}(z) : \text{int}$
 <proof>

lemma *zminus-type* [TC,iff]: $\$-z : \text{int}$
 <proof>

lemma *raw-zminus-inject*:
 $[\text{raw-zminus}(z) = \text{raw-zminus}(w); z : \text{int}; w : \text{int}] \implies z = w$
 <proof>

lemma *zminus-inject-intify* [dest!]: $\$-z = \$-w \implies \text{intify}(z) = \text{intify}(w)$
 <proof>

lemma *zminus-inject*: $[\$-z = \$-w; z : \text{int}; w : \text{int}] \implies z = w$
 <proof>

lemma *raw-zminus*:
 $[\text{raw-zminus}(z) = \text{raw-zminus}(w); z : \text{int}; w : \text{int}] \implies z = w$
 <proof>

lemma *zminus*:
 $[\text{zminus}(z) = \text{zminus}(w); z : \text{int}; w : \text{int}] \implies z = w$
 <proof>

lemma *raw-zminus-zminus*: $z : \text{int} \implies \text{raw-zminus}(\text{raw-zminus}(z)) = z$
 <proof>

lemma *zminus-zminus-intify* [simp]: $\$-(\$-z) = \text{intify}(z)$
 <proof>

lemma *zminus-int0* [simp]: $\$-(\$ \# 0) = \$ \# 0$
 <proof>

lemma *zminus-zminus*: $z : \text{int} \implies \$-(\$-z) = z$
 <proof>

30.4 *znegative*: the test for negative integers

lemma *znegative*: $[\text{znegative}(z) = \text{znegative}(w); z : \text{int}; w : \text{int}] \implies z < w \leftrightarrow w < z$
 <proof>

lemma *not-znegative-int-of* [iff]: $\sim \text{znegative}(\$ \# n)$
 ⟨proof⟩

lemma *znegative-zminus-int-of* [simp]: $\text{znegative}(\$ - \$ \# \text{succ}(n))$
 ⟨proof⟩

lemma *not-znegative-imp-zero*: $\sim \text{znegative}(\$ - \$ \# n) \implies \text{natify}(n)=0$
 ⟨proof⟩

30.5 *nat-of*: Coercion of an Integer to a Natural Number

lemma *nat-of-intify* [simp]: $\text{nat-of}(\text{intify}(z)) = \text{nat-of}(z)$
 ⟨proof⟩

lemma *nat-of-congruent*: $(\lambda x. (\lambda \langle x, y \rangle. x \# - y)(x))$ respects *intrel*
 ⟨proof⟩

lemma *raw-nat-of*:
 $[\mid x \in \text{nat}; y \in \text{nat} \mid] \implies \text{raw-nat-of}(\text{intrel}^{\text{“}\{<x,y>\}\text{”}}) = x \# - y$
 ⟨proof⟩

lemma *raw-nat-of-int-of*: $\text{raw-nat-of}(\$ \# n) = \text{natify}(n)$
 ⟨proof⟩

lemma *nat-of-int-of* [simp]: $\text{nat-of}(\$ \# n) = \text{natify}(n)$
 ⟨proof⟩

lemma *raw-nat-of-type*: $\text{raw-nat-of}(z) \in \text{nat}$
 ⟨proof⟩

lemma *nat-of-type* [iff, TC]: $\text{nat-of}(z) \in \text{nat}$
 ⟨proof⟩

30.6 *zmagnitude*: magnitide of an integer, as a natural number

lemma *zmagnitude-int-of* [simp]: $\text{zmagnitude}(\$ \# n) = \text{natify}(n)$
 ⟨proof⟩

lemma *natify-int-of-eq*: $\text{natify}(x)=n \implies \$ \# x = \$ \# n$
 ⟨proof⟩

lemma *zmagnitude-zminus-int-of* [simp]: $\text{zmagnitude}(\$ - \$ \# n) = \text{natify}(n)$
 ⟨proof⟩

lemma *zmagnitude-type* [iff, TC]: $\text{zmagnitude}(z) \in \text{nat}$
 ⟨proof⟩

lemma *not-zneg-int-of*:

$\llbracket z : \text{int}; \sim \text{znegative}(z) \rrbracket \implies \exists n \in \text{nat}. z = \$\# n$
 $\langle \text{proof} \rangle$

lemma *not-zneg-mag [simp]*:

$\llbracket z : \text{int}; \sim \text{znegative}(z) \rrbracket \implies \$\# (\text{zmagnitude}(z)) = z$
 $\langle \text{proof} \rangle$

lemma *zneg-int-of*:

$\llbracket \text{znegative}(z); z : \text{int} \rrbracket \implies \exists n \in \text{nat}. z = \$- (\$ \# \text{succ}(n))$
 $\langle \text{proof} \rangle$

lemma *zneg-mag [simp]*:

$\llbracket \text{znegative}(z); z : \text{int} \rrbracket \implies \$\# (\text{zmagnitude}(z)) = \$- z$
 $\langle \text{proof} \rangle$

lemma *int-cases*: $z : \text{int} \implies \exists n \in \text{nat}. z = \$\# n \mid z = \$- (\$ \# \text{succ}(n))$

$\langle \text{proof} \rangle$

lemma *not-zneg-raw-nat-of*:

$\llbracket \sim \text{znegative}(z); z : \text{int} \rrbracket \implies \$\# (\text{raw-nat-of}(z)) = z$
 $\langle \text{proof} \rangle$

lemma *not-zneg-nat-of-intify*:

$\sim \text{znegative}(\text{intify}(z)) \implies \$\# (\text{nat-of}(z)) = \text{intify}(z)$
 $\langle \text{proof} \rangle$

lemma *not-zneg-nat-of*: $\llbracket \sim \text{znegative}(z); z : \text{int} \rrbracket \implies \$\# (\text{nat-of}(z)) = z$

$\langle \text{proof} \rangle$

lemma *zneg-nat-of [simp]*: $\text{znegative}(\text{intify}(z)) \implies \text{nat-of}(z) = 0$

$\langle \text{proof} \rangle$

30.7 op \$+: addition on int

Congruence Property for Addition

lemma *zadd-congruent2*:

$(\%z1 \ z2. \text{let } \langle x1, y1 \rangle = z1; \langle x2, y2 \rangle = z2$
 $\text{in } \text{intrel}''\{\langle x1 \# + x2, y1 \# + y2 \rangle\})$
 $\text{respects2 } \text{intrel}$
 $\langle \text{proof} \rangle$

lemma *raw-zadd-type*: $\llbracket z : \text{int}; w : \text{int} \rrbracket \implies \text{raw-zadd}(z, w) : \text{int}$

$\langle \text{proof} \rangle$

lemma *zadd-type [iff, TC]*: $z \# + w : \text{int}$

$\langle \text{proof} \rangle$

lemma *raw-zadd*:

$$[| x1 \in nat; y1 \in nat; x2 \in nat; y2 \in nat |]$$

$$\implies raw_zadd (intrel\{\langle x1, y1 \rangle\}, intrel\{\langle x2, y2 \rangle\}) =$$

$$intrel\{\langle x1 \# + x2, y1 \# + y2 \rangle\}$$

$$\langle proof \rangle$$

lemma *zadd*:

$$[| x1 \in nat; y1 \in nat; x2 \in nat; y2 \in nat |]$$

$$\implies (intrel\{\langle x1, y1 \rangle\} \$+ (intrel\{\langle x2, y2 \rangle\}) =$$

$$intrel\{\langle x1 \# + x2, y1 \# + y2 \rangle\}$$

$$\langle proof \rangle$$

lemma *raw-zadd-int0*: $z : int \implies raw_zadd (\$ \# 0, z) = z$

$$\langle proof \rangle$$

lemma *zadd-int0-intify [simp]*: $\$ \# 0 \$+ z = intify(z)$

$$\langle proof \rangle$$

lemma *zadd-int0*: $z : int \implies \$ \# 0 \$+ z = z$

$$\langle proof \rangle$$

lemma *raw-zminus-zadd-distrib*:

$$[| z : int; w : int |] \implies \$- raw_zadd(z, w) = raw_zadd(\$- z, \$- w)$$

$$\langle proof \rangle$$

lemma *zminus-zadd-distrib [simp]*: $\$- (z \$+ w) = \$- z \$+ \$- w$

$$\langle proof \rangle$$

lemma *raw-zadd-commute*:

$$[| z : int; w : int |] \implies raw_zadd(z, w) = raw_zadd(w, z)$$

$$\langle proof \rangle$$

lemma *zadd-commute*: $z \$+ w = w \$+ z$

$$\langle proof \rangle$$

lemma *raw-zadd-assoc*:

$$[| z1 : int; z2 : int; z3 : int |]$$

$$\implies raw_zadd (raw_zadd(z1, z2), z3) = raw_zadd(z1, raw_zadd(z2, z3))$$

$$\langle proof \rangle$$

lemma *zadd-assoc*: $(z1 \$+ z2) \$+ z3 = z1 \$+ (z2 \$+ z3)$

$$\langle proof \rangle$$

lemma *zadd-left-commute*: $z1 \$+ (z2 \$+ z3) = z2 \$+ (z1 \$+ z3)$

$$\langle proof \rangle$$

lemmas *zadd-ac = zadd-assoc zadd-commute zadd-left-commute*

lemma *int-of-add*: $\$ \# (m \# + n) = (\$ \# m) \$ + (\$ \# n)$
 $\langle \text{proof} \rangle$

lemma *int-succ-int-1*: $\$ \# \text{succ}(m) = \$ \# 1 \$ + (\$ \# m)$
 $\langle \text{proof} \rangle$

lemma *int-of-diff*:
 $[[m \in \text{nat}; \ n \leq m]] \implies \$ \# (m \# - n) = (\$ \# m) \$ - (\$ \# n)$
 $\langle \text{proof} \rangle$

lemma *raw-zadd-zminus-inverse*: $z : \text{int} \implies \text{raw-zadd } (z, \$ - z) = \$ \# 0$
 $\langle \text{proof} \rangle$

lemma *zadd-zminus-inverse* [simp]: $z \$ + (\$ - z) = \$ \# 0$
 $\langle \text{proof} \rangle$

lemma *zadd-zminus-inverse2* [simp]: $(\$ - z) \$ + z = \$ \# 0$
 $\langle \text{proof} \rangle$

lemma *zadd-int0-right-intify* [simp]: $z \$ + \$ \# 0 = \text{intify}(z)$
 $\langle \text{proof} \rangle$

lemma *zadd-int0-right*: $z : \text{int} \implies z \$ + \$ \# 0 = z$
 $\langle \text{proof} \rangle$

30.8 *op* \times : Integer Multiplication

Congruence property for multiplication

lemma *zmult-congruent2*:
 $(\%p1 \ p2. \text{split}(\%x1 \ y1. \text{split}(\%x2 \ y2. \\ \text{intrel}''\{\langle x1 \# * x2 \# + y1 \# * y2, x1 \# * y2 \# + y1 \# * x2 \rangle\}, p2), p1)) \\ \text{respects2 intrel}$
 $\langle \text{proof} \rangle$

lemma *raw-zmult-type*: $[[z : \text{int}; \ w : \text{int}]] \implies \text{raw-zmult}(z, w) : \text{int}$
 $\langle \text{proof} \rangle$

lemma *zmult-type* [iff, TC]: $z \$ * w : \text{int}$
 $\langle \text{proof} \rangle$

lemma *raw-zmult*:
 $[[x1 \in \text{nat}; \ y1 \in \text{nat}; \ x2 \in \text{nat}; \ y2 \in \text{nat}]] \\ \implies \text{raw-zmult}(\text{intrel}''\{\langle x1, y1 \rangle\}, \text{intrel}''\{\langle x2, y2 \rangle\}) = \\ \text{intrel}''\{\langle x1 \# * x2 \# + y1 \# * y2, x1 \# * y2 \# + y1 \# * x2 \rangle\}$
 $\langle \text{proof} \rangle$

lemma *zmult*:
 $[[x1 \in \text{nat}; \ y1 \in \text{nat}; \ x2 \in \text{nat}; \ y2 \in \text{nat}]]$

$$\implies (\text{intrel}^{\prime\prime}\{\langle x1, y1 \rangle\}) \$* (\text{intrel}^{\prime\prime}\{\langle x2, y2 \rangle\}) =$$

$$\text{intrel}^{\prime\prime}\{\langle x1 \#* x2 \# + y1 \#* y2, x1 \#* y2 \# + y1 \#* x2 \rangle\}$$

$$\langle \text{proof} \rangle$$

lemma *raw-zmult-int0*: $z : \text{int} \implies \text{raw-zmult } (\$ \# 0, z) = \$ \# 0$
 $\langle \text{proof} \rangle$

lemma *zmult-int0 [simp]*: $\$ \# 0 \$* z = \$ \# 0$
 $\langle \text{proof} \rangle$

lemma *raw-zmult-int1*: $z : \text{int} \implies \text{raw-zmult } (\$ \# 1, z) = z$
 $\langle \text{proof} \rangle$

lemma *zmult-int1-intify [simp]*: $\$ \# 1 \$* z = \text{intify}(z)$
 $\langle \text{proof} \rangle$

lemma *zmult-int1*: $z : \text{int} \implies \$ \# 1 \$* z = z$
 $\langle \text{proof} \rangle$

lemma *raw-zmult-commute*:

$$[\mid z : \text{int}; \ w : \text{int} \mid] \implies \text{raw-zmult}(z, w) = \text{raw-zmult}(w, z)$$
 $\langle \text{proof} \rangle$

lemma *zmult-commute*: $z \$* w = w \$* z$
 $\langle \text{proof} \rangle$

lemma *raw-zmult-zminus*:

$$[\mid z : \text{int}; \ w : \text{int} \mid] \implies \text{raw-zmult}(\$ - z, w) = \$ - \text{raw-zmult}(z, w)$$
 $\langle \text{proof} \rangle$

lemma *zmult-zminus [simp]*: $(\$ - z) \$* w = \$ - (z \$* w)$
 $\langle \text{proof} \rangle$

lemma *zmult-zminus-right [simp]*: $w \$* (\$ - z) = \$ - (w \$* z)$
 $\langle \text{proof} \rangle$

lemma *raw-zmult-assoc*:

$$[\mid z1 : \text{int}; \ z2 : \text{int}; \ z3 : \text{int} \mid]$$

$$\implies \text{raw-zmult } (\text{raw-zmult}(z1, z2), z3) = \text{raw-zmult}(z1, \text{raw-zmult}(z2, z3))$$
 $\langle \text{proof} \rangle$

lemma *zmult-assoc*: $(z1 \$* z2) \$* z3 = z1 \$* (z2 \$* z3)$
 $\langle \text{proof} \rangle$

lemma *zmult-left-commute*: $z1 \$* (z2 \$* z3) = z2 \$* (z1 \$* z3)$
 $\langle \text{proof} \rangle$

lemmas *zmult-ac = zmult-assoc zmult-commute zmult-left-commute*

lemma *raw-zadd-zmult-distrib:*

$[| \text{ } z1 : \text{int}; \text{ } z2 : \text{int}; \text{ } w : \text{int} \text{ } |]$
 $\implies \text{raw-zmult}(\text{raw-zadd}(z1, z2), w) =$
 $\text{raw-zadd} (\text{raw-zmult}(z1, w), \text{raw-zmult}(z2, w))$
 $\langle \text{proof} \rangle$

lemma *zadd-zmult-distrib:* $(z1 \ \$+ \ z2) \ \$* \ w = (z1 \ \$* \ w) \ \$+ \ (z2 \ \$* \ w)$
 $\langle \text{proof} \rangle$

lemma *zadd-zmult-distrib2:* $w \ \$* \ (z1 \ \$+ \ z2) = (w \ \$* \ z1) \ \$+ \ (w \ \$* \ z2)$
 $\langle \text{proof} \rangle$

lemmas *int-typechecks =*
int-of-type zminus-type zmagnitude-type zadd-type zmult-type

lemma *zdiff-type [iff, TC]:* $z \ \$- \ w : \text{int}$
 $\langle \text{proof} \rangle$

lemma *zminus-zdiff-eq [simp]:* $\$- \ (z \ \$- \ y) = y \ \$- \ z$
 $\langle \text{proof} \rangle$

lemma *zdiff-zmult-distrib:* $(z1 \ \$- \ z2) \ \$* \ w = (z1 \ \$* \ w) \ \$- \ (z2 \ \$* \ w)$
 $\langle \text{proof} \rangle$

lemma *zdiff-zmult-distrib2:* $w \ \$* \ (z1 \ \$- \ z2) = (w \ \$* \ z1) \ \$- \ (w \ \$* \ z2)$
 $\langle \text{proof} \rangle$

lemma *zadd-zdiff-eq:* $x \ \$+ \ (y \ \$- \ z) = (x \ \$+ \ y) \ \$- \ z$
 $\langle \text{proof} \rangle$

lemma *zdiff-zadd-eq:* $(x \ \$- \ y) \ \$+ \ z = (x \ \$+ \ z) \ \$- \ y$
 $\langle \text{proof} \rangle$

30.9 The "Less Than" Relation

lemma *zless-linear-lemma:*

$[| \text{ } z : \text{int}; \text{ } w : \text{int} \text{ } |] \implies z \ \$< \ w \mid z = w \mid w \ \$< \ z$
 $\langle \text{proof} \rangle$

lemma *zless-linear:* $z \ \$< \ w \mid \text{intify}(z) = \text{intify}(w) \mid w \ \$< \ z$
 $\langle \text{proof} \rangle$

lemma *zless-not-refl [iff]:* $\sim (z \ \$< \ z)$
 $\langle \text{proof} \rangle$

lemma *neq-iff-zless*: $[| x: int; y: int |] ==> (x \sim = y) <-> (x \$< y \mid y \$< x)$
 $\langle proof \rangle$

lemma *zless-imp-intify-neq*: $w \$< z ==> intify(w) \sim = intify(z)$
 $\langle proof \rangle$

lemma *zless-imp-succ-zadd-lemma*:
 $[| w \$< z; w: int; z: int |] ==> (\exists n \in nat. z = w \$+ \$\#(succ(n)))$
 $\langle proof \rangle$

lemma *zless-imp-succ-zadd*:
 $w \$< z ==> (\exists n \in nat. w \$+ \$\#(succ(n)) = intify(z))$
 $\langle proof \rangle$

lemma *zless-succ-zadd-lemma*:
 $w : int ==> w \$< w \$+ \$\# succ(n)$
 $\langle proof \rangle$

lemma *zless-succ-zadd*: $w \$< w \$+ \$\# succ(n)$
 $\langle proof \rangle$

lemma *zless-iff-succ-zadd*:
 $w \$< z <-> (\exists n \in nat. w \$+ \$\#(succ(n)) = intify(z))$
 $\langle proof \rangle$

lemma *zless-int-of [simp]*: $[| m \in nat; n \in nat |] ==> (\$ \# m \$< \$ \# n) <-> (m < n)$
 $\langle proof \rangle$

lemma *zless-trans-lemma*:
 $[| x \$< y; y \$< z; x: int; y: int; z: int |] ==> x \$< z$
 $\langle proof \rangle$

lemma *zless-trans*: $[| x \$< y; y \$< z |] ==> x \$< z$
 $\langle proof \rangle$

lemma *zless-not-sym*: $z \$< w ==> \sim (w \$< z)$
 $\langle proof \rangle$

lemmas *zless-asm* = *zless-not-sym* [*THEN swap, standard*]

lemma *zless-imp-zle*: $z \$< w ==> z \$<= w$
 $\langle proof \rangle$

lemma *zle-linear*: $z \$<= w \mid w \$<= z$
 $\langle proof \rangle$

30.10 Less Than or Equals

lemma *zle-refl*: $z \leq z$
 $\langle proof \rangle$

lemma *zle-eq-refl*: $x=y \implies x \leq y$
 $\langle proof \rangle$

lemma *zle-anti-sym-intify*: $[| x \leq y; y \leq x |] \implies \text{intify}(x) = \text{intify}(y)$
 $\langle proof \rangle$

lemma *zle-anti-sym*: $[| x \leq y; y \leq x; x: \text{int}; y: \text{int} |] \implies x=y$
 $\langle proof \rangle$

lemma *zle-trans-lemma*:
 $[| x: \text{int}; y: \text{int}; z: \text{int}; x \leq y; y \leq z |] \implies x \leq z$
 $\langle proof \rangle$

lemma *zle-trans*: $[| x \leq y; y \leq z |] \implies x \leq z$
 $\langle proof \rangle$

lemma *zle-zless-trans*: $[| i \leq j; j < k |] \implies i < k$
 $\langle proof \rangle$

lemma *zless-zle-trans*: $[| i < j; j \leq k |] \implies i < k$
 $\langle proof \rangle$

lemma *not-zless-iff-zle*: $\sim (z < w) \iff (w \leq z)$
 $\langle proof \rangle$

lemma *not-zle-iff-zless*: $\sim (z \leq w) \iff (w < z)$
 $\langle proof \rangle$

30.11 More subtraction laws (for *zcompare-rls*)

lemma *zdiff-zdiff-eq*: $(x - y) - z = x - (y + z)$
 $\langle proof \rangle$

lemma *zdiff-zdiff-eq2*: $x - (y - z) = (x + z) - y$
 $\langle proof \rangle$

lemma *zdiff-zless-iff*: $(x - y < z) \iff (x < z + y)$
 $\langle proof \rangle$

lemma *zless-zdiff-iff*: $(x < z - y) \iff (x + y < z)$
 $\langle proof \rangle$

lemma *zdiff-eq-iff*: $[| x: \text{int}; z: \text{int} |] \implies (x - y = z) \iff (x = z + y)$
 $\langle proof \rangle$

lemma *eq-zdiff-iff*: $[[\ x: \text{int}; z: \text{int} \]] \implies (x = z\$-y) <-> (x \$+ y = z)$
 $\langle \text{proof} \rangle$

lemma *zdiff-zle-iff-lemma*:
 $[[\ x: \text{int}; z: \text{int} \]] \implies (x\$-y \$<= z) <-> (x \$<= z \$+ y)$
 $\langle \text{proof} \rangle$

lemma *zdiff-zle-iff*: $(x\$-y \$<= z) <-> (x \$<= z \$+ y)$
 $\langle \text{proof} \rangle$

lemma *zle-zdiff-iff-lemma*:
 $[[\ x: \text{int}; z: \text{int} \]] \implies (x \$<= z\$-y) <-> (x \$+ y \$<= z)$
 $\langle \text{proof} \rangle$

lemma *zle-zdiff-iff*: $(x \$<= z\$-y) <-> (x \$+ y \$<= z)$
 $\langle \text{proof} \rangle$

This list of rewrites simplifies (in)equalities by bringing subtractions to the top and then moving negative terms to the other side. Use with *zadd-ac*

lemmas *zcompare-rls* =
zdiff-def [*symmetric*]
zadd-zdiff-eq *zdiff-zadd-eq* *zdiff-zdiff-eq* *zdiff-zdiff-eq2*
zdiff-zless-iff *zless-zdiff-iff* *zdiff-zle-iff* *zle-zdiff-iff*
zdiff-eq-iff *eq-zdiff-iff*

30.12 Monotonicity and Cancellation Results for Instantiation of the CancelNumerals Simprocs

lemma *zadd-left-cancel*:
 $[[\ w: \text{int}; w': \text{int} \]] \implies (z \$+ w' = z \$+ w) <-> (w' = w)$
 $\langle \text{proof} \rangle$

lemma *zadd-left-cancel-intify* [*simp*]:
 $(z \$+ w' = z \$+ w) <-> \text{intify}(w') = \text{intify}(w)$
 $\langle \text{proof} \rangle$

lemma *zadd-right-cancel*:
 $[[\ w: \text{int}; w': \text{int} \]] \implies (w' \$+ z = w \$+ z) <-> (w' = w)$
 $\langle \text{proof} \rangle$

lemma *zadd-right-cancel-intify* [*simp*]:
 $(w' \$+ z = w \$+ z) <-> \text{intify}(w') = \text{intify}(w)$
 $\langle \text{proof} \rangle$

lemma *zadd-right-cancel-zless* [*simp*]: $(w' \$+ z \$< w \$+ z) <-> (w' \$< w)$
 $\langle \text{proof} \rangle$

lemma *zadd-left-cancel-zless* [*simp*]: $(z \$+ w' \$< z \$+ w) <-> (w' \$< w)$
 $\langle \text{proof} \rangle$

lemma *zadd-right-cancel-zle* [*simp*]: $(w' \$+ z \$\leq w \$+ z) <-> w' \$\leq w$
 $\langle proof \rangle$

lemma *zadd-left-cancel-zle* [*simp*]: $(z \$+ w' \$\leq z \$+ w) <-> w' \$\leq w$
 $\langle proof \rangle$

lemmas *zadd-zless-mono1* = *zadd-right-cancel-zless* [*THEN iffD2, standard*]

lemmas *zadd-zless-mono2* = *zadd-left-cancel-zless* [*THEN iffD2, standard*]

lemmas *zadd-zle-mono1* = *zadd-right-cancel-zle* [*THEN iffD2, standard*]

lemmas *zadd-zle-mono2* = *zadd-left-cancel-zle* [*THEN iffD2, standard*]

lemma *zadd-zle-mono*: $[| w' \$\leq w; z' \$\leq z |] ==> w' \$+ z' \$\leq w \$+ z$
 $\langle proof \rangle$

lemma *zadd-zless-mono*: $[| w' \$< w; z' \$\leq z |] ==> w' \$+ z' \$< w \$+ z$
 $\langle proof \rangle$

30.13 Comparison laws

lemma *zminus-zless-zminus* [*simp*]: $(\$- x \$< \$- y) <-> (y \$< x)$
 $\langle proof \rangle$

lemma *zminus-zle-zminus* [*simp*]: $(\$- x \$\leq \$- y) <-> (y \$\leq x)$
 $\langle proof \rangle$

30.13.1 More inequality lemmas

lemma *equation-zminus*: $[| x: int; y: int |] ==> (x = \$- y) <-> (y = \$- x)$
 $\langle proof \rangle$

lemma *zminus-equation*: $[| x: int; y: int |] ==> (\$- x = y) <-> (\$- y = x)$
 $\langle proof \rangle$

lemma *equation-zminus-intify*: $(intify(x) = \$- y) <-> (intify(y) = \$- x)$
 $\langle proof \rangle$

lemma *zminus-equation-intify*: $(\$- x = intify(y)) <-> (\$- y = intify(x))$
 $\langle proof \rangle$

30.13.2 The next several equations are permutative: watch out!

lemma *zless-zminus*: $(x \text{ \$< \$- } y) <-> (y \text{ \$< \$- } x)$
 $\langle \text{proof} \rangle$

lemma *zminus-zless*: $(\text{\$- } x \text{ \$< } y) <-> (\text{\$- } y \text{ \$< } x)$
 $\langle \text{proof} \rangle$

lemma *zle-zminus*: $(x \text{ \$<= \$- } y) <-> (y \text{ \$<= \$- } x)$
 $\langle \text{proof} \rangle$

lemma *zminus-zle*: $(\text{\$- } x \text{ \$<= } y) <-> (\text{\$- } y \text{ \$<= } x)$
 $\langle \text{proof} \rangle$

end

31 Bin: Arithmetic on Binary Integers

theory *Bin*
imports *Int-ZF Datatype-ZF*
uses (*Tools/numeral-syntax.ML*)
begin

consts *bin* :: *i*
datatype
 bin = *Pls*
 | *Min*
 | *Bit* (*w*: *bin*, *b*: *bool*) (**infixl** *BIT* 90)

$\langle \text{ML} \rangle$

syntax
 -Int :: *xnum* => *i* (-)

consts
 integ-of :: *i* => *i*
 NCons :: [*i*,*i*] => *i*
 bin-succ :: *i* => *i*
 bin-pred :: *i* => *i*
 bin-minus :: *i* => *i*
 bin-adder :: *i* => *i*
 bin-mult :: [*i*,*i*] => *i*

primrec
 integ-of-Pls: *integ-of* (*Pls*) = $\text{\$}\# 0$
 integ-of-Min: *integ-of* (*Min*) = $\text{\$-}(\text{\$}\# 1)$
 integ-of-BIT: *integ-of* (*w BIT b*) = $\text{\$}\# b \text{\$+ } \text{integ-of}(w) \text{\$+ } \text{integ-of}(w)$

primrec

$NCons\text{-}Pls: NCons\ (Pls, b) = cond(b, Pls\ BIT\ b, Pls)$
 $NCons\text{-}Min: NCons\ (Min, b) = cond(b, Min, Min\ BIT\ b)$
 $NCons\text{-}BIT: NCons\ (w\ BIT\ c, b) = w\ BIT\ c\ BIT\ b$

primrec

$bin\text{-}succ\text{-}Pls: bin\text{-}succ\ (Pls) = Pls\ BIT\ 1$
 $bin\text{-}succ\text{-}Min: bin\text{-}succ\ (Min) = Pls$
 $bin\text{-}succ\text{-}BIT: bin\text{-}succ\ (w\ BIT\ b) = cond(b, bin\text{-}succ(w)\ BIT\ 0, NCons(w, 1))$

primrec

$bin\text{-}pred\text{-}Pls: bin\text{-}pred\ (Pls) = Min$
 $bin\text{-}pred\text{-}Min: bin\text{-}pred\ (Min) = Min\ BIT\ 0$
 $bin\text{-}pred\text{-}BIT: bin\text{-}pred\ (w\ BIT\ b) = cond(b, NCons(w, 0), bin\text{-}pred(w)\ BIT\ 1)$

primrec

$bin\text{-}minus\text{-}Pls:$
 $bin\text{-}minus\ (Pls) = Pls$
 $bin\text{-}minus\text{-}Min:$
 $bin\text{-}minus\ (Min) = Pls\ BIT\ 1$
 $bin\text{-}minus\text{-}BIT:$
 $bin\text{-}minus\ (w\ BIT\ b) = cond(b, bin\text{-}pred(NCons(bin\text{-}minus(w), 0)), bin\text{-}minus(w)\ BIT\ 0)$

primrec

$bin\text{-}adder\text{-}Pls:$
 $bin\text{-}adder\ (Pls) = (lam\ w:bin.\ w)$
 $bin\text{-}adder\text{-}Min:$
 $bin\text{-}adder\ (Min) = (lam\ w:bin.\ bin\text{-}pred(w))$
 $bin\text{-}adder\text{-}BIT:$
 $bin\text{-}adder\ (v\ BIT\ x) =$
 $(lam\ w:bin.$
 $bin\text{-}case\ (v\ BIT\ x, bin\text{-}pred(v\ BIT\ x),$
 $\%w\ y.\ NCons(bin\text{-}adder\ (v)\ ' cond(x\ and\ y, bin\text{-}succ(w), w),$
 $x\ xor\ y),$
 $w))$

definition

$bin\text{-}add :: [i, i] => i$ **where**
 $bin\text{-}add(v, w) == bin\text{-}adder(v)\ 'w$

primrec

$bin\text{-}mult\text{-}Pls:$
 $bin\text{-}mult\ (Pls, w) = Pls$

bin-mult-Min:
 $\text{bin-mult } (Min, w) = \text{bin-minus}(w)$
bin-mult-BIT:
 $\text{bin-mult } (v \text{ BIT } b, w) = \text{cond}(b, \text{bin-add}(NCons(\text{bin-mult}(v, w), 0), w), NCons(\text{bin-mult}(v, w), 0))$

$\langle ML \rangle$

declare *bin.intros* [*simp*, *TC*]

lemma *NCons-Pls-0*: $NCons(Pls, 0) = Pls$
 $\langle proof \rangle$

lemma *NCons-Pls-1*: $NCons(Pls, 1) = Pls \text{ BIT } 1$
 $\langle proof \rangle$

lemma *NCons-Min-0*: $NCons(Min, 0) = Min \text{ BIT } 0$
 $\langle proof \rangle$

lemma *NCons-Min-1*: $NCons(Min, 1) = Min$
 $\langle proof \rangle$

lemma *NCons-BIT*: $NCons(w \text{ BIT } x, b) = w \text{ BIT } x \text{ BIT } b$
 $\langle proof \rangle$

lemmas *NCons-simps* [*simp*] =
NCons-Pls-0 NCons-Pls-1 NCons-Min-0 NCons-Min-1 NCons-BIT

lemma *integ-of-type* [*TC*]: $w: \text{bin} \implies \text{integ-of}(w) : \text{int}$
 $\langle proof \rangle$

lemma *NCons-type* [*TC*]: $[[w: \text{bin}; b: \text{bool}]] \implies NCons(w, b) : \text{bin}$
 $\langle proof \rangle$

lemma *bin-succ-type* [*TC*]: $w: \text{bin} \implies \text{bin-succ}(w) : \text{bin}$
 $\langle proof \rangle$

lemma *bin-pred-type* [*TC*]: $w: \text{bin} \implies \text{bin-pred}(w) : \text{bin}$
 $\langle proof \rangle$

lemma *bin-minus-type* [*TC*]: $w: \text{bin} \implies \text{bin-minus}(w) : \text{bin}$
 $\langle proof \rangle$

lemma *bin-add-type* [*rule-format, TC*]:
 $v: \text{bin} \implies \text{ALL } w: \text{bin}. \text{bin-add}(v, w) : \text{bin}$
 $\langle \text{proof} \rangle$

lemma *bin-mult-type* [*TC*]: $[[v: \text{bin}; w: \text{bin}]] \implies \text{bin-mult}(v, w) : \text{bin}$
 $\langle \text{proof} \rangle$

31.0.3 The Carry and Borrow Functions, *bin-succ* and *bin-pred*

lemma *integ-of-NCons* [*simp*]:
 $[[w: \text{bin}; b: \text{bool}]] \implies \text{integ-of}(\text{NCons}(w, b)) = \text{integ-of}(w \text{ BIT } b)$
 $\langle \text{proof} \rangle$

lemma *integ-of-succ* [*simp*]:
 $w: \text{bin} \implies \text{integ-of}(\text{bin-succ}(w)) = \$\#1 \ \$+ \text{integ-of}(w)$
 $\langle \text{proof} \rangle$

lemma *integ-of-pred* [*simp*]:
 $w: \text{bin} \implies \text{integ-of}(\text{bin-pred}(w)) = \$- \ (\$ \#1) \ \$+ \text{integ-of}(w)$
 $\langle \text{proof} \rangle$

31.0.4 *bin-minus*: Unary Negation of Binary Integers

lemma *integ-of-minus*: $w: \text{bin} \implies \text{integ-of}(\text{bin-minus}(w)) = \$- \text{integ-of}(w)$
 $\langle \text{proof} \rangle$

31.0.5 *bin-add*: Binary Addition

lemma *bin-add-Pls* [*simp*]: $w: \text{bin} \implies \text{bin-add}(\text{Pls}, w) = w$
 $\langle \text{proof} \rangle$

lemma *bin-add-Pls-right*: $w: \text{bin} \implies \text{bin-add}(w, \text{Pls}) = w$
 $\langle \text{proof} \rangle$

lemma *bin-add-Min* [*simp*]: $w: \text{bin} \implies \text{bin-add}(\text{Min}, w) = \text{bin-pred}(w)$
 $\langle \text{proof} \rangle$

lemma *bin-add-Min-right*: $w: \text{bin} \implies \text{bin-add}(w, \text{Min}) = \text{bin-pred}(w)$
 $\langle \text{proof} \rangle$

lemma *bin-add-BIT-Pls* [*simp*]: $\text{bin-add}(v \text{ BIT } x, \text{Pls}) = v \text{ BIT } x$
 $\langle \text{proof} \rangle$

lemma *bin-add-BIT-Min* [*simp*]: $\text{bin-add}(v \text{ BIT } x, \text{Min}) = \text{bin-pred}(v \text{ BIT } x)$
 $\langle \text{proof} \rangle$

lemma *bin-add-BIT-BIT* [*simp*]:
 $[[w: \text{bin}; y: \text{bool}]]$
 $\implies \text{bin-add}(v \text{ BIT } x, w \text{ BIT } y) =$
 $\text{NCons}(\text{bin-add}(v, \text{cond}(x \text{ and } y, \text{bin-succ}(w), w)), x \text{ xor } y)$

$\langle proof \rangle$

lemma *integ-of-add* [rule-format]:

$v: bin \implies$

$ALL w: bin. integ-of(bin-add(v,w)) = integ-of(v) \$+ integ-of(w)$

$\langle proof \rangle$

lemma *diff-integ-of-eq*:

$[| v: bin; w: bin |]$

$\implies integ-of(v) \$- integ-of(w) = integ-of(bin-add(v, bin-minus(w)))$

$\langle proof \rangle$

31.0.6 *bin-mult*: Binary Multiplication

lemma *integ-of-mult*:

$[| v: bin; w: bin |]$

$\implies integ-of(bin-mult(v,w)) = integ-of(v) \$* integ-of(w)$

$\langle proof \rangle$

31.1 Computations

lemma *bin-succ-1*: $bin-succ(w BIT 1) = bin-succ(w) BIT 0$

$\langle proof \rangle$

lemma *bin-succ-0*: $bin-succ(w BIT 0) = NCons(w,1)$

$\langle proof \rangle$

lemma *bin-pred-1*: $bin-pred(w BIT 1) = NCons(w,0)$

$\langle proof \rangle$

lemma *bin-pred-0*: $bin-pred(w BIT 0) = bin-pred(w) BIT 1$

$\langle proof \rangle$

lemma *bin-minus-1*: $bin-minus(w BIT 1) = bin-pred(NCons(bin-minus(w), 0))$

$\langle proof \rangle$

lemma *bin-minus-0*: $bin-minus(w BIT 0) = bin-minus(w) BIT 0$

$\langle proof \rangle$

lemma *bin-add-BIT-11*: $w: bin \implies bin-add(v BIT 1, w BIT 1) =$

$NCons(bin-add(v, bin-succ(w)), 0)$

$\langle proof \rangle$

lemma *bin-add-BIT-10*: $w: bin \implies bin-add(v BIT 1, w BIT 0) =$

$NCons(bin-add(v,w), 1)$

$\langle proof \rangle$

lemma *bin-add-BIT-0*: $[| w: bin; y: bool |]$
 $\implies bin-add(v \text{ BIT } 0, w \text{ BIT } y) = NCons(bin-add(v, w), y)$
 $\langle proof \rangle$

lemma *bin-mult-1*: $bin-mult(v \text{ BIT } 1, w) = bin-add(NCons(bin-mult(v, w), 0), w)$
 $\langle proof \rangle$

lemma *bin-mult-0*: $bin-mult(v \text{ BIT } 0, w) = NCons(bin-mult(v, w), 0)$
 $\langle proof \rangle$

lemma *int-of-0*: $\$ \# 0 = \# 0$
 $\langle proof \rangle$

lemma *int-of-succ*: $\$ \# succ(n) = \# 1 \$ + \$ \# n$
 $\langle proof \rangle$

lemma *zminus-0* [simp]: $\$ - \# 0 = \# 0$
 $\langle proof \rangle$

lemma *zadd-0-intify* [simp]: $\# 0 \$ + z = intify(z)$
 $\langle proof \rangle$

lemma *zadd-0-right-intify* [simp]: $z \$ + \# 0 = intify(z)$
 $\langle proof \rangle$

lemma *zmult-1-intify* [simp]: $\# 1 \$ * z = intify(z)$
 $\langle proof \rangle$

lemma *zmult-1-right-intify* [simp]: $z \$ * \# 1 = intify(z)$
 $\langle proof \rangle$

lemma *zmult-0* [simp]: $\# 0 \$ * z = \# 0$
 $\langle proof \rangle$

lemma *zmult-0-right* [simp]: $z \$ * \# 0 = \# 0$
 $\langle proof \rangle$

lemma *zmult-minus1* [simp]: $\# -1 \$ * z = \$ - z$
 $\langle proof \rangle$

lemma *zmult-minus1-right* [simp]: $z \$ * \# -1 = \$ - z$
 $\langle proof \rangle$

31.2 Simplification Rules for Comparison of Binary Numbers

Thanks to Norbert Voelker

lemma *eq-integ-of-eq*:

$$\begin{aligned} & [[\ v: \text{bin};\ w: \text{bin}\]] \\ & \implies ((\text{integ-of}(v)) = \text{integ-of}(w)) <-> \\ & \quad \text{iszero} (\text{integ-of} (\text{bin-add} (v, \text{bin-minus}(w)))) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *iszero-integ-of-Pls*: $\text{iszero} (\text{integ-of}(Pls))$

$\langle \text{proof} \rangle$

lemma *nonzero-integ-of-Min*: $\sim \text{iszero} (\text{integ-of}(Min))$

$\langle \text{proof} \rangle$

lemma *iszero-integ-of-BIT*:

$$\begin{aligned} & [[\ w: \text{bin};\ x: \text{bool}\]] \\ & \implies \text{iszero} (\text{integ-of} (w \text{ BIT } x)) <-> (x=0 \ \& \ \text{iszero} (\text{integ-of}(w))) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *iszero-integ-of-0*:

$$\begin{aligned} & w: \text{bin} \implies \text{iszero} (\text{integ-of} (w \text{ BIT } 0)) <-> \text{iszero} (\text{integ-of}(w)) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *iszero-integ-of-1*: $w: \text{bin} \implies \sim \text{iszero} (\text{integ-of} (w \text{ BIT } 1))$

$\langle \text{proof} \rangle$

lemma *less-integ-of-eq-neg*:

$$\begin{aligned} & [[\ v: \text{bin};\ w: \text{bin}\]] \\ & \implies \text{integ-of}(v) \$< \text{integ-of}(w) \\ & \quad <-> \text{znegative} (\text{integ-of} (\text{bin-add} (v, \text{bin-minus}(w)))) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *not-neg-integ-of-Pls*: $\sim \text{znegative} (\text{integ-of}(Pls))$

$\langle \text{proof} \rangle$

lemma *neg-integ-of-Min*: $\text{znegative} (\text{integ-of}(Min))$

$\langle \text{proof} \rangle$

lemma *neg-integ-of-BIT*:

$$\begin{aligned} & [[\ w: \text{bin};\ x: \text{bool}\]] \\ & \implies \text{znegative} (\text{integ-of} (w \text{ BIT } x)) <-> \text{znegative} (\text{integ-of}(w)) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *le-integ-of-eq-not-less*:
 $(\text{integ-of}(x) \$<= (\text{integ-of}(w))) <-> \sim (\text{integ-of}(w) \$< (\text{integ-of}(x)))$
 $\langle \text{proof} \rangle$

declare *bin-succ-BIT* [*simp del*]
bin-pred-BIT [*simp del*]
bin-minus-BIT [*simp del*]
NCons-Pls [*simp del*]
NCons-Min [*simp del*]
bin-adder-BIT [*simp del*]
bin-mult-BIT [*simp del*]

declare *integ-of-Pls* [*simp del*] *integ-of-Min* [*simp del*] *integ-of-BIT* [*simp del*]

lemmas *bin-arith-extra-simps* =
integ-of-add [*symmetric*]
integ-of-minus [*symmetric*]
integ-of-mult [*symmetric*]
bin-succ-1 bin-succ-0
bin-pred-1 bin-pred-0
bin-minus-1 bin-minus-0
bin-add-Pls-right bin-add-Min-right
bin-add-BIT-0 bin-add-BIT-10 bin-add-BIT-11
diff-integ-of-eq
bin-mult-1 bin-mult-0 NCons-simps

lemmas *bin-arith-simps* =
bin-pred-Pls bin-pred-Min
bin-succ-Pls bin-succ-Min
bin-add-Pls bin-add-Min
bin-minus-Pls bin-minus-Min
bin-mult-Pls bin-mult-Min
bin-arith-extra-simps

lemmas *bin-rel-simps* =
eq-integ-of-eq iszero-integ-of-Pls nonzero-integ-of-Min
iszero-integ-of-0 iszero-integ-of-1
less-integ-of-eq-neg
not-neg-integ-of-Pls neg-integ-of-Min neg-integ-of-BIT

le-integ-of-eq-not-less

declare *bin-arith-simps* [*simp*]
declare *bin-rel-simps* [*simp*]

lemma *add-integ-of-left* [*simp*]:

$$[| v: \text{bin}; w: \text{bin} |] \\
\implies \text{integ-of}(v) \$+ (\text{integ-of}(w) \$+ z) = (\text{integ-of}(\text{bin-add}(v,w)) \$+ z)$$
 $\langle \text{proof} \rangle$

lemma *mult-integ-of-left* [*simp*]:

$$[| v: \text{bin}; w: \text{bin} |] \\
\implies \text{integ-of}(v) \$* (\text{integ-of}(w) \$* z) = (\text{integ-of}(\text{bin-mult}(v,w)) \$* z)$$
 $\langle \text{proof} \rangle$

lemma *add-integ-of-diff1* [*simp*]:

$$[| v: \text{bin}; w: \text{bin} |] \\
\implies \text{integ-of}(v) \$+ (\text{integ-of}(w) \$- c) = \text{integ-of}(\text{bin-add}(v,w)) \$- (c)$$
 $\langle \text{proof} \rangle$

lemma *add-integ-of-diff2* [*simp*]:

$$[| v: \text{bin}; w: \text{bin} |] \\
\implies \text{integ-of}(v) \$+ (c \$- \text{integ-of}(w)) = \\
\text{integ-of}(\text{bin-add}(v, \text{bin-minus}(w))) \$+ (c)$$
 $\langle \text{proof} \rangle$

declare *int-of-0* [*simp*] *int-of-succ* [*simp*]

lemma *zdiff0* [*simp*]: $\#0 \$- x = \$-x$
 $\langle \text{proof} \rangle$

lemma *zdiff0-right* [*simp*]: $x \$- \#0 = \text{intify}(x)$
 $\langle \text{proof} \rangle$

lemma *zdiff-self* [*simp*]: $x \$- x = \#0$
 $\langle \text{proof} \rangle$

lemma *znegative-iff-zless-0*: $k: \text{int} \implies \text{znegative}(k) <-> k \$< \#0$
 $\langle \text{proof} \rangle$

lemma *zero-zless-imp-znegative-zminus*: $[| \#0 \$< k; k: \text{int} |] \implies \text{znegative}(\$-k)$
 $\langle \text{proof} \rangle$

lemma *zero-zle-int-of* [simp]: $\#0 \leq \#n$
 $\langle \text{proof} \rangle$

lemma *nat-of-0* [simp]: $\text{nat-of}(\#0) = 0$
 $\langle \text{proof} \rangle$

lemma *nat-le-int0-lemma*: $[\#0 \leq z; z: \text{int}] \implies \text{nat-of}(z) = 0$
 $\langle \text{proof} \rangle$

lemma *nat-le-int0*: $z \leq \#0 \implies \text{nat-of}(z) = 0$
 $\langle \text{proof} \rangle$

lemma *int-of-eq-0-imp-natify-eq-0*: $\#n = \#0 \implies \text{natify}(n) = 0$
 $\langle \text{proof} \rangle$

lemma *nat-of-zminus-int-of*: $\text{nat-of}(\#- \#n) = 0$
 $\langle \text{proof} \rangle$

lemma *int-of-nat-of*: $\#0 \leq z \implies \# \text{nat-of}(z) = \text{intify}(z)$
 $\langle \text{proof} \rangle$

declare *int-of-nat-of* [simp] *nat-of-zminus-int-of* [simp]

lemma *int-of-nat-of-if*: $\# \text{nat-of}(z) = (\text{if } \#0 \leq z \text{ then } \text{intify}(z) \text{ else } \#0)$
 $\langle \text{proof} \rangle$

lemma *zless-nat-iff-int-zless*: $[\#m: \text{nat}; z: \text{int}] \implies (m < \text{nat-of}(z)) \iff (\#m \leq z)$
 $\langle \text{proof} \rangle$

lemma *zless-nat-conj-lemma*: $\#0 \leq z \implies (\text{nat-of}(w) < \text{nat-of}(z)) \iff (w \leq z)$
 $\langle \text{proof} \rangle$

lemma *zless-nat-conj*: $(\text{nat-of}(w) < \text{nat-of}(z)) \iff (\#0 \leq z \ \& \ w \leq z)$
 $\langle \text{proof} \rangle$

lemma *integ-of-minus-reorient* [simp]:
 $(\text{integ-of}(w) = \#- x) \iff (\#- x = \text{integ-of}(w))$
 $\langle \text{proof} \rangle$

lemma *integ-of-add-reorient* [simp]:
 $(\text{integ-of}(w) = x \#+ y) \iff (x \#+ y = \text{integ-of}(w))$

$\langle proof \rangle$

lemma *integ-of-diff-reorient* [simp]:

$$(integ-of(w) = x \$- y) <-> (x \$- y = integ-of(w))$$

$\langle proof \rangle$

lemma *integ-of-mult-reorient* [simp]:

$$(integ-of(w) = x \$* y) <-> (x \$* y = integ-of(w))$$

$\langle proof \rangle$

end

theory *IntArith* **imports** *Bin*

uses (*int-arith.ML*)

begin

lemmas [simp] =

zminus-equation [where $y = integ-of(w)$, standard]

equation-zminus [where $x = integ-of(w)$, standard]

lemmas [iff] =

zminus-zless [where $y = integ-of(w)$, standard]

zless-zminus [where $x = integ-of(w)$, standard]

lemmas [iff] =

zminus-zle [where $y = integ-of(w)$, standard]

zle-zminus [where $x = integ-of(w)$, standard]

lemmas [simp] =

Let-def [where $s = integ-of(w)$, standard]

lemma *zless-iff-zdiff-zless-0*: $(x \$< y) <-> (x \$-y \$< \#0)$

$\langle proof \rangle$

lemma *eq-iff-zdiff-eq-0*: $[| x: int; y: int |] ==> (x = y) <-> (x \$-y = \#0)$

$\langle proof \rangle$

lemma *zle-iff-zdiff-zle-0*: $(x \$<= y) <-> (x \$-y \$<= \#0)$

$\langle proof \rangle$

lemma *left-zadd-zmult-distrib*: $i\$*u \$+ (j\$*u \$+ k) = (i\$+j)\$*u \$+ k$
 $\langle proof \rangle$

lemmas *rel-iff-rel-0-rls* =
zless-iff-zdiff-zless-0 [where $y = u \$+ v$, *standard*]
eq-iff-zdiff-eq-0 [where $y = u \$+ v$, *standard*]
zle-iff-zdiff-zle-0 [where $y = u \$+ v$, *standard*]
zless-iff-zdiff-zless-0 [where $y = n$]
eq-iff-zdiff-eq-0 [where $y = n$]
zle-iff-zdiff-zle-0 [where $y = n$]

lemma *eq-add-iff1*: $(i\$*u \$+ m = j\$*u \$+ n) <-> ((i\$-j)\$*u \$+ m = intify(n))$
 $\langle proof \rangle$

lemma *eq-add-iff2*: $(i\$*u \$+ m = j\$*u \$+ n) <-> (intify(m) = (j\$-i)\$*u \$+ n)$
 $\langle proof \rangle$

lemma *less-add-iff1*: $(i\$*u \$+ m \$< j\$*u \$+ n) <-> ((i\$-j)\$*u \$+ m \$< n)$
 $\langle proof \rangle$

lemma *less-add-iff2*: $(i\$*u \$+ m \$< j\$*u \$+ n) <-> (m \$< (j\$-i)\$*u \$+ n)$
 $\langle proof \rangle$

lemma *le-add-iff1*: $(i\$*u \$+ m \$<= j\$*u \$+ n) <-> ((i\$-j)\$*u \$+ m \$<= n)$
 $\langle proof \rangle$

lemma *le-add-iff2*: $(i\$*u \$+ m \$<= j\$*u \$+ n) <-> (m \$<= (j\$-i)\$*u \$+ n)$
 $\langle proof \rangle$

$\langle ML \rangle$

end

32 IntDiv-ZF: The Division Operators Div and Mod

theory *IntDiv-ZF* **imports** *IntArith OrderArith* **begin**

definition

$quorem :: [i, i] \Rightarrow o$ **where**
 $quorem == \%<a, b> <q, r>.$
 $a = b\$*q \$+ r \ \&$
 $(\#0\$<b \ \& \ \#0\$<=r \ \& \ r\$<b \mid \sim(\#0\$<b) \ \& \ b\$<r \ \& \ r \$<= \#0)$

definition

$adjust :: [i, i] \Rightarrow i$ **where**
 $adjust(b) == \%<q, r>. \text{ if } \#0 \$<= r\$-b \text{ then } <\#2\$*q \$+ \#1, r\$-b>$
 $\text{ else } <\#2\$*q, r>$

definition

$posDivAlg :: i \Rightarrow i$ **where**
 $posDivAlg(ab) ==$
 $wfrec(measure(int*int, \%<a, b>. \text{ nat-of } (a \$- b \$+ \#1)),$
 $ab,$
 $\%<a, b> f. \text{ if } (a\$<b \mid b\$<=\#0) \text{ then } <\#0, a>$
 $\text{ else } adjust(b, f \text{ ‘ } <a, \#2\$*b>))$

definition

$negDivAlg :: i \Rightarrow i$ **where**
 $negDivAlg(ab) ==$
 $wfrec(measure(int*int, \%<a, b>. \text{ nat-of } (\$- a \$- b)),$
 $ab,$
 $\%<a, b> f. \text{ if } (\#0 \$<= a\$+b \mid b\$<=\#0) \text{ then } <\#-1, a\$+b>$
 $\text{ else } adjust(b, f \text{ ‘ } <a, \#2\$*b>))$

definition

$negateSnd :: i \Rightarrow i$ **where**
 $negateSnd == \%<q, r>. <q, \$-r>$

definition

$divAlg :: i \Rightarrow i$ **where**
 $divAlg ==$
 $\%<a, b>. \text{ if } \#0 \$<= a \text{ then}$
 $\text{ if } \#0 \$<= b \text{ then } posDivAlg (<a, b>)$
 $\text{ else if } a=\#0 \text{ then } <\#0, \#0>$
 $\text{ else } negateSnd (negDivAlg (<\$-a, \$-b>))$

else
if $\#0 \$< b$ *then* $\text{negDivAlg } (<a, b>)$
else $\text{negateSnd } (\text{posDivAlg } (<\$-a, \$-b>))$

definition

$\text{zdiv} :: [i, i] \Rightarrow i$ (**infixl** zdiv 70) **where**
 $a \text{ zdiv } b == \text{fst } (\text{divAlg } (<\text{intify}(a), \text{intify}(b)>))$

definition

$\text{zmod} :: [i, i] \Rightarrow i$ (**infixl** zmod 70) **where**
 $a \text{ zmod } b == \text{snd } (\text{divAlg } (<\text{intify}(a), \text{intify}(b)>))$

lemma $\text{zspos-add-zspos-imp-zspos}$: $[\#0 \$< x; \#0 \$< y] \Rightarrow \#0 \$< x \$+ y$
 $\langle \text{proof} \rangle$

lemma $\text{zpos-add-zpos-imp-zpos}$: $[\#0 \$\leq x; \#0 \$\leq y] \Rightarrow \#0 \$\leq x \$+ y$
 $\langle \text{proof} \rangle$

lemma $\text{zneg-add-zneg-imp-zneg}$: $[x \$< \#0; y \$< \#0] \Rightarrow x \$+ y \$< \#0$
 $\langle \text{proof} \rangle$

lemma $\text{zneg-or-0-add-zneg-or-0-imp-zneg-or-0}$:
 $[x \$\leq \#0; y \$\leq \#0] \Rightarrow x \$+ y \$\leq \#0$
 $\langle \text{proof} \rangle$

lemma $\text{zero-lt-zmagnitude}$: $[\#0 \$< k; k \in \text{int}] \Rightarrow 0 < \text{zmagnitude}(k)$
 $\langle \text{proof} \rangle$

lemma $\text{zless-add-succ-iff}$:
 $(w \$< z \$+ \$\# \text{succ}(m)) <-> (w \$< z \$+ \$\#m \mid \text{intify}(w) = z \$+ \$\#m)$
 $\langle \text{proof} \rangle$

lemma zadd-succ-lemma :
 $z \in \text{int} \Rightarrow (w \$+ \$\# \text{succ}(m) \$\leq z) <-> (w \$+ \$\#m \$< z)$
 $\langle \text{proof} \rangle$

lemma zadd-succ-zle-iff : $(w \$+ \$\# \text{succ}(m) \$\leq z) <-> (w \$+ \$\#m \$< z)$
 $\langle \text{proof} \rangle$

lemma *zless-add1-iff-zle*: $(w \leq z + \#1) \leftrightarrow (w \leq z)$
 $\langle proof \rangle$

lemma *add1-zle-iff*: $(w + \#1 \leq z) \leftrightarrow (w \leq z)$
 $\langle proof \rangle$

lemma *add1-left-zle-iff*: $(\#1 + w \leq z) \leftrightarrow (w \leq z)$
 $\langle proof \rangle$

lemma *zmult-mono-lemma*: $k \in nat \implies i \leq j \implies i * \#k \leq j * \#k$
 $\langle proof \rangle$

lemma *zmult-zle-mono1*: $[i \leq j; \#0 \leq k] \implies i * k \leq j * k$
 $\langle proof \rangle$

lemma *zmult-zle-mono1-neg*: $[i \leq j; k \leq \#0] \implies j * k \leq i * k$
 $\langle proof \rangle$

lemma *zmult-zle-mono2*: $[i \leq j; \#0 \leq k] \implies k * i \leq k * j$
 $\langle proof \rangle$

lemma *zmult-zle-mono2-neg*: $[i \leq j; k \leq \#0] \implies k * j \leq k * i$
 $\langle proof \rangle$

lemma *zmult-zle-mono*:
 $[i \leq j; k \leq l; \#0 \leq j; \#0 \leq k] \implies i * k \leq j * l$
 $\langle proof \rangle$

lemma *zmult-zless-mono2-lemma* [rule-format]:
 $[i < j; k \in nat] \implies 0 < k \longrightarrow \#k * i < \#k * j$
 $\langle proof \rangle$

lemma *zmult-zless-mono2*: $[i < j; \#0 < k] \implies k * i < k * j$
 $\langle proof \rangle$

lemma *zmult-zless-mono1*: $[i < j; \#0 < k] \implies i * k < j * k$
 $\langle proof \rangle$

lemma *zmult-zless-mono*:
 $[i < j; k < l; \#0 < j; \#0 < k] \implies i * k < j * l$
 $\langle proof \rangle$

lemma *zmult-zless-mono1-neg*: $[[i \$< j; k \$< \#0]] ==> j\$*k \$< i\$*k$
 $\langle proof \rangle$

lemma *zmult-zless-mono2-neg*: $[[i \$< j; k \$< \#0]] ==> k\$*j \$< k\$*i$
 $\langle proof \rangle$

lemma *zmult-eq-lemma*:
 $[[m \in int; n \in int]] ==> (m = \#0 \mid n = \#0) <-> (m\$*n = \#0)$
 $\langle proof \rangle$

lemma *zmult-eq-0-iff* [iff]: $(m\$*n = \#0) <-> (intify(m) = \#0 \mid intify(n) = \#0)$
 $\langle proof \rangle$

lemma *zmult-zless-lemma*:
 $[[k \in int; m \in int; n \in int]] ==> (m\$*k \$< n\$*k) <-> ((\#0 \$< k \& m\$<n) \mid (k \$< \#0 \& n\$<m))$
 $\langle proof \rangle$

lemma *zmult-zless-cancel2*:
 $(m\$*k \$< n\$*k) <-> ((\#0 \$< k \& m\$<n) \mid (k \$< \#0 \& n\$<m))$
 $\langle proof \rangle$

lemma *zmult-zless-cancel1*:
 $(k\$*m \$< k\$*n) <-> ((\#0 \$< k \& m\$<n) \mid (k \$< \#0 \& n\$<m))$
 $\langle proof \rangle$

lemma *zmult-zle-cancel2*:
 $(m\$*k \$<= n\$*k) <-> ((\#0 \$< k --> m\$<=n) \& (k \$< \#0 --> n\$<=m))$
 $\langle proof \rangle$

lemma *zmult-zle-cancel1*:
 $(k\$*m \$<= k\$*n) <-> ((\#0 \$< k --> m\$<=n) \& (k \$< \#0 --> n\$<=m))$
 $\langle proof \rangle$

lemma *int-eq-iff-zle*: $[[m \in int; n \in int]] ==> m=n <-> (m \$<= n \& n \$<= m)$
 $\langle proof \rangle$

lemma *zmult-cancel2-lemma*:

$$[[k \in \text{int}; m \in \text{int}; n \in \text{int}]] \implies (m * k = n * k) \leftrightarrow (k = \#0 \mid m = n)$$

 $\langle \text{proof} \rangle$

lemma *zmult-cancel2* [simp]:

$$(m * k = n * k) \leftrightarrow (\text{intify}(k) = \#0 \mid \text{intify}(m) = \text{intify}(n))$$

 $\langle \text{proof} \rangle$

lemma *zmult-cancel1* [simp]:

$$(k * m = k * n) \leftrightarrow (\text{intify}(k) = \#0 \mid \text{intify}(m) = \text{intify}(n))$$

 $\langle \text{proof} \rangle$

32.1 Uniqueness and monotonicity of quotients and remainders

lemma *unique-quotient-lemma*:

$$[[b * q' \$+ r' \$\leq b * q \$+ r; \#0 \$\leq r'; \#0 \$\leq b; r \$\leq b]]$$

$$\implies q' \$\leq q$$

 $\langle \text{proof} \rangle$

lemma *unique-quotient-lemma-neg*:

$$[[b * q' \$+ r' \$\leq b * q \$+ r; r \$\leq \#0; b \$\leq \#0; b \$\leq r']]$$

$$\implies q \$\leq q'$$

 $\langle \text{proof} \rangle$

lemma *unique-quotient*:

$$[[\text{quorem}(<a, b>, <q, r>); \text{quorem}(<a, b>, <q', r'>); b \in \text{int}; b \sim \#0;$$

$$q \in \text{int}; q' \in \text{int}]] \implies q = q'$$

 $\langle \text{proof} \rangle$

lemma *unique-remainder*:

$$[[\text{quorem}(<a, b>, <q, r>); \text{quorem}(<a, b>, <q', r'>); b \in \text{int}; b \sim \#0;$$

$$q \in \text{int}; q' \in \text{int};$$

$$r \in \text{int}; r' \in \text{int}]] \implies r = r'$$

 $\langle \text{proof} \rangle$

32.2 Correctness of posDivAlg, the Division Algorithm for $a \geq 0$ and $b > 0$

lemma *adjust-eq* [simp]:

$$\text{adjust}(b, <q, r>) = (\text{let } \text{diff} = r \$- b \text{ in}$$

$$\text{if } \#0 \$\leq \text{diff} \text{ then } <\#2 * q \$+ \#1, \text{diff}>$$

$$\text{else } <\#2 * q, r>)$$

 $\langle \text{proof} \rangle$

lemma *posDivAlg-termination*:

$$[[\#0 \$\leq b; \sim a \$\leq b]]$$

$$\implies \text{nat-of}(a \$- \#2 \$\times b \$+ \#1) < \text{nat-of}(a \$- b \$+ \#1)$$

$\langle proof \rangle$

lemmas *posDivAlg-unfold* = *def-wfrec* [*OF posDivAlg-def wf-measure*]

lemma *posDivAlg-eqn*:

$[[\#0 \$< b; a \in int; b \in int]] ==>$

$posDivAlg(<a,b>) =$

$(if\ a\$<b\ then\ <\#0,a>\ else\ adjust(b,\ posDivAlg\ (<a,\ \#2\$*b>)))$

$\langle proof \rangle$

lemma *posDivAlg-induct-lemma* [*rule-format*]:

assumes *prem*:

$!!a\ b.\ [[\ a \in int; b \in int;$

$\sim (a \$< b \mid b \$\leq \#0) \dashrightarrow P(<a,\ \#2 \$* b>)]] ==> P(<a,b>)$

shows $<u,v> \in int*int \dashrightarrow P(<u,v>)$

$\langle proof \rangle$

lemma *posDivAlg-induct* [*consumes 2*]:

assumes *u-int*: $u \in int$

and *v-int*: $v \in int$

and *ih*: $!!a\ b.\ [[\ a \in int; b \in int;$

$\sim (a \$< b \mid b \$\leq \#0) \dashrightarrow P(a,\ \#2 \$* b)]] ==> P(a,b)$

shows $P(u,v)$

$\langle proof \rangle$

lemma *intify-eq-0-iff-zle*: $intify(m) = \#0 \leftrightarrow (m \$\leq \#0 \ \& \ \#0 \$\leq m)$

$\langle proof \rangle$

32.3 Some convenient biconditionals for products of signs

lemma *zmult-pos*: $[[\#0 \$< i; \#0 \$< j]] ==> \#0 \$< i \$* j$

$\langle proof \rangle$

lemma *zmult-neg*: $[[i \$< \#0; j \$< \#0]] ==> \#0 \$< i \$* j$

$\langle proof \rangle$

lemma *zmult-pos-neg*: $[[\#0 \$< i; j \$< \#0]] ==> i \$* j \$< \#0$

$\langle proof \rangle$

lemma *int-0-less-lemma*:

$[[x \in int; y \in int]]$

$==> (\#0 \$< x \$* y) \leftrightarrow (\#0 \$< x \ \& \ \#0 \$< y \mid x \$< \#0 \ \& \ y \$< \#0)$

$\langle proof \rangle$

lemma *int-0-less-mult-iff*:

$(\#0 \ \$< x \ \$* y) <-> (\#0 \ \$< x \ \& \ \#0 \ \$< y \mid x \ \$< \#0 \ \& \ y \ \$< \#0)$
 $\langle proof \rangle$

lemma *int-0-le-lemma*:

$[\mid x \in int; y \in int \mid]$
 $==> (\#0 \ \$<= x \ \$* y) <-> (\#0 \ \$<= x \ \& \ \#0 \ \$<= y \mid x \ \$<= \#0 \ \& \ y \ \$<= \#0)$
 $\langle proof \rangle$

lemma *int-0-le-mult-iff*:

$(\#0 \ \$<= x \ \$* y) <-> ((\#0 \ \$<= x \ \& \ \#0 \ \$<= y) \mid (x \ \$<= \#0 \ \& \ y \ \$<= \#0))$
 $\langle proof \rangle$

lemma *zmult-less-0-iff*:

$(x \ \$* y \ \$< \#0) <-> (\#0 \ \$< x \ \& \ y \ \$< \#0 \mid x \ \$< \#0 \ \& \ \#0 \ \$< y)$
 $\langle proof \rangle$

lemma *zmult-le-0-iff*:

$(x \ \$* y \ \$<= \#0) <-> (\#0 \ \$<= x \ \& \ y \ \$<= \#0 \mid x \ \$<= \#0 \ \& \ \#0 \ \$<= y)$
 $\langle proof \rangle$

lemma *posDivAlg-type* [rule-format]:

$[\mid a \in int; b \in int \mid] ==> posDivAlg(<a,b>) \in int * int$
 $\langle proof \rangle$

lemma *posDivAlg-correct* [rule-format]:

$[\mid a \in int; b \in int \mid]$
 $==> \#0 \ \$<= a \ ---> \#0 \ \$< b \ ---> quorem (<a,b>, posDivAlg(<a,b>))$
 $\langle proof \rangle$

32.4 Correctness of negDivAlg, the division algorithm for $a \neq 0$ and $b \neq 0$

lemma *negDivAlg-termination*:

$[\mid \#0 \ \$< b; a \ \$+ b \ \$< \#0 \mid]$
 $==> nat-of(\$- a \ \$- \#2 \ \$* b) < nat-of(\$- a \ \$- b)$
 $\langle proof \rangle$

lemmas *negDivAlg-unfold* = def-wfrec [OF negDivAlg-def wf-measure]

lemma *negDivAlg-eqn*:

$[\mid \#0 \ \$< b; a : int; b : int \mid] ==>$
 $negDivAlg(<a,b>) =$
 $(if \ \#0 \ \$<= a \$+ b \ then \ <\#-1, a \$+ b>$
 $\quad \text{else } adjust(b, negDivAlg (<a, \#2 \$* b>)))$

$\langle proof \rangle$

lemma *negDivAlg-induct-lemma* [rule-format]:

assumes *prem*:

!!*a b*. [| *a* ∈ *int*; *b* ∈ *int*;
 $\sim (\#0 \ \$\leq a \ \$+ b \mid b \ \$\leq \#0) \longrightarrow P(<a, \#2 \ \$* b>)$ |]
 $\implies P(<a, b>)$

shows $<u, v> \in int * int \longrightarrow P(<u, v>)$

$\langle proof \rangle$

lemma *negDivAlg-induct* [consumes 2]:

assumes *u-int*: *u* ∈ *int*

and *v-int*: *v* ∈ *int*

and *ih*: !!*a b*. [| *a* ∈ *int*; *b* ∈ *int*;
 $\sim (\#0 \ \$\leq a \ \$+ b \mid b \ \$\leq \#0) \longrightarrow P(a, \#2 \ \$* b)$ |]
 $\implies P(a, b)$

shows $P(u, v)$

$\langle proof \rangle$

lemma *negDivAlg-type*:

[| *a* ∈ *int*; *b* ∈ *int* |] $\implies negDivAlg(<a, b>) \in int * int$

$\langle proof \rangle$

lemma *negDivAlg-correct* [rule-format]:

[| *a* ∈ *int*; *b* ∈ *int* |]
 $\implies a \ \$< \#0 \longrightarrow \#0 \ \$< b \longrightarrow quorem(<a, b>, negDivAlg(<a, b>))$

$\langle proof \rangle$

32.5 Existence shown by proving the division algorithm to be correct

lemma *quorem-0*: [| *b* ≠ #0; *b* ∈ *int* |] $\implies quorem(<\#0, b>, <\#0, \#0>)$

$\langle proof \rangle$

lemma *posDivAlg-zero-divisor*: $posDivAlg(<a, \#0>) = <\#0, a>$

$\langle proof \rangle$

lemma *posDivAlg-0* [simp]: $posDivAlg(<\#0, b>) = <\#0, \#0>$

$\langle proof \rangle$

lemma *linear-arith-lemma*: $\sim (\#0 \ \$\leq \#-1 \ \$+ b) \implies (b \ \$\leq \#0)$

$\langle proof \rangle$

lemma *negDivAlg-minus1* [simp]: $\text{negDivAlg } (<\#-1, b>) = <\#-1, b\$-\#1>$
 $\langle \text{proof} \rangle$

lemma *negateSnd-eq* [simp]: $\text{negateSnd } (<q, r>) = <q, \$-r>$
 $\langle \text{proof} \rangle$

lemma *negateSnd-type*: $qr \in \text{int} * \text{int} \implies \text{negateSnd } (qr) \in \text{int} * \text{int}$
 $\langle \text{proof} \rangle$

lemma *quorem-neg*:
 $[[\text{quorem } (<\$-a, \$-b>, qr); a \in \text{int}; b \in \text{int}; qr \in \text{int} * \text{int}]]$
 $\implies \text{quorem } (<a, b>, \text{negateSnd}(qr))$
 $\langle \text{proof} \rangle$

lemma *divAlg-correct*:
 $[[b \neq \#0; a \in \text{int}; b \in \text{int}]] \implies \text{quorem } (<a, b>, \text{divAlg } (<a, b>))$
 $\langle \text{proof} \rangle$

lemma *divAlg-type*: $[[a \in \text{int}; b \in \text{int}]] \implies \text{divAlg } (<a, b>) \in \text{int} * \text{int}$
 $\langle \text{proof} \rangle$

lemma *zdiv-intify1* [simp]: $\text{intify}(x) \text{ zdiv } y = x \text{ zdiv } y$
 $\langle \text{proof} \rangle$

lemma *zdiv-intify2* [simp]: $x \text{ zdiv } \text{intify}(y) = x \text{ zdiv } y$
 $\langle \text{proof} \rangle$

lemma *zdiv-type* [iff, TC]: $z \text{ zdiv } w \in \text{int}$
 $\langle \text{proof} \rangle$

lemma *zmod-intify1* [simp]: $\text{intify}(x) \text{ zmod } y = x \text{ zmod } y$
 $\langle \text{proof} \rangle$

lemma *zmod-intify2* [simp]: $x \text{ zmod } \text{intify}(y) = x \text{ zmod } y$
 $\langle \text{proof} \rangle$

lemma *zmod-type* [iff, TC]: $z \text{ zmod } w \in \text{int}$
 $\langle \text{proof} \rangle$

lemma *DIVISION-BY-ZERO-ZDIV*: $a \text{ zdiv } \#0 = \#0$
 $\langle \text{proof} \rangle$

lemma *DIVISION-BY-ZERO-ZMOD*: $a \text{ zmod } \#0 = \text{intify}(a)$

$\langle proof \rangle$

lemma *raw-zmod-zdiv-equality*:

$[[a \in int; b \in int]] \implies a = b \$* (a \text{ zdiv } b) \$+ (a \text{ zmod } b)$
 $\langle proof \rangle$

lemma *zmod-zdiv-equality*: $intify(a) = b \$* (a \text{ zdiv } b) \$+ (a \text{ zmod } b)$
 $\langle proof \rangle$

lemma *pos-mod*: $\#0 \$< b \implies \#0 \$<= a \text{ zmod } b \ \& \ a \text{ zmod } b \$< b$
 $\langle proof \rangle$

lemmas *pos-mod-sign* = *pos-mod* [*THEN* *conjunct1*, *standard*]
and *pos-mod-bound* = *pos-mod* [*THEN* *conjunct2*, *standard*]

lemma *neg-mod*: $b \$< \#0 \implies a \text{ zmod } b \$<= \#0 \ \& \ b \$< a \text{ zmod } b$
 $\langle proof \rangle$

lemmas *neg-mod-sign* = *neg-mod* [*THEN* *conjunct1*, *standard*]
and *neg-mod-bound* = *neg-mod* [*THEN* *conjunct2*, *standard*]

lemma *quorem-div-mod*:

$[[b \neq \#0; a \in int; b \in int]]$
 $\implies quorem (<a,b>, <a \text{ zdiv } b, a \text{ zmod } b>)$
 $\langle proof \rangle$

lemma *quorem-div*:

$[[quorem (<a,b>, <q,r>); b \neq \#0; a \in int; b \in int; q \in int]]$
 $\implies a \text{ zdiv } b = q$
 $\langle proof \rangle$

lemma *quorem-mod*:

$[[quorem (<a,b>, <q,r>); b \neq \#0; a \in int; b \in int; q \in int; r \in int]]$
 $\implies a \text{ zmod } b = r$
 $\langle proof \rangle$

lemma *zdiv-pos-pos-trivial-raw*:

$[[a \in int; b \in int; \#0 \$<= a; a \$< b]]$ $\implies a \text{ zdiv } b = \#0$
 $\langle proof \rangle$

lemma *zdiv-pos-pos-trivial*: $[[\#0 \$<= a; a \$< b]]$ $\implies a \text{ zdiv } b = \#0$

$\langle proof \rangle$

lemma *zdiv-neg-neg-trivial-raw*:

$\llbracket a \in \text{int}; b \in \text{int}; a \leq 0; b < a \rrbracket \implies a \text{ zdiv } b = 0$
 $\langle proof \rangle$

lemma *zdiv-neg-neg-trivial*: $\llbracket a \leq 0; b < a \rrbracket \implies a \text{ zdiv } b = 0$

$\langle proof \rangle$

lemma *zadd-le-0-lemma*: $\llbracket a+b \leq 0; 0 < a; 0 < b \rrbracket \implies \text{False}$

$\langle proof \rangle$

lemma *zdiv-pos-neg-trivial-raw*:

$\llbracket a \in \text{int}; b \in \text{int}; 0 < a; a+b \leq 0 \rrbracket \implies a \text{ zdiv } b = -1$
 $\langle proof \rangle$

lemma *zdiv-pos-neg-trivial*: $\llbracket 0 < a; a+b \leq 0 \rrbracket \implies a \text{ zdiv } b = -1$

$\langle proof \rangle$

lemma *zmod-pos-pos-trivial-raw*:

$\llbracket a \in \text{int}; b \in \text{int}; 0 \leq a; a < b \rrbracket \implies a \text{ zmod } b = a$
 $\langle proof \rangle$

lemma *zmod-pos-pos-trivial*: $\llbracket 0 \leq a; a < b \rrbracket \implies a \text{ zmod } b = \text{intify}(a)$

$\langle proof \rangle$

lemma *zmod-neg-neg-trivial-raw*:

$\llbracket a \in \text{int}; b \in \text{int}; a \leq 0; b < a \rrbracket \implies a \text{ zmod } b = a$
 $\langle proof \rangle$

lemma *zmod-neg-neg-trivial*: $\llbracket a \leq 0; b < a \rrbracket \implies a \text{ zmod } b = \text{intify}(a)$

$\langle proof \rangle$

lemma *zmod-pos-neg-trivial-raw*:

$\llbracket a \in \text{int}; b \in \text{int}; 0 < a; a+b \leq 0 \rrbracket \implies a \text{ zmod } b = a+b$
 $\langle proof \rangle$

lemma *zmod-pos-neg-trivial*: $\llbracket 0 < a; a+b \leq 0 \rrbracket \implies a \text{ zmod } b = a+b$

$\langle proof \rangle$

lemma *zdiv-zminus-zminus-raw*:

$[|a \in \text{int}; b \in \text{int}|] \implies (\$-a) \text{ zdiv } (\$-b) = a \text{ zdiv } b$
 $\langle \text{proof} \rangle$

lemma *zdiv-zminus-zminus [simp]*: $(\$-a) \text{ zdiv } (\$-b) = a \text{ zdiv } b$

$\langle \text{proof} \rangle$

lemma *zmod-zminus-zminus-raw*:

$[|a \in \text{int}; b \in \text{int}|] \implies (\$-a) \text{ zmod } (\$-b) = \$- (a \text{ zmod } b)$
 $\langle \text{proof} \rangle$

lemma *zmod-zminus-zminus [simp]*: $(\$-a) \text{ zmod } (\$-b) = \$- (a \text{ zmod } b)$

$\langle \text{proof} \rangle$

32.6 division of a number by itself

lemma *self-quotient-aux1*: $[| \#0 \$< a; a = r \$+ a\$*q; r \$< a |] \implies \#1 \$<= q$
 $\langle \text{proof} \rangle$

lemma *self-quotient-aux2*: $[| \#0 \$< a; a = r \$+ a\$*q; \#0 \$<= r |] \implies q \$<= \#1$
 $\langle \text{proof} \rangle$

lemma *self-quotient*:

$[| \text{quorem}(<a,a>,<q,r>); a \in \text{int}; q \in \text{int}; a \neq \#0 |] \implies q = \#1$
 $\langle \text{proof} \rangle$

lemma *self-remainder*:

$[| \text{quorem}(<a,a>,<q,r>); a \in \text{int}; q \in \text{int}; r \in \text{int}; a \neq \#0 |] \implies r = \#0$
 $\langle \text{proof} \rangle$

lemma *zdiv-self-raw*: $[|a \neq \#0; a \in \text{int}|] \implies a \text{ zdiv } a = \#1$
 $\langle \text{proof} \rangle$

lemma *zdiv-self [simp]*: $\text{intify}(a) \neq \#0 \implies a \text{ zdiv } a = \#1$
 $\langle \text{proof} \rangle$

lemma *zmod-self-raw*: $a \in \text{int} \implies a \text{ zmod } a = \#0$
 $\langle \text{proof} \rangle$

lemma *zmod-self [simp]*: $a \text{ zmod } a = \#0$
 $\langle \text{proof} \rangle$

32.7 Computation of division and remainder

lemma *zdiv-zero [simp]*: $\#0 \text{ zdiv } b = \#0$
 $\langle \text{proof} \rangle$

lemma *zdiv-eq-minus1*: $\#0 \ \$< \ b \implies \#-1 \ zdiv \ b = \#-1$
 $\langle proof \rangle$

lemma *zmod-zero* [*simp*]: $\#0 \ zmod \ b = \#0$
 $\langle proof \rangle$

lemma *zdiv-minus1*: $\#0 \ \$< \ b \implies \#-1 \ zdiv \ b = \#-1$
 $\langle proof \rangle$

lemma *zmod-minus1*: $\#0 \ \$< \ b \implies \#-1 \ zmod \ b = b \ \$- \ #1$
 $\langle proof \rangle$

lemma *zdiv-pos-pos*: $[\#0 \ \$< \ a; \ \#0 \ \$\leq \ b]$
 $\implies a \ zdiv \ b = fst \ (posDivAlg(<intify(a), \ intify(b)>))$
 $\langle proof \rangle$

lemma *zmod-pos-pos*:
 $[\#0 \ \$< \ a; \ \#0 \ \$\leq \ b]$
 $\implies a \ zmod \ b = snd \ (posDivAlg(<intify(a), \ intify(b)>))$
 $\langle proof \rangle$

lemma *zdiv-neg-pos*:
 $[a \ \$< \ \#0; \ \#0 \ \$< \ b]$
 $\implies a \ zdiv \ b = fst \ (negDivAlg(<intify(a), \ intify(b)>))$
 $\langle proof \rangle$

lemma *zmod-neg-pos*:
 $[a \ \$< \ \#0; \ \#0 \ \$< \ b]$
 $\implies a \ zmod \ b = snd \ (negDivAlg(<intify(a), \ intify(b)>))$
 $\langle proof \rangle$

lemma *zdiv-pos-neg*:
 $[\#0 \ \$< \ a; \ b \ \$< \ \#0]$
 $\implies a \ zdiv \ b = fst \ (negateSnd(negDivAlg \ (<\$-a, \ \$-b>)))$
 $\langle proof \rangle$

lemma *zmod-pos-neg*:
 $[\#0 \ \$< \ a; \ b \ \$< \ \#0]$
 $\implies a \ zmod \ b = snd \ (negateSnd(negDivAlg \ (<\$-a, \ \$-b>)))$
 $\langle proof \rangle$

lemma *zdiv-neg-neg*:

$$[| a \$ < \#0; b \$ \leq \#0 |] \implies a \text{ zdiv } b = \text{fst } (\text{negateSnd}(\text{posDivAlg}(<\$-a, \$-b>)))$$
 $\langle \text{proof} \rangle$

lemma *zmod-neg-neg*:

$$[| a \$ < \#0; b \$ \leq \#0 |] \implies a \text{ zmod } b = \text{snd } (\text{negateSnd}(\text{posDivAlg}(<\$-a, \$-b>)))$$
 $\langle \text{proof} \rangle$

declare *zdiv-pos-pos* [of integ-of (v) integ-of (w), standard, simp]
declare *zdiv-neg-pos* [of integ-of (v) integ-of (w), standard, simp]
declare *zdiv-pos-neg* [of integ-of (v) integ-of (w), standard, simp]
declare *zdiv-neg-neg* [of integ-of (v) integ-of (w), standard, simp]
declare *zmod-pos-pos* [of integ-of (v) integ-of (w), standard, simp]
declare *zmod-neg-pos* [of integ-of (v) integ-of (w), standard, simp]
declare *zmod-pos-neg* [of integ-of (v) integ-of (w), standard, simp]
declare *zmod-neg-neg* [of integ-of (v) integ-of (w), standard, simp]
declare *posDivAlg-eqn* [of concl: integ-of (v) integ-of (w), standard, simp]
declare *negDivAlg-eqn* [of concl: integ-of (v) integ-of (w), standard, simp]

lemma *zmod-1* [simp]: $a \text{ zmod } \#1 = \#0$
 $\langle \text{proof} \rangle$

lemma *zdiv-1* [simp]: $a \text{ zdiv } \#1 = \text{intify}(a)$
 $\langle \text{proof} \rangle$

lemma *zmod-minus1-right* [simp]: $a \text{ zmod } \#-1 = \#0$
 $\langle \text{proof} \rangle$

lemma *zdiv-minus1-right-raw*: $a \in \text{int} \implies a \text{ zdiv } \#-1 = \$-a$
 $\langle \text{proof} \rangle$

lemma *zdiv-minus1-right*: $a \text{ zdiv } \#-1 = \$-a$
 $\langle \text{proof} \rangle$

declare *zdiv-minus1-right* [simp]

32.8 Monotonicity in the first argument (divisor)

lemma *zdiv-mono1*: $[| a \$ \leq a'; \#0 \$ < b |] \implies a \text{ zdiv } b \$ \leq a' \text{ zdiv } b$
 $\langle \text{proof} \rangle$

lemma *zdiv-mono1-neg*: $[| a \$ \leq a'; b \$ < \#0 |] \implies a' \text{ zdiv } b \$ \leq a \text{ zdiv } b$
 $\langle \text{proof} \rangle$

32.9 Monotonicity in the second argument (dividend)

lemma *q-pos-lemma*:

$[[\#0 \leq b' * q' + r'; r' < b'; \#0 < b']] \implies \#0 \leq q'$
 $\langle proof \rangle$

lemma *zdiv-mono2-lemma*:

$[[b * q + r = b' * q' + r'; \#0 \leq b' * q' + r';$
 $r' < b'; \#0 \leq r; \#0 < b'; b' \leq b]]$
 $\implies q \leq q'$
 $\langle proof \rangle$

lemma *zdiv-mono2-raw*:

$[[\#0 \leq a; \#0 < b'; b' \leq b; a \in int]]$
 $\implies a \text{ zdiv } b \leq a \text{ zdiv } b'$
 $\langle proof \rangle$

lemma *zdiv-mono2*:

$[[\#0 \leq a; \#0 < b'; b' \leq b]]$
 $\implies a \text{ zdiv } b \leq a \text{ zdiv } b'$
 $\langle proof \rangle$

lemma *q-neg-lemma*:

$[[b' * q' + r' < \#0; \#0 \leq r'; \#0 < b']] \implies q' < \#0$
 $\langle proof \rangle$

lemma *zdiv-mono2-neg-lemma*:

$[[b * q + r = b' * q' + r'; b' * q' + r' < \#0;$
 $r < b; \#0 \leq r'; \#0 < b'; b' \leq b]]$
 $\implies q' \leq q$
 $\langle proof \rangle$

lemma *zdiv-mono2-neg-raw*:

$[[a < \#0; \#0 < b'; b' \leq b; a \in int]]$
 $\implies a \text{ zdiv } b' \leq a \text{ zdiv } b$
 $\langle proof \rangle$

lemma *zdiv-mono2-neg*: $[[a < \#0; \#0 < b'; b' \leq b]]$

$\implies a \text{ zdiv } b' \leq a \text{ zdiv } b$
 $\langle proof \rangle$

32.10 More algebraic laws for zdiv and zmod

lemma *zmult1-lemma*:

$[[\text{quorem}(\langle b, c \rangle, \langle q, r \rangle); c \in int; c \neq \#0]]$
 $\implies \text{quorem}(\langle a * b, c \rangle, \langle a * q + (a * r) \text{ zdiv } c, (a * r) \text{ zmod } c \rangle)$
 $\langle proof \rangle$

lemma *zdiv-zmult1-eq-raw*:

$[[b \in \text{int}; c \in \text{int}]]$
 $\implies (a\$*b) \text{ zdiv } c = a\$*(b \text{ zdiv } c) \$+ a\$*(b \text{ zmod } c) \text{ zdiv } c$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult1-eq*: $(a\$*b) \text{ zdiv } c = a\$*(b \text{ zdiv } c) \$+ a\$*(b \text{ zmod } c) \text{ zdiv } c$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult1-eq-raw*:

$[[b \in \text{int}; c \in \text{int}]] \implies (a\$*b) \text{ zmod } c = a\$*(b \text{ zmod } c) \text{ zmod } c$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult1-eq*: $(a\$*b) \text{ zmod } c = a\$*(b \text{ zmod } c) \text{ zmod } c$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult1-eq'*: $(a\$*b) \text{ zmod } c = ((a \text{ zmod } c) \$* b) \text{ zmod } c$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult-distrib*: $(a\$*b) \text{ zmod } c = ((a \text{ zmod } c) \$* (b \text{ zmod } c)) \text{ zmod } c$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult-self1* [simp]: $\text{intify}(b) \neq \#0 \implies (a\$*b) \text{ zdiv } b = \text{intify}(a)$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult-self2* [simp]: $\text{intify}(b) \neq \#0 \implies (b\$*a) \text{ zdiv } b = \text{intify}(a)$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult-self1* [simp]: $(a\$*b) \text{ zmod } b = \#0$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult-self2* [simp]: $(b\$*a) \text{ zmod } b = \#0$
 $\langle \text{proof} \rangle$

lemma *zadd1-lemma*:

$[[\text{quorem}(\langle a, c \rangle, \langle aq, ar \rangle); \text{quorem}(\langle b, c \rangle, \langle bq, br \rangle);$
 $c \in \text{int}; c \neq \#0]]$
 $\implies \text{quorem}(\langle a\$+b, c \rangle, \langle aq \$+ bq \$+ (ar\$+br) \text{ zdiv } c, (ar\$+br) \text{ zmod } c \rangle)$
 $\langle \text{proof} \rangle$

lemma *zdiv-zadd1-eq-raw*:

$[[a \in \text{int}; b \in \text{int}; c \in \text{int}]] \implies$
 $(a\$+b) \text{ zdiv } c = a \text{ zdiv } c \$+ b \text{ zdiv } c \$+ ((a \text{ zmod } c \$+ b \text{ zmod } c) \text{ zdiv } c)$
 $\langle \text{proof} \rangle$

lemma *zdiv-zadd1-eq*:

$$(a\$+b) \text{ zdiv } c = a \text{ zdiv } c \$+ b \text{ zdiv } c \$+ ((a \text{ zmod } c \$+ b \text{ zmod } c) \text{ zdiv } c)$$

<proof>

lemma *zmod-zadd1-eq-raw*:

$$[[a \in \text{int}; b \in \text{int}; c \in \text{int}]] \\ ==> (a\$+b) \text{ zmod } c = (a \text{ zmod } c \$+ b \text{ zmod } c) \text{ zmod } c$$

<proof>

lemma *zmod-zadd1-eq*: $(a\$+b) \text{ zmod } c = (a \text{ zmod } c \$+ b \text{ zmod } c) \text{ zmod } c$
<proof>

lemma *zmod-div-trivial-raw*:

$$[[a \in \text{int}; b \in \text{int}]] ==> (a \text{ zmod } b) \text{ zdiv } b = \#0$$

<proof>

lemma *zmod-div-trivial* [simp]: $(a \text{ zmod } b) \text{ zdiv } b = \#0$
<proof>

lemma *zmod-mod-trivial-raw*:

$$[[a \in \text{int}; b \in \text{int}]] ==> (a \text{ zmod } b) \text{ zmod } b = a \text{ zmod } b$$

<proof>

lemma *zmod-mod-trivial* [simp]: $(a \text{ zmod } b) \text{ zmod } b = a \text{ zmod } b$
<proof>

lemma *zmod-zadd-left-eq*: $(a\$+b) \text{ zmod } c = ((a \text{ zmod } c) \$+ b) \text{ zmod } c$
<proof>

lemma *zmod-zadd-right-eq*: $(a\$+b) \text{ zmod } c = (a \$+ (b \text{ zmod } c)) \text{ zmod } c$
<proof>

lemma *zdiv-zadd-self1* [simp]:

$$\text{intify}(a) \neq \#0 ==> (a\$+b) \text{ zdiv } a = b \text{ zdiv } a \$+ \#1$$

<proof>

lemma *zdiv-zadd-self2* [simp]:

$$\text{intify}(a) \neq \#0 ==> (b\$+a) \text{ zdiv } a = b \text{ zdiv } a \$+ \#1$$

<proof>

lemma *zmod-zadd-self1* [simp]: $(a\$+b) \text{ zmod } a = b \text{ zmod } a$
<proof>

lemma *zmod-zadd-self2* [simp]: $(b\$+a) \text{ zmod } a = b \text{ zmod } a$
<proof>

32.11 proving a zdiv (b*c) = (a zdiv b) zdiv c

lemma *zdiv-zmult2-aux1*:

$[| \#0 \$< c; \ b \$< r; \ r \$\leq \#0 \ |] \implies b\$*c \$< b\$*(q \text{ zmod } c) \$+ r$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult2-aux2*:

$[| \#0 \$< c; \ \ b \$< r; \ r \$\leq \#0 \ |] \implies b \$* (q \text{ zmod } c) \$+ r \$\leq \#0$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult2-aux3*:

$[| \#0 \$< c; \ \#0 \$\leq r; \ r \$< b \ |] \implies \#0 \$\leq b \$* (q \text{ zmod } c) \$+ r$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult2-aux4*:

$[| \#0 \$< c; \ \#0 \$\leq r; \ r \$< b \ |] \implies b \$* (q \text{ zmod } c) \$+ r \$< b \$* c$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult2-lemma*:

$[| \text{quorem } (<a,b>, <q,r>); \ a \in \text{int}; \ b \in \text{int}; \ b \neq \#0; \ \#0 \$< c \ |]$
 $\implies \text{quorem } (<a,b\$*c>, <q \text{ zdiv } c, b\$*(q \text{ zmod } c) \$+ r>)$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult2-eq-row*:

$[| \#0 \$< c; \ a \in \text{int}; \ b \in \text{int} \ |] \implies a \text{ zdiv } (b\$*c) = (a \text{ zdiv } b) \text{ zdiv } c$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult2-eq*: $\#0 \$< c \implies a \text{ zdiv } (b\$*c) = (a \text{ zdiv } b) \text{ zdiv } c$

$\langle \text{proof} \rangle$

lemma *zmod-zmult2-eq-row*:

$[| \#0 \$< c; \ a \in \text{int}; \ b \in \text{int} \ |]$
 $\implies a \text{ zmod } (b\$*c) = b\$*(a \text{ zdiv } b \text{ zmod } c) \$+ a \text{ zmod } b$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult2-eq*:

$\#0 \$< c \implies a \text{ zmod } (b\$*c) = b\$*(a \text{ zdiv } b \text{ zmod } c) \$+ a \text{ zmod } b$
 $\langle \text{proof} \rangle$

32.12 Cancellation of common factors in "zdiv"

lemma *zdiv-zmult-zmult1-aux1*:

$[| \#0 \$< b; \ \text{intify}(c) \neq \#0 \ |] \implies (c\$*a) \text{ zdiv } (c\$*b) = a \text{ zdiv } b$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult-zmult1-aux2*:

$[| b \$< \#0; \ \text{intify}(c) \neq \#0 \ |] \implies (c\$*a) \text{ zdiv } (c\$*b) = a \text{ zdiv } b$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult-zmult1-row*:

$$[[\text{intify}(c) \neq \#0; b \in \text{int}]] \implies (c\$*a) \text{ zdiv } (c\$*b) = a \text{ zdiv } b$$

 $\langle \text{proof} \rangle$

lemma *zdiv-zmult-zmult1*: $\text{intify}(c) \neq \#0 \implies (c\$*a) \text{ zdiv } (c\$*b) = a \text{ zdiv } b$
 $\langle \text{proof} \rangle$

lemma *zdiv-zmult-zmult2*: $\text{intify}(c) \neq \#0 \implies (a\$*c) \text{ zdiv } (b\$*c) = a \text{ zdiv } b$
 $\langle \text{proof} \rangle$

32.13 Distribution of factors over "zmod"

lemma *zmod-zmult-zmult1-aux1*:

$$[[\#0 \$< b; \text{intify}(c) \neq \#0]] \implies (c\$*a) \text{ zmod } (c\$*b) = c \$* (a \text{ zmod } b)$$

 $\langle \text{proof} \rangle$

lemma *zmod-zmult-zmult1-aux2*:

$$[[b \$< \#0; \text{intify}(c) \neq \#0]] \implies (c\$*a) \text{ zmod } (c\$*b) = c \$* (a \text{ zmod } b)$$

 $\langle \text{proof} \rangle$

lemma *zmod-zmult-zmult1-raw*:

$$[[b \in \text{int}; c \in \text{int}]] \implies (c\$*a) \text{ zmod } (c\$*b) = c \$* (a \text{ zmod } b)$$

 $\langle \text{proof} \rangle$

lemma *zmod-zmult-zmult1*: $(c\$*a) \text{ zmod } (c\$*b) = c \$* (a \text{ zmod } b)$
 $\langle \text{proof} \rangle$

lemma *zmod-zmult-zmult2*: $(a\$*c) \text{ zmod } (b\$*c) = (a \text{ zmod } b) \$* c$
 $\langle \text{proof} \rangle$

lemma *zdiv-neg-pos-less0*: $[[a \$< \#0; \#0 \$< b]] \implies a \text{ zdiv } b \$< \#0$
 $\langle \text{proof} \rangle$

lemma *zdiv-nonneg-neg-le0*: $[[\#0 \$<= a; b \$< \#0]] \implies a \text{ zdiv } b \$<= \#0$
 $\langle \text{proof} \rangle$

lemma *pos-imp-zdiv-nonneg-iff*: $\#0 \$< b \implies (\#0 \$<= a \text{ zdiv } b) \leftrightarrow (\#0 \$<= a)$
 $\langle \text{proof} \rangle$

lemma *neg-imp-zdiv-nonneg-iff*: $b \$< \#0 \implies (\#0 \$<= a \text{ zdiv } b) \leftrightarrow (a \$<= \#0)$
 $\langle \text{proof} \rangle$

lemma *pos-imp-zdiv-neg-iff*: $\#0 \leq b \implies (a \text{ zdiv } b \leq \#0) \iff (a \leq \#0)$
 $\langle \text{proof} \rangle$

lemma *neg-imp-zdiv-neg-iff*: $b \leq \#0 \implies (a \text{ zdiv } b \leq \#0) \iff (\#0 \leq a)$
 $\langle \text{proof} \rangle$

end

33 CardinalArith: Cardinal Arithmetic Without the Axiom of Choice

theory *CardinalArith* **imports** *Cardinal OrderArith ArithSimp Finite* **begin**

definition

InfCard $:: i \Rightarrow o$ **where**
InfCard(*i*) == *Card*(*i*) & nat le *i*

definition

cmult $:: [i, i] \Rightarrow i$ (**infixl** $|*|$ 70) **where**
 $i \text{ } |*| \text{ } j == |i*j|$

definition

cadd $:: [i, i] \Rightarrow i$ (**infixl** $|+|$ 65) **where**
 $i \text{ } |+| \text{ } j == |i+j|$

definition

csquare-rel $:: i \Rightarrow i$ **where**
csquare-rel(*K*) ==
 $\text{rvimage}(K*K,$
 $\text{lam } \langle x, y \rangle : K*K. \langle x \text{ Un } y, x, y \rangle,$
 $\text{rmult}(K, \text{Memrel}(K), K*K, \text{rmult}(K, \text{Memrel}(K), K, \text{Memrel}(K))))$

definition

jump-cardinal $:: i \Rightarrow i$ **where**
— This def is more complex than Kunen’s but it more easily proved to be a cardinal
jump-cardinal(*K*) ==
 $\bigcup X \in \text{Pow}(K). \{z. r: \text{Pow}(K*K), \text{well-ord}(X, r) \ \& \ z = \text{ordertype}(X, r)\}$

definition

csucc $:: i \Rightarrow i$ **where**
— needed because *jump-cardinal*(*K*) might not be the successor of *K*
csucc(*K*) == *LEAST* *L*. *Card*(*L*) & *K* < *L*

notation (*xsymbols output*)

cadd (**infixl** \oplus 65) **and**

cmult (**infixl** \otimes 70)

notation (*HTML output*)

cadd (**infixl** \oplus 65) **and**

cmult (**infixl** \otimes 70)

lemma *Card-Union* [*simp,intro,TC*]: $(\text{ALL } x:A. \text{Card}(x)) \implies \text{Card}(\text{Union}(A))$
<proof>

lemma *Card-UN*: $(!\!x. x:A \implies \text{Card}(K(x))) \implies \text{Card}(\bigcup_{x \in A} K(x))$
<proof>

lemma *Card-OUN* [*simp,intro,TC*]:
 $(!\!x. x:A \implies \text{Card}(K(x))) \implies \text{Card}(\bigcup_{x < A} K(x))$
<proof>

lemma *n-lesspoll-nat*: $n \in \text{nat} \implies n \prec \text{nat}$
<proof>

lemma *in-Card-imp-lesspoll*: $[\mid \text{Card}(K); b \in K \mid] \implies b \prec K$
<proof>

lemma *lesspoll-lemma*: $[\mid \sim A \prec B; C \prec B \mid] \implies A - C \neq 0$
<proof>

33.1 Cardinal addition

Note: Could omit proving the algebraic laws for cardinal addition and multiplication. On finite cardinals these operations coincide with addition and multiplication of natural numbers; on infinite cardinals they coincide with union (maximum). Either way we get most laws for free.

33.1.1 Cardinal addition is commutative

lemma *sum-commute-epoll*: $A+B \approx B+A$
<proof>

lemma *cadd-commute*: $i \mid + \mid j = j \mid + \mid i$
<proof>

33.1.2 Cardinal addition is associative

lemma *sum-assoc-epoll*: $(A+B)+C \approx A+(B+C)$
<proof>

lemma *well-ord-cadd-assoc*:

$$[\text{well-ord}(i, ri); \text{well-ord}(j, rj); \text{well-ord}(k, rk)] \implies (i \mid\mid j) \mid\mid k = i \mid\mid (j \mid\mid k)$$

 $\langle \text{proof} \rangle$

33.1.3 0 is the identity for addition

lemma *sum-0-epoll*: $0 + A \approx A$

$\langle \text{proof} \rangle$

lemma *cadd-0 [simp]*: $\text{Card}(K) \implies 0 \mid\mid K = K$

$\langle \text{proof} \rangle$

33.1.4 Addition by another cardinal

lemma *sum-lepoll-self*: $A \lesssim A + B$

$\langle \text{proof} \rangle$

lemma *cadd-le-self*:

$$[\text{Card}(K); \text{Ord}(L)] \implies K \text{ le } (K \mid\mid L)$$

 $\langle \text{proof} \rangle$

33.1.5 Monotonicity of addition

lemma *sum-lepoll-mono*:

$$[A \lesssim C; B \lesssim D] \implies A + B \lesssim C + D$$

 $\langle \text{proof} \rangle$

lemma *cadd-le-mono*:

$$[K' \text{ le } K; L' \text{ le } L] \implies (K' \mid\mid L') \text{ le } (K \mid\mid L)$$

 $\langle \text{proof} \rangle$

33.1.6 Addition of finite cardinals is "ordinary" addition

lemma *sum-succ-epoll*: $\text{succ}(A) + B \approx \text{succ}(A + B)$

$\langle \text{proof} \rangle$

lemma *cadd-succ-lemma*:

$$[\text{Ord}(m); \text{Ord}(n)] \implies \text{succ}(m) \mid\mid n = |\text{succ}(m \mid\mid n)|$$

 $\langle \text{proof} \rangle$

lemma *nat-cadd-eq-add*: $[m: \text{nat}; n: \text{nat}] \implies m \mid\mid n = m \# + n$

$\langle \text{proof} \rangle$

33.2 Cardinal multiplication

33.2.1 Cardinal multiplication is commutative

lemma *prod-commute-epoll*: $A*B \approx B*A$
<proof>

lemma *cmult-commute*: $i \mid * \mid j = j \mid * \mid i$
<proof>

33.2.2 Cardinal multiplication is associative

lemma *prod-assoc-epoll*: $(A*B)*C \approx A*(B*C)$
<proof>

lemma *well-ord-cmult-assoc*:
[[*well-ord*(*i*,*ri*); *well-ord*(*j*,*rj*); *well-ord*(*k*,*rk*)]]
==> (*i* $\mid * \mid j$) $\mid * \mid k = i \mid * \mid (j \mid * \mid k)$
<proof>

33.2.3 Cardinal multiplication distributes over addition

lemma *sum-prod-distrib-epoll*: $(A+B)*C \approx (A*C)+(B*C)$
<proof>

lemma *well-ord-cadd-cmult-distrib*:
[[*well-ord*(*i*,*ri*); *well-ord*(*j*,*rj*); *well-ord*(*k*,*rk*)]]
==> (*i* $\mid + \mid j$) $\mid * \mid k = (i \mid * \mid k) \mid + \mid (j \mid * \mid k)$
<proof>

33.2.4 Multiplication by 0 yields 0

lemma *prod-0-epoll*: $0*A \approx 0$
<proof>

lemma *cmult-0 [simp]*: $0 \mid * \mid i = 0$
<proof>

33.2.5 1 is the identity for multiplication

lemma *prod-singleton-epoll*: $\{x\}*A \approx A$
<proof>

lemma *cmult-1 [simp]*: $\text{Card}(K) ==> 1 \mid * \mid K = K$
<proof>

33.3 Some inequalities for multiplication

lemma *prod-square-lepoll*: $A \lesssim A*A$
<proof>

lemma *cmult-square-le*: $\text{Card}(K) \implies K \text{ le } K \mid * \mid K$
 $\langle \text{proof} \rangle$

33.3.1 Multiplication by a non-zero cardinal

lemma *prod-lepoll-self*: $b: B \implies A \lesssim A * B$
 $\langle \text{proof} \rangle$

lemma *cmult-le-self*:
 $\llbracket \text{Card}(K); \text{Ord}(L); 0 < L \rrbracket \implies K \text{ le } (K \mid * \mid L)$
 $\langle \text{proof} \rangle$

33.3.2 Monotonicity of multiplication

lemma *prod-lepoll-mono*:
 $\llbracket A \lesssim C; B \lesssim D \rrbracket \implies A * B \lesssim C * D$
 $\langle \text{proof} \rangle$

lemma *cmult-le-mono*:
 $\llbracket K' \text{ le } K; L' \text{ le } L \rrbracket \implies (K' \mid * \mid L') \text{ le } (K \mid * \mid L)$
 $\langle \text{proof} \rangle$

33.4 Multiplication of finite cardinals is "ordinary" multiplication

lemma *prod-succ-epoll*: $\text{succ}(A) * B \approx B + A * B$
 $\langle \text{proof} \rangle$

lemma *cmult-succ-lemma*:
 $\llbracket \text{Ord}(m); \text{Ord}(n) \rrbracket \implies \text{succ}(m) \mid * \mid n = n \mid + \mid (m \mid * \mid n)$
 $\langle \text{proof} \rangle$

lemma *nat-cmult-eq-mult*: $\llbracket m: \text{nat}; n: \text{nat} \rrbracket \implies m \mid * \mid n = m \# * n$
 $\langle \text{proof} \rangle$

lemma *cmult-2*: $\text{Card}(n) \implies 2 \mid * \mid n = n \mid + \mid n$
 $\langle \text{proof} \rangle$

lemma *sum-lepoll-prod*: $2 \lesssim C \implies B + B \lesssim C * B$
 $\langle \text{proof} \rangle$

lemma *lepoll-imp-sum-lepoll-prod*: $\llbracket A \lesssim B; 2 \lesssim A \rrbracket \implies A + B \lesssim A * B$
 $\langle \text{proof} \rangle$

33.5 Infinite Cardinals are Limit Ordinals

lemma *nat-cons-lepoll*: $\text{nat} \lesssim A \implies \text{cons}(u, A) \lesssim A$
 $\langle \text{proof} \rangle$

lemma *nat-cons-epoll*: $\text{nat} \lesssim A \implies \text{cons}(u, A) \approx A$
 $\langle \text{proof} \rangle$

lemma *nat-succ-epoll*: $\text{nat} \leq A \implies \text{succ}(A) \approx A$
 $\langle \text{proof} \rangle$

lemma *InfCard-nat*: $\text{InfCard}(\text{nat})$
 $\langle \text{proof} \rangle$

lemma *InfCard-is-Card*: $\text{InfCard}(K) \implies \text{Card}(K)$
 $\langle \text{proof} \rangle$

lemma *InfCard-Un*:
 $\llbracket \text{InfCard}(K); \text{Card}(L) \rrbracket \implies \text{InfCard}(K \text{ Un } L)$
 $\langle \text{proof} \rangle$

lemma *InfCard-is-Limit*: $\text{InfCard}(K) \implies \text{Limit}(K)$
 $\langle \text{proof} \rangle$

lemma *ordermap-epoll-pred*:
 $\llbracket \text{well-ord}(A, r); x:A \rrbracket \implies \text{ordermap}(A, r) \text{ ' } x \approx \text{Order.pred}(A, x, r)$
 $\langle \text{proof} \rangle$

33.5.1 Establishing the well-ordering

lemma *csquare-lam-inj*:
 $\text{Ord}(K) \implies (\text{lam } \langle x, y \rangle : K * K. \langle x \text{ Un } y, x, y \rangle) : \text{inj}(K * K, K * K * K)$
 $\langle \text{proof} \rangle$

lemma *well-ord-csquare*: $\text{Ord}(K) \implies \text{well-ord}(K * K, \text{csquare-rel}(K))$
 $\langle \text{proof} \rangle$

33.5.2 Characterising initial segments of the well-ordering

lemma *csquareD*:
 $\llbracket \langle \langle x, y \rangle, \langle z, z \rangle \rangle : \text{csquare-rel}(K); x < K; y < K; z < K \rrbracket \implies x \text{ le } z \ \& \ y \text{ le } z$
 $\langle \text{proof} \rangle$

lemma *pred-csquare-subset*:

$z < K \implies \text{Order.pred}(K * K, <z, z>, \text{csquare-rel}(K)) \leq \text{succ}(z) * \text{succ}(z)$
 $\langle \text{proof} \rangle$

lemma *csquare-ltI*:

$[| x < z; y < z; z < K |] \implies <<x, y>, <z, z>> : \text{csquare-rel}(K)$
 $\langle \text{proof} \rangle$

lemma *csquare-or-eqI*:

$[| x \leq z; y \leq z; z < K |] \implies <<x, y>, <z, z>> : \text{csquare-rel}(K) \mid x = z \ \& \ y = z$
 $\langle \text{proof} \rangle$

33.5.3 The cardinality of initial segments

lemma *ordermap-z-lt*:

$[| \text{Limit}(K); x < K; y < K; z = \text{succ}(x \text{ Un } y) |] \implies$
 $\text{ordermap}(K * K, \text{csquare-rel}(K)) \text{ ' } <x, y> <$
 $\text{ordermap}(K * K, \text{csquare-rel}(K)) \text{ ' } <z, z>$
 $\langle \text{proof} \rangle$

lemma *ordermap-csquare-le*:

$[| \text{Limit}(K); x < K; y < K; z = \text{succ}(x \text{ Un } y) |]$
 $\implies \mid \text{ordermap}(K * K, \text{csquare-rel}(K)) \text{ ' } <x, y> \mid \leq \mid \text{succ}(z) \mid * \mid \text{succ}(z) \mid$
 $\langle \text{proof} \rangle$

lemma *ordertype-csquare-le*:

$[| \text{InfCard}(K); \text{ALL } y:K. \text{InfCard}(y) \dashrightarrow y * y = y |]$
 $\implies \text{ordertype}(K * K, \text{csquare-rel}(K)) \leq K$
 $\langle \text{proof} \rangle$

lemma *InfCard-csquare-eq*: $\text{InfCard}(K) \implies K * K = K$

$\langle \text{proof} \rangle$

lemma *well-ord-InfCard-square-eq*:

$[| \text{well-ord}(A, r); \text{InfCard}(|A|) |] \implies A * A \approx A$
 $\langle \text{proof} \rangle$

lemma *InfCard-square-eqpoll*: $\text{InfCard}(K) \implies K \times K \approx K$

$\langle \text{proof} \rangle$

lemma *Inf-Card-is-InfCard*: $[| \sim \text{Finite}(i); \text{Card}(i) |] \implies \text{InfCard}(i)$

$\langle \text{proof} \rangle$

33.5.4 Toward's Kunen's Corollary 10.13 (1)

lemma *InfCard-le-cmult-eq*: $[[\text{InfCard}(K); L \leq K; 0 < L]] \implies K \mid * \mid L = K$
 $\langle \text{proof} \rangle$

lemma *InfCard-cmult-eq*: $[[\text{InfCard}(K); \text{InfCard}(L)]] \implies K \mid * \mid L = K \cup_n L$
 $\langle \text{proof} \rangle$

lemma *InfCard-cdouble-eq*: $\text{InfCard}(K) \implies K \mid + \mid K = K$
 $\langle \text{proof} \rangle$

lemma *InfCard-le-cadd-eq*: $[[\text{InfCard}(K); L \leq K]] \implies K \mid + \mid L = K$
 $\langle \text{proof} \rangle$

lemma *InfCard-cadd-eq*: $[[\text{InfCard}(K); \text{InfCard}(L)]] \implies K \mid + \mid L = K \cup_n L$
 $\langle \text{proof} \rangle$

33.6 For Every Cardinal Number There Exists A Greater One

This result is Kunen's Theorem 10.16, which would be trivial using AC

lemma *Ord-jump-cardinal*: $\text{Ord}(\text{jump-cardinal}(K))$
 $\langle \text{proof} \rangle$

lemma *jump-cardinal-iff*:
 $i : \text{jump-cardinal}(K) < - >$
 $(\exists X \ r \ X. \ r \leq K * K \ \& \ X \leq K \ \& \ \text{well-ord}(X, r) \ \& \ i = \text{ordertype}(X, r))$
 $\langle \text{proof} \rangle$

lemma *K-lt-jump-cardinal*: $\text{Ord}(K) \implies K < \text{jump-cardinal}(K)$
 $\langle \text{proof} \rangle$

lemma *Card-jump-cardinal-lemma*:
 $[[\text{well-ord}(X, r); \ r \leq K * K; \ X \leq K;$
 $\quad f : \text{bij}(\text{ordertype}(X, r), \text{jump-cardinal}(K)) \]]$
 $\implies \text{jump-cardinal}(K) : \text{jump-cardinal}(K)$
 $\langle \text{proof} \rangle$

lemma *Card-jump-cardinal*: $\text{Card}(\text{jump-cardinal}(K))$
 $\langle \text{proof} \rangle$

33.7 Basic Properties of Successor Cardinals

lemma *csucc-basic*: $\text{Ord}(K) \implies \text{Card}(\text{csucc}(K)) \ \& \ K < \text{csucc}(K)$
 $\langle \text{proof} \rangle$

lemmas *Card-csucc* = *csucc-basic* [*THEN* *conjunct1*, *standard*]

lemmas *lt-csucc* = *csucc-basic* [*THEN* *conjunct2*, *standard*]

lemma *Ord-0-lt-csucc*: $\text{Ord}(K) \implies 0 < \text{csucc}(K)$
 $\langle \text{proof} \rangle$

lemma *csucc-le*: $[\text{Card}(L); K < L] \implies \text{csucc}(K) \text{ le } L$
 $\langle \text{proof} \rangle$

lemma *lt-csucc-iff*: $[\text{Ord}(i); \text{Card}(K)] \implies i < \text{csucc}(K) \iff |i| \text{ le } K$
 $\langle \text{proof} \rangle$

lemma *Card-lt-csucc-iff*:
 $[\text{Card}(K'); \text{Card}(K)] \implies K' < \text{csucc}(K) \iff K' \text{ le } K$
 $\langle \text{proof} \rangle$

lemma *InfCard-csucc*: $\text{InfCard}(K) \implies \text{InfCard}(\text{csucc}(K))$
 $\langle \text{proof} \rangle$

33.7.1 Removing elements from a finite set decreases its cardinality

lemma *Fin-imp-not-cons-lepoll*: $A: \text{Fin}(U) \implies x \sim : A \dashrightarrow \sim \text{cons}(x, A) \lesssim A$
 $\langle \text{proof} \rangle$

lemma *Finite-imp-cardinal-cons* [*simp*]:
 $[\text{Finite}(A); a \sim : A] \implies |\text{cons}(a, A)| = \text{succ}(|A|)$
 $\langle \text{proof} \rangle$

lemma *Finite-imp-succ-cardinal-Diff*:
 $[\text{Finite}(A); a : A] \implies \text{succ}(|A - \{a\}|) = |A|$
 $\langle \text{proof} \rangle$

lemma *Finite-imp-cardinal-Diff*: $[\text{Finite}(A); a : A] \implies |A - \{a\}| < |A|$
 $\langle \text{proof} \rangle$

lemma *Finite-cardinal-in-nat* [*simp*]: $\text{Finite}(A) \implies |A| : \text{nat}$
 $\langle \text{proof} \rangle$

lemma *card-Un-Int*:
 $[\text{Finite}(A); \text{Finite}(B)] \implies |A| \# + |B| = |A \text{ Un } B| \# + |A \text{ Int } B|$
 $\langle \text{proof} \rangle$

lemma *card-Un-disjoint*:

$[|Finite(A); Finite(B); A \text{ Int } B = 0|] ==> |A \text{ Un } B| = |A| \# + |B|$
 $\langle proof \rangle$

lemma *card-partition* [rule-format]:

$Finite(C) ==>$
 $Finite(\bigcup C) -->$
 $(\forall c \in C. |c| = k) -->$
 $(\forall c1 \in C. \forall c2 \in C. c1 \neq c2 --> c1 \cap c2 = 0) -->$
 $k \# * |C| = |\bigcup C|$
 $\langle proof \rangle$

33.7.2 Theorems by Krzysztof Grabczewski, proofs by lcp

lemmas *nat-implies-well-ord* = *nat-into-Ord* [THEN *well-ord-Memrel*, *standard*]

lemma *nat-sum-egpoll-sum*: $[| m:nat; n:nat |] ==> m + n \approx m \# + n$
 $\langle proof \rangle$

lemma *Ord-subset-natD* [rule-format]: $Ord(i) ==> i \leq nat --> i : nat \mid i=nat$
 $\langle proof \rangle$

lemma *Ord-nat-subset-into-Card*: $[| Ord(i); i \leq nat |] ==> Card(i)$
 $\langle proof \rangle$

lemma *Finite-Diff-sing-eq-diff-1*: $[| Finite(A); x:A |] ==> |A - \{x\}| = |A| \# - 1$
 $\langle proof \rangle$

lemma *cardinal-lt-imp-Diff-not-0* [rule-format]:

$Finite(B) ==> ALL A. |B| < |A| --> A - B \sim = 0$
 $\langle proof \rangle$

$\langle ML \rangle$

end

34 Main-ZF: Theory Main: Everything Except AC

theory *Main-ZF* **imports** *List-ZF IntDiv-ZF CardinalArith* **begin**

34.1 Iteration of the function F

consts *iterates* :: $[i=>i,i,i] ==> i \quad ((-^{\wedge} - '(-')) [60,1000,1000] 60)$

primrec

$F^{\wedge} 0 (x) = x$
 $F^{\wedge} (succ(n)) (x) = F(F^{\wedge} n (x))$

definition

$iterates\text{-}\omega :: [i \Rightarrow i, i] \Rightarrow i$ **where**
 $iterates\text{-}\omega(F, x) == \bigcup_{n \in nat.} F^n(x)$

notation (*xsymbols*)

$iterates\text{-}\omega \quad ((-)^{\omega} \text{ '(-)}) \quad [60, 1000] \quad 60)$

notation (*HTML output*)

$iterates\text{-}\omega \quad ((-)^{\omega} \text{ '(-)}) \quad [60, 1000] \quad 60)$

lemma *iterates-triv*:

$[| \ n \in nat; \ F(x) = x \ |] \Rightarrow F^n(x) = x$
 $\langle proof \rangle$

lemma *iterates-type* [TC]:

$[| \ n \in nat; \ a : A; \ !x. x : A \Rightarrow F(x) : A \ |]$
 $\Rightarrow F^n(a) : A$
 $\langle proof \rangle$

lemma *iterates-omega-triv*:

$F(x) = x \Rightarrow F^{\omega}(x) = x$
 $\langle proof \rangle$

lemma *Ord-iterates* [simp]:

$[| \ n \in nat; \ !i. Ord(i) \Rightarrow Ord(F(i)); \ Ord(x) \ |]$
 $\Rightarrow Ord(F^n(x))$
 $\langle proof \rangle$

lemma *iterates-commute*: $n \in nat \Rightarrow F(F^n(x)) = F^n(F(x))$

$\langle proof \rangle$

34.2 Transfinite Recursion

Transfinite recursion for definitions based on the three cases of ordinals

definition

$transrec3 :: [i, i, [i, i] \Rightarrow i, [i, i] \Rightarrow i] \Rightarrow i$ **where**
 $transrec3(k, a, b, c) ==$
 $transrec(k, \lambda x. r.$
 $\quad \text{if } x=0 \text{ then } a$
 $\quad \text{else if } Limit(x) \text{ then } c(x, \lambda y \in x. r'y)$
 $\quad \text{else } b(Arith.pred(x), r \text{ ' } Arith.pred(x)))$

lemma *transrec3-0* [simp]: $transrec3(0, a, b, c) = a$

$\langle proof \rangle$

lemma *transrec3-succ* [simp]:

$transrec3(succ(i), a, b, c) = b(i, transrec3(i, a, b, c))$
 $\langle proof \rangle$

lemma *transrec3-Limit*:
 $Limit(i) ==>$
 $transrec3(i, a, b, c) = c(i, \lambda j \in i. transrec3(j, a, b, c))$
 $\langle proof \rangle$

$\langle ML \rangle$

end

theory *Main*
imports *Main-ZF*
begin

end

35 AC: The Axiom of Choice

theory *AC* **imports** *Main-ZF* **begin**

This definition comes from Halmos (1960), page 59.

axiomatization **where**

$AC: [\mid a: A; \mid \! \! \! \exists x. x: A ==> (EX y. y: B(x)) \mid] ==> EX z. z: Pi(A, B)$

lemma *AC-Pi*: $[\mid \! \! \! \exists x. x \in A ==> (\exists y. y \in B(x)) \mid] ==> \exists z. z \in Pi(A, B)$
 $\langle proof \rangle$

lemma *AC-ball-Pi*: $\forall x \in A. \exists y. y \in B(x) ==> \exists y. y \in Pi(A, B)$
 $\langle proof \rangle$

lemma *AC-Pi-Pow*: $\exists f. f \in (\Pi X \in Pow(C) - \{0\}. X)$
 $\langle proof \rangle$

lemma *AC-func*:
 $[\mid \! \! \! \exists x. x \in A ==> (\exists y. y \in x) \mid] ==> \exists f \in A \rightarrow Union(A). \forall x \in A. f'x \in x$
 $\langle proof \rangle$

lemma *non-empty-family*: $[\mid 0 \notin A; x \in A \mid] ==> \exists y. y \in x$
 $\langle proof \rangle$

lemma *AC-func0*: $0 \notin A ==> \exists f \in A \rightarrow Union(A). \forall x \in A. f'x \in x$
 $\langle proof \rangle$

lemma *AC-func-Pow*: $\exists f \in (Pow(C) - \{0\}) \rightarrow C. \forall x \in Pow(C) - \{0\}. f'x \in x$

$\langle proof \rangle$

lemma *AC-Pi0*: $0 \notin A \implies \exists f. f \in (\Pi x \in A. x)$

$\langle proof \rangle$

end

36 Zorn: Zorn's Lemma

theory *Zorn* **imports** *OrderArith AC Inductive-ZF* **begin**

Based upon the unpublished article “Towards the Mechanization of the Proofs of Some Classical Theorems of Set Theory,” by Abrial and Laffitte.

definition

Subset-rel :: $i \Rightarrow i$ **where**

$Subset-rel(A) == \{z \in A * A . \exists x y. z = \langle x, y \rangle \ \& \ x \leq y \ \& \ x \neq y\}$

definition

chain :: $i \Rightarrow i$ **where**

$chain(A) == \{F \in Pow(A). \forall X \in F. \forall Y \in F. X \leq Y \mid Y \leq X\}$

definition

super :: $[i, i] \Rightarrow i$ **where**

$super(A, c) == \{d \in chain(A). c \leq d \ \& \ c \neq d\}$

definition

maxchain :: $i \Rightarrow i$ **where**

$maxchain(A) == \{c \in chain(A). super(A, c) = 0\}$

definition

increasing :: $i \Rightarrow i$ **where**

$increasing(A) == \{f \in Pow(A) \rightarrow Pow(A). \forall x. x \leq A \implies x \leq f'x\}$

Lemma for the inductive definition below

lemma *Union-in-Pow*: $Y \in Pow(Pow(A)) \implies Union(Y) \in Pow(A)$

$\langle proof \rangle$

We could make the inductive definition conditional on $next \in increasing(S)$ but instead we make this a side-condition of an introduction rule. Thus the induction rule lets us assume that condition! Many inductive proofs are therefore unconditional.

consts

TFin :: $[i, i] \Rightarrow i$

inductive

domains $TFin(S, next) \leq Pow(S)$

intros

nextI: $\llbracket x \in TFin(S, next); next \in increasing(S) \rrbracket$
 $\implies next'x \in TFin(S, next)$

Pow-UnionI: $Y \in Pow(TFin(S, next)) \implies Union(Y) \in TFin(S, next)$

monos *Pow-mono*
con-defs *increasing-def*
type-intros *CollectD1 [THEN apply-funtype] Union-in-Pow*

36.1 Mathematical Preamble

lemma *Union-lemma0*: $(\forall x \in C. x \leq A \mid B \leq x) \implies Union(C) \leq A \mid B \leq Union(C)$
 $\langle proof \rangle$

lemma *Inter-lemma0*:
 $\llbracket c \in C; \forall x \in C. A \leq x \mid x \leq B \rrbracket \implies A \leq Inter(C) \mid Inter(C) \leq B$
 $\langle proof \rangle$

36.2 The Transfinite Construction

lemma *increasingD1*: $f \in increasing(A) \implies f \in Pow(A) \multimap Pow(A)$
 $\langle proof \rangle$

lemma *increasingD2*: $\llbracket f \in increasing(A); x \leq A \rrbracket \implies x \leq f'x$
 $\langle proof \rangle$

lemmas *TFin-UnionI = PowI [THEN TFin.Pow-UnionI, standard]*

lemmas *TFin-is-subset = TFin.dom-subset [THEN subsetD, THEN PowD, standard]*

Structural induction on $TFin(S, next)$

lemma *TFin-induct*:
 $\llbracket n \in TFin(S, next);$
 $\quad !!x. \llbracket x \in TFin(S, next); P(x); next \in increasing(S) \rrbracket \implies P(next'x);$
 $\quad !!Y. \llbracket Y \leq TFin(S, next); \forall y \in Y. P(y) \rrbracket \implies P(Union(Y))$
 $\rrbracket \implies P(n)$
 $\langle proof \rangle$

36.3 Some Properties of the Transfinite Construction

lemmas *increasing-trans = subset-trans [OF - increasingD2,*
OF - - TFin-is-subset]

Lemma 1 of section 3.1

lemma *TFin-linear-lemma1*:
 $\llbracket n \in TFin(S, next); m \in TFin(S, next);$
 $\quad \forall x \in TFin(S, next). x \leq m \dashv\dashv x = m \mid next'x \leq m \rrbracket$
 $\implies n \leq m \mid next'm \leq n$

$\langle proof \rangle$

Lemma 2 of section 3.2. Interesting in its own right! Requires $next \in increasing(S)$ in the second induction step.

lemma *TFin-linear-lemma2*:

$[| m \in TFin(S, next); next \in increasing(S) |]$
 $\implies \forall n \in TFin(S, next). n \leq m \iff n = m \mid next'n \leq m$

$\langle proof \rangle$

a more convenient form for Lemma 2

lemma *TFin-subsetD*:

$[| n \leq m; m \in TFin(S, next); n \in TFin(S, next); next \in increasing(S) |]$
 $\implies n = m \mid next'n \leq m$

$\langle proof \rangle$

Consequences from section 3.3 – Property 3.2, the ordering is total

lemma *TFin-subset-linear*:

$[| m \in TFin(S, next); n \in TFin(S, next); next \in increasing(S) |]$
 $\implies n \leq m \mid m \leq n$

$\langle proof \rangle$

Lemma 3 of section 3.3

lemma *equal-next-upper*:

$[| n \in TFin(S, next); m \in TFin(S, next); m = next'm |] \implies n \leq m$

$\langle proof \rangle$

Property 3.3 of section 3.3

lemma *equal-next-Union*:

$[| m \in TFin(S, next); next \in increasing(S) |]$
 $\implies m = next'm \iff m = Union(TFin(S, next))$

$\langle proof \rangle$

36.4 Hausdorff's Theorem: Every Set Contains a Maximal Chain

NOTE: We assume the partial ordering is \subseteq , the subset relation!

* Defining the "next" operation for Hausdorff's Theorem *

lemma *chain-subset-Pow*: $chain(A) \leq Pow(A)$

$\langle proof \rangle$

lemma *super-subset-chain*: $super(A, c) \leq chain(A)$

$\langle proof \rangle$

lemma *maxchain-subset-chain*: $maxchain(A) \leq chain(A)$

$\langle proof \rangle$

lemma *choice-super*:

$[[ch \in (\Pi X \in Pow(chain(S)) - \{0\}. X); X \in chain(S); X \notin maxchain(S)$
 $]]$
 $==> ch \text{ ' } super(S,X) \in super(S,X)$
 $\langle proof \rangle$

lemma *choice-not-equals*:

$[[ch \in (\Pi X \in Pow(chain(S)) - \{0\}. X); X \in chain(S); X \notin maxchain(S)$
 $]]$
 $==> ch \text{ ' } super(S,X) \neq X$
 $\langle proof \rangle$

This justifies Definition 4.4

lemma *Hausdorff-next-exists*:

$ch \in (\Pi X \in Pow(chain(S)) - \{0\}. X) ==>$
 $\exists next \in increasing(S). \forall X \in Pow(S).$
 $next \text{ ' } X = if(X \in chain(S) - maxchain(S), ch \text{ ' } super(S,X), X)$
 $\langle proof \rangle$

Lemma 4

lemma *TFin-chain-lemma4*:

$[[c \in TFin(S,next);$
 $ch \in (\Pi X \in Pow(chain(S)) - \{0\}. X);$
 $next \in increasing(S);$
 $\forall X \in Pow(S). next \text{ ' } X =$
 $if(X \in chain(S) - maxchain(S), ch \text{ ' } super(S,X), X)]]$
 $==> c \in chain(S)$
 $\langle proof \rangle$

theorem *Hausdorff*: $\exists c. c \in maxchain(S)$

$\langle proof \rangle$

36.5 Zorn's Lemma: If All Chains in S Have Upper Bounds In S, then S contains a Maximal Element

Used in the proof of Zorn's Lemma

lemma *chain-extend*:

$[[c \in chain(A); z \in A; \forall x \in c. x \leq z]]$ $==> cons(z,c) \in chain(A)$
 $\langle proof \rangle$

lemma *Zorn*: $\forall c \in chain(S). Union(c) \in S ==> \exists y \in S. \forall z \in S. y \leq z \text{ --> } y=z$

$\langle proof \rangle$

Alternative version of Zorn's Lemma

theorem *Zorn2*:

$\forall c \in chain(S). \exists y \in S. \forall x \in c. x \leq y ==> \exists y \in S. \forall z \in S. y \leq z \text{ --> } y=z$

$\langle proof \rangle$

36.6 Zermelo's Theorem: Every Set can be Well-Ordered

Lemma 5

lemma *TFin-well-lemma5*:

$$[[n \in TFin(S, next); Z \leq TFin(S, next); z:Z; \sim Inter(Z) \in Z]] \\ \implies \forall m \in Z. n \leq m$$

<proof>

Well-ordering of $TFin(S, next)$

lemma *well-ord-TFin-lemma*: $[[Z \leq TFin(S, next); z \in Z]] \implies Inter(Z) \in Z$

<proof>

This theorem just packages the previous result

lemma *well-ord-TFin*:

$$next \in increasing(S) \\ \implies well\text{-}ord(TFin(S, next), Subset\text{-}rel(TFin(S, next)))$$

<proof>

* Defining the "next" operation for Zermelo's Theorem *

lemma *choice-Diff*:

$$[[ch \in (\Pi X \in Pow(S) - \{0\}. X); X \subseteq S; X \neq S]] \implies ch'(S - X) \in S - X$$

<proof>

This justifies Definition 6.1

lemma *Zermelo-next-exists*:

$$ch \in (\Pi X \in Pow(S) - \{0\}. X) \implies \\ \exists next \in increasing(S). \forall X \in Pow(S). \\ next'X = (if X=S then S else cons(ch'(S-X), X))$$

<proof>

The construction of the injection

lemma *choice-imp-injection*:

$$[[ch \in (\Pi X \in Pow(S) - \{0\}. X); \\ next \in increasing(S); \\ \forall X \in Pow(S). next'X = if(X=S, S, cons(ch'(S-X), X))]] \\ \implies (\lambda x \in S. Union(\{y \in TFin(S, next). x \notin y\})) \\ \in inj(S, TFin(S, next) - \{S\})$$

<proof>

The wellordering theorem

theorem *AC-well-ord*: $\exists r. well\text{-}ord(S, r)$

<proof>

36.7 Zorn's Lemma for Partial Orders

Reimported from HOL by Clemens Ballarin.

definition *Chain* :: $i \Rightarrow i$ **where**

$Chain(r) = \{A : Pow(field(r)). \text{ ALL } a:A. \text{ ALL } b:A. \langle a, b \rangle : r \mid \langle b, a \rangle : r\}$

lemma *mono-Chain*:

$r \subseteq s \Rightarrow Chain(r) \subseteq Chain(s)$

$\langle proof \rangle$

theorem *Zorn-po*:

assumes *po*: *Partial-order*(r)

and u : *ALL* $C:Chain(r)$. *EX* $u:field(r)$. *ALL* $a:C$. $\langle a, u \rangle : r$

shows *EX* $m:field(r)$. *ALL* $a:field(r)$. $\langle m, a \rangle : r \dashv\dashv a = m$

$\langle proof \rangle$

end

37 Cardinal-AC: Cardinal Arithmetic Using AC

theory *Cardinal-AC* **imports** *CardinalArith* *Zorn* **begin**

37.1 Strengthened Forms of Existing Theorems on Cardinals

lemma *cardinal-eqpoll*: $|A| \text{ eqpoll } A$

$\langle proof \rangle$

The theorem $||A|| = |A|$

lemmas *cardinal-idem* = *cardinal-eqpoll* [*THEN* *cardinal-cong*, *standard*, *simp*]

lemma *cardinal-eqE*: $|X| = |Y| \Rightarrow X \text{ eqpoll } Y$

$\langle proof \rangle$

lemma *cardinal-eqpoll-iff*: $|X| = |Y| \Leftrightarrow X \text{ eqpoll } Y$

$\langle proof \rangle$

lemma *cardinal-disjoint-Un*:

$[| |A|=|B|; |C|=|D|; A \text{ Int } C = 0; B \text{ Int } D = 0]$

$\Rightarrow |A \text{ Un } C| = |B \text{ Un } D|$

$\langle proof \rangle$

lemma *lepoll-imp-Card-le*: $A \text{ lepoll } B \Rightarrow |A| \text{ le } |B|$

$\langle proof \rangle$

lemma *cadd-assoc*: $(i \mid + \mid j) \mid + \mid k = i \mid + \mid (j \mid + \mid k)$

$\langle proof \rangle$

lemma *cmult-assoc*: $(i \mid * \mid j) \mid * \mid k = i \mid * \mid (j \mid * \mid k)$

$\langle proof \rangle$

lemma *cadd-cmult-distrib*: $(i \mid + \mid j) \mid * \mid k = (i \mid * \mid k) \mid + \mid (j \mid * \mid k)$

$\langle proof \rangle$

lemma *InfCard-square-eq*: $InfCard(|A|) ==> A * A \text{ eqpoll } A$
 $\langle proof \rangle$

37.2 The relationship between cardinality and le-pollence

lemma *Card-le-imp-lepoll*: $|A| \text{ le } |B| ==> A \text{ lepoll } B$
 $\langle proof \rangle$

lemma *le-Card-iff*: $Card(K) ==> |A| \text{ le } K <-> A \text{ lepoll } K$
 $\langle proof \rangle$

lemma *cardinal-0-iff-0 [simp]*: $|A| = 0 <-> A = 0$
 $\langle proof \rangle$

lemma *cardinal-lt-iff-lesspoll*: $Ord(i) ==> i < |A| <-> i \text{ lesspoll } A$
 $\langle proof \rangle$

lemma *cardinal-le-imp-lepoll*: $i \leq |A| ==> i \lesssim A$
 $\langle proof \rangle$

37.3 Other Applications of AC

lemma *surj-implies-inj*: $f: \text{surj}(X, Y) ==> \exists X \text{ g. } g: \text{inj}(Y, X)$
 $\langle proof \rangle$

lemma *surj-implies-cardinal-le*: $f: \text{surj}(X, Y) ==> |Y| \text{ le } |X|$
 $\langle proof \rangle$

lemma *cardinal-UN-le*:
 $[| \text{InfCard}(K); \text{ALL } i:K. |X(i)| \text{ le } K |] ==> |\bigcup i \in K. X(i)| \text{ le } K$
 $\langle proof \rangle$

lemma *cardinal-UN-lt-csucc*:
 $[| \text{InfCard}(K); \text{ALL } i:K. |X(i)| < \text{csucc}(K) |]$
 $==> |\bigcup i \in K. X(i)| < \text{csucc}(K)$
 $\langle proof \rangle$

lemma *cardinal-UN-Ord-lt-csucc*:
 $[| \text{InfCard}(K); \text{ALL } i:K. j(i) < \text{csucc}(K) |]$
 $==> (\bigcup i \in K. j(i)) < \text{csucc}(K)$
 $\langle proof \rangle$

lemma *inj-UN-subset*:

$$[| f: \text{inj}(A,B); \ a:A |] ==>$$

$$(\bigcup_{x \in A}. C(x)) \leq (\bigcup_{y \in B}. C(\text{if } y: \text{range}(f) \text{ then } \text{converse}(f) 'y \text{ else } a))$$

$$\langle \text{proof} \rangle$$

lemma *le-UN-Ord-lt-csucc*:

$$[| \text{InfCard}(K); \ |W| \text{ le } K; \ \text{ALL } w:W. j(w) < \text{csucc}(K) |]$$

$$==> (\bigcup_{w \in W}. j(w)) < \text{csucc}(K)$$

$$\langle \text{proof} \rangle$$

$$\langle ML \rangle$$

end

38 InfDatatype: Infinite-Branching Datatype Definitions

theory *InfDatatype* **imports** *Datatype-ZF Univ Finite Cardinal-AC* **begin**

lemmas *fun-Limit-VfromE* =

$$\text{Limit-VfromE} \ [OF \ \text{apply-funtype} \ \text{InfCard-csucc} \ [THEN \ \text{InfCard-is-Limit}]]$$

lemma *fun-Vcsucc-lemma*:

$$[| f: D \rightarrow Vfrom(A, \text{csucc}(K)); \ |D| \text{ le } K; \ \text{InfCard}(K) |]$$

$$==> \text{EX } j. f: D \rightarrow Vfrom(A, j) \ \& \ j < \text{csucc}(K)$$

$$\langle \text{proof} \rangle$$

lemma *subset-Vcsucc*:

$$[| D \leq Vfrom(A, \text{csucc}(K)); \ |D| \text{ le } K; \ \text{InfCard}(K) |]$$

$$==> \text{EX } j. D \leq Vfrom(A, j) \ \& \ j < \text{csucc}(K)$$

$$\langle \text{proof} \rangle$$

lemma *fun-Vcsucc*:

$$[| |D| \text{ le } K; \ \text{InfCard}(K); \ D \leq Vfrom(A, \text{csucc}(K)) |] ==>$$

$$D \rightarrow Vfrom(A, \text{csucc}(K)) \leq Vfrom(A, \text{csucc}(K))$$

$$\langle \text{proof} \rangle$$

lemma *fun-in-Vcsucc*:

$$[| f: D \rightarrow Vfrom(A, \text{csucc}(K)); \ |D| \text{ le } K; \ \text{InfCard}(K);$$

$$D \leq Vfrom(A, \text{csucc}(K)) |]$$

$$==> f: Vfrom(A, \text{csucc}(K))$$

$$\langle \text{proof} \rangle$$

lemmas $\text{fun-in-Vcsucc}' = \text{fun-in-Vcsucc}$ [OF - - - subsetI]

lemma *Card-fun-Vcsucc:*

$\text{InfCard}(K) ==> K \rightarrow \text{Vfrom}(A, \text{csucc}(K)) \leq \text{Vfrom}(A, \text{csucc}(K))$
 <proof>

lemma *Card-fun-in-Vcsucc:*

$[\mid f: K \rightarrow \text{Vfrom}(A, \text{csucc}(K)); \text{InfCard}(K) \mid] ==> f: \text{Vfrom}(A, \text{csucc}(K))$
 <proof>

lemma *Limit-csucc:* $\text{InfCard}(K) ==> \text{Limit}(\text{csucc}(K))$

<proof>

lemmas $\text{Pair-in-Vcsucc} = \text{Pair-in-VLimit}$ [OF - - Limit-csucc]

lemmas $\text{Inl-in-Vcsucc} = \text{Inl-in-VLimit}$ [OF - Limit-csucc]

lemmas $\text{Inr-in-Vcsucc} = \text{Inr-in-VLimit}$ [OF - Limit-csucc]

lemmas $\text{zero-in-Vcsucc} = \text{Limit-csucc}$ [THEN zero-in-VLimit]

lemmas $\text{nat-into-Vcsucc} = \text{nat-into-VLimit}$ [OF - Limit-csucc]

lemmas $\text{InfCard-nat-Un-cardinal} = \text{InfCard-Un}$ [OF InfCard-nat Card-cardinal]

lemmas $\text{le-nat-Un-cardinal} =$

Un-upper2-le [OF Ord-nat Card-cardinal [THEN Card-is-Ord]]

lemmas $\text{UN-upper-cardinal} = \text{UN-upper}$ [THEN subset-imp-lepoll, THEN lepoll-imp-Card-le]

lemmas *Data-Arg-intros =*

SigmaI InlI InrI

Pair-in-univ Inl-in-univ Inr-in-univ

zero-in-univ A-into-univ nat-into-univ UnCI

lemmas *inf-datatype-intros =*

InfCard-nat InfCard-nat-Un-cardinal

Pair-in-Vcsucc Inl-in-Vcsucc Inr-in-Vcsucc

zero-in-Vcsucc A-into-Vfrom nat-into-Vcsucc

Card-fun-in-Vcsucc fun-in-Vcsucc' UN-I

end

```
theory Main-ZFC imports Main-ZF InfDatatype begin  
end
```