

The Constructible Universe and the Relative Consistency of the Axiom of Choice

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Abstract

Gödel's proof of the relative consistency of the axiom of choice [1] is one of the most important results in the foundations of mathematics. It bears on Hilbert's first problem, namely the continuum hypothesis, and indeed Gödel also proved the relative consistency of the continuum hypothesis. Just as important, Gödel's proof introduced the *inner model* method of proving relative consistency, and it introduced the concept of *constructible set*. Kunen [2] gives an excellent description of this body of work.

This Isabelle/ZF formalization demonstrates Gödel's claim that his proof can be undertaken without using metamathematical arguments, for example arguments based on the general syntactic structure of a formula. Isabelle's automation replaces the metamathematics, although it does not eliminate the requirement at least to state many tedious results that would otherwise be unnecessary.

This formalization [4] is by far the deepest result in set theory proved in any automated theorem prover. It rests on a previous formal development of the reflection theorem [3].

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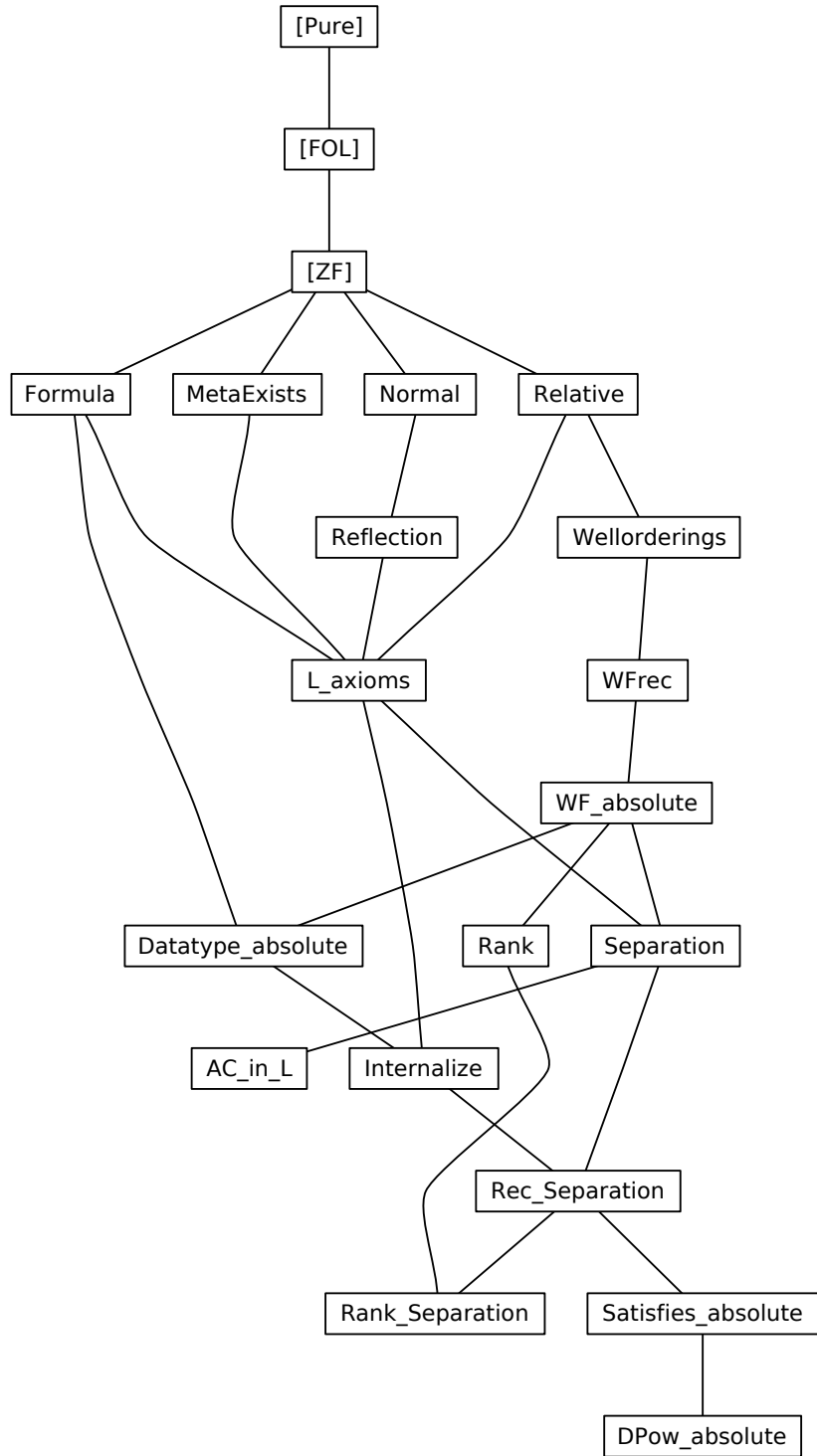
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1 First-Order Formulas and the Definition of the Class L

theory *Formula* imports ZF begin

1.1 Internalized formulas of FOL

De Bruijn representation. Unbound variables get their denotations from an environment.

```
consts formula :: i
datatype
  "formula" = Member ("x ∈ nat", "y ∈ nat")
              | Equal  ("x ∈ nat", "y ∈ nat")
              | Nand   ("p ∈ formula", "q ∈ formula")
              | Forall ("p ∈ formula")
```

declare *formula.intros* [TC]

definition

```
Neg :: "i=>i" where
  "Neg(p) == Nand(p,p)"
```

definition

```
And :: "[i,i]=>i" where
  "And(p,q) == Neg(Nand(p,q))"
```

definition

```
Or :: "[i,i]=>i" where
  "Or(p,q) == Nand(Neg(p),Neg(q))"
```

definition

```
Implies :: "[i,i]=>i" where
  "Implies(p,q) == Nand(p,Neg(q))"
```

definition

```
Iff :: "[i,i]=>i" where
  "Iff(p,q) == And(Implies(p,q), Implies(q,p))"
```

definition

```
Exists :: "i=>i" where
  "Exists(p) == Neg(Forall(Neg(p)))"
```

lemma *Neg_type* [TC]: " $p \in \text{formula} \implies \text{Neg}(p) \in \text{formula}$ "
⟨*proof*⟩

lemma *And_type* [TC]: " $[p \in \text{formula}; q \in \text{formula}] \implies \text{And}(p,q) \in \text{formula}$ "
⟨*proof*⟩

```

lemma Or_type [TC]: "[| p ∈ formula; q ∈ formula |] ==> Or(p,q) ∈ formula"
⟨proof⟩

lemma Implies_type [TC]:
  "[| p ∈ formula; q ∈ formula |] ==> Implies(p,q) ∈ formula"
⟨proof⟩

lemma Iff_type [TC]:
  "[| p ∈ formula; q ∈ formula |] ==> Iff(p,q) ∈ formula"
⟨proof⟩

lemma Exists_type [TC]: "p ∈ formula ==> Exists(p) ∈ formula"
⟨proof⟩

consts    satisfies :: "[i,i]=>i"
primrec
  "satisfies(A,Member(x,y)) =
    (λenv ∈ list(A). bool_of_o (nth(x,env) ∈ nth(y,env)))"

  "satisfies(A,Equal(x,y)) =
    (λenv ∈ list(A). bool_of_o (nth(x,env) = nth(y,env)))"

  "satisfies(A,Nand(p,q)) =
    (λenv ∈ list(A). not ((satisfies(A,p)‘env) and (satisfies(A,q)‘env)))"

  "satisfies(A,Forall(p)) =
    (λenv ∈ list(A). bool_of_o (∀x∈A. satisfies(A,p) ‘ (Cons(x,env))
= 1))"

lemma satisfies_type: "p ∈ formula ==> satisfies(A,p) ∈ list(A) -> bool"
⟨proof⟩

abbreviation
  sats :: "[i,i,i] => o" where
  "sats(A,p,env) == satisfies(A,p)‘env = 1"

lemma sats_Member_iff [simp]:
  "env ∈ list(A) ==> sats(A, Member(x,y), env) ⟷ nth(x,env) ∈ nth(y,env)"
⟨proof⟩

lemma sats_Equal_iff [simp]:
  "env ∈ list(A) ==> sats(A, Equal(x,y), env) ⟷ nth(x,env) = nth(y,env)"
⟨proof⟩

lemma sats_Nand_iff [simp]:
  "env ∈ list(A)

```

```

    ==> (sats(A, Nand(p,q), env)) <=> ~ (sats(A,p,env) & sats(A,q,env))"
  <proof>

```

```

lemma sats_Forall_iff [simp]:
  "env ∈ list(A)
  ==> sats(A, Forall(p), env) <=> (∀ x∈A. sats(A, p, Cons(x,env)))"
  <proof>

```

```

declare satisfies.simps [simp del]

```

1.2 Dividing line between primitive and derived connectives

```

lemma sats_Neg_iff [simp]:
  "env ∈ list(A)
  ==> sats(A, Neg(p), env) <=> ~ sats(A,p,env)"
  <proof>

```

```

lemma sats_And_iff [simp]:
  "env ∈ list(A)
  ==> (sats(A, And(p,q), env)) <=> sats(A,p,env) & sats(A,q,env)"
  <proof>

```

```

lemma sats_Or_iff [simp]:
  "env ∈ list(A)
  ==> (sats(A, Or(p,q), env)) <=> sats(A,p,env) | sats(A,q,env)"
  <proof>

```

```

lemma sats_Implies_iff [simp]:
  "env ∈ list(A)
  ==> (sats(A, Implies(p,q), env)) <=> (sats(A,p,env) → sats(A,q,env))"
  <proof>

```

```

lemma sats_Iff_iff [simp]:
  "env ∈ list(A)
  ==> (sats(A, Iff(p,q), env)) <=> (sats(A,p,env) <=> sats(A,q,env))"
  <proof>

```

```

lemma sats_Exists_iff [simp]:
  "env ∈ list(A)
  ==> sats(A, Exists(p), env) <=> (∃ x∈A. sats(A, p, Cons(x,env)))"
  <proof>

```

1.2.1 Derived rules to help build up formulas

```

lemma mem_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; env ∈ list(A) |]
  ==> (x∈y) <=> sats(A, Member(i,j), env)"
  <proof>

```

```

lemma equal_iff_sats:

```

```

    "[| nth(i,env) = x; nth(j,env) = y; env ∈ list(A)|]
    ==> (x=y) <=> sats(A, Equal(i,j), env)"
  <proof>

lemma not_iff_sats:
  "[| P <=> sats(A,p,env); env ∈ list(A)|]
  ==> (~P) <=> sats(A, Neg(p), env)"
  <proof>

lemma conj_iff_sats:
  "[| P <=> sats(A,p,env); Q <=> sats(A,q,env); env ∈ list(A)|]
  ==> (P & Q) <=> sats(A, And(p,q), env)"
  <proof>

lemma disj_iff_sats:
  "[| P <=> sats(A,p,env); Q <=> sats(A,q,env); env ∈ list(A)|]
  ==> (P | Q) <=> sats(A, Or(p,q), env)"
  <proof>

lemma iff_iff_sats:
  "[| P <=> sats(A,p,env); Q <=> sats(A,q,env); env ∈ list(A)|]
  ==> (P <=> Q) <=> sats(A, Iff(p,q), env)"
  <proof>

lemma imp_iff_sats:
  "[| P <=> sats(A,p,env); Q <=> sats(A,q,env); env ∈ list(A)|]
  ==> (P -> Q) <=> sats(A, Implies(p,q), env)"
  <proof>

lemma ball_iff_sats:
  "[| !!x. x∈A ==> P(x) <=> sats(A, p, Cons(x, env)); env ∈ list(A)|]
  ==> (∀x∈A. P(x)) <=> sats(A, Forall(p), env)"
  <proof>

lemma bex_iff_sats:
  "[| !!x. x∈A ==> P(x) <=> sats(A, p, Cons(x, env)); env ∈ list(A)|]
  ==> (∃x∈A. P(x)) <=> sats(A, Exists(p), env)"
  <proof>

lemmas FOL_iff_sats =
  mem_iff_sats equal_iff_sats not_iff_sats conj_iff_sats
  disj_iff_sats imp_iff_sats iff_iff_sats imp_iff_sats ball_iff_sats
  bex_iff_sats

```

1.3 Arity of a Formula: Maximum Free de Bruijn Index

```

consts  arity :: "i=>i"
primrec
  "arity(Member(x,y)) = succ(x) ∪ succ(y)"

```

```

"arity(Equal(x,y)) = succ(x) ∪ succ(y)"

"arity(Nand(p,q)) = arity(p) ∪ arity(q)"

"arity(Forall(p)) = Arith.pred(arity(p))"

lemma arity_type [TC]: "p ∈ formula ==> arity(p) ∈ nat"
⟨proof⟩

lemma arity_Neg [simp]: "arity(Neg(p)) = arity(p)"
⟨proof⟩

lemma arity_And [simp]: "arity(And(p,q)) = arity(p) ∪ arity(q)"
⟨proof⟩

lemma arity_Or [simp]: "arity(Or(p,q)) = arity(p) ∪ arity(q)"
⟨proof⟩

lemma arity_Implies [simp]: "arity(Implies(p,q)) = arity(p) ∪ arity(q)"
⟨proof⟩

lemma arity_Iff [simp]: "arity(Iff(p,q)) = arity(p) ∪ arity(q)"
⟨proof⟩

lemma arity_Exists [simp]: "arity(Exists(p)) = Arith.pred(arity(p))"
⟨proof⟩

lemma arity_sats_iff [rule_format]:
  "[| p ∈ formula; extra ∈ list(A) |]
  ==> ∀ env ∈ list(A).
    arity(p) ≤ length(env) →
    sats(A, p, env @ extra) ↔ sats(A, p, env)"
⟨proof⟩

lemma arity_sats1_iff:
  "[| arity(p) ≤ succ(length(env)); p ∈ formula; x ∈ A; env ∈ list(A);
    extra ∈ list(A) |]
  ==> sats(A, p, Cons(x, env @ extra)) ↔ sats(A, p, Cons(x, env))"
⟨proof⟩

```

1.4 Renaming Some de Bruijn Variables

definition

```

incr_var :: "[i,i]=>i" where
  "incr_var(x,nq) == if x<nq then x else succ(x)"

```

lemma *incr_var_lt*: " $x < nq \implies \text{incr_var}(x, nq) = x$ "
 <proof>

lemma *incr_var_le*: " $nq \leq x \implies \text{incr_var}(x, nq) = \text{succ}(x)$ "
 <proof>

consts *incr_bv* :: " $i \Rightarrow i$ "
primrec
 "incr_bv(Member(x,y)) =
 ($\lambda nq \in \text{nat}. \text{Member}(\text{incr_var}(x, nq), \text{incr_var}(y, nq))$)"

 "incr_bv(Equal(x,y)) =
 ($\lambda nq \in \text{nat}. \text{Equal}(\text{incr_var}(x, nq), \text{incr_var}(y, nq))$)"

 "incr_bv(Nand(p,q)) =
 ($\lambda nq \in \text{nat}. \text{Nand}(\text{incr_bv}(p) \text{ 'nq}, \text{incr_bv}(q) \text{ 'nq})$)"

 "incr_bv(Forall(p)) =
 ($\lambda nq \in \text{nat}. \text{Forall}(\text{incr_bv}(p) \text{ ' succ}(nq))$)"

lemma [TC]: " $x \in \text{nat} \implies \text{incr_var}(x, nq) \in \text{nat}$ "
 <proof>

lemma *incr_bv_type* [TC]: " $p \in \text{formula} \implies \text{incr_bv}(p) \in \text{nat} \rightarrow \text{formula}$ "
 <proof>

Obviously, *DPow* is closed under complements and finite intersections and unions. Needs an inductive lemma to allow two lists of parameters to be combined.

lemma *sats_incr_bv_iff* [rule_format]:
 "[| $p \in \text{formula}; \text{env} \in \text{list}(A); x \in A$ |]
 $\implies \forall \text{bvs} \in \text{list}(A).$
 $\text{sats}(A, \text{incr_bv}(p) \text{ ' length}(\text{bvs}), \text{bvs} @ \text{Cons}(x, \text{env})) \longleftrightarrow$
 $\text{sats}(A, p, \text{bvs} @ \text{env})$ "
 <proof>

lemma *incr_var_lemma*:
 "[| $x \in \text{nat}; y \in \text{nat}; nq \leq x$ |]
 $\implies \text{succ}(x) \cup \text{incr_var}(y, nq) = \text{succ}(x \cup y)$ "
 <proof>

lemma *incr_And_lemma*:
 " $y < x \implies y \cup \text{succ}(x) = \text{succ}(x \cup y)$ "
 <proof>

lemma *arity_incr_bv_lemma* [rule_format]:

```


p ∈ formula  

  ==> ∀ n ∈ nat. arity (incr_bv(p) ' n) =  

    (if n < arity(p) then succ(arity(p)) else arity(p))"


<proof>

```

1.5 Renaming all but the First de Bruijn Variable

definition

```

incr_bv1 :: "i => i" where
  "incr_bv1(p) == incr_bv(p) ' 1"

```

```

lemma incr_bv1_type [TC]: "p ∈ formula ==> incr_bv1(p) ∈ formula"
<proof>

```

lemma sats_incr_bv1_iff:

```

"[| p ∈ formula; env ∈ list(A); x ∈ A; y ∈ A |]"
==> sats(A, incr_bv1(p), Cons(x, Cons(y, env))) <=>
  sats(A, p, Cons(x, env))"
<proof>

```

lemma formula_add_params1 [rule_format]:

```

"[| p ∈ formula; n ∈ nat; x ∈ A |]"
==> ∀ bvs ∈ list(A). ∀ env ∈ list(A).
  length(bvs) = n →
  sats(A, iterates(incr_bv1, n, p), Cons(x, bvs@env)) <=>
  sats(A, p, Cons(x, env))"
<proof>

```

lemma arity_incr_bv1_eq:

```

"p ∈ formula
==> arity(incr_bv1(p)) =
  (if 1 < arity(p) then succ(arity(p)) else arity(p))"
<proof>

```

lemma arity_iterates_incr_bv1_eq:

```

"[| p ∈ formula; n ∈ nat |]"
==> arity(incr_bv1^n(p)) =
  (if 1 < arity(p) then n #+ arity(p) else arity(p))"
<proof>

```

1.6 Definable Powerset

The definable powerset operation: Kunen's definition VI 1.1, page 165.

definition

```

DPow :: "i => i" where
  "DPow(A) == {X ∈ Pow(A)."

```

$$\exists \text{env} \in \text{list}(A). \exists p \in \text{formula}. \\ \text{arity}(p) \leq \text{succ}(\text{length}(\text{env})) \ \& \\ X = \{x \in A. \text{sats}(A, p, \text{Cons}(x, \text{env}))\}$$

lemma DPowI:

```
"[|env ∈ list(A); p ∈ formula; arity(p) ≤ succ(length(env))|]
==> {x∈A. sats(A, p, Cons(x,env))} ∈ DPow(A)"
⟨proof⟩
```

With this rule we can specify p later.

lemma DPowI2 [rule_format]:

```
"[|∀ x∈A. P(x) ⟷ sats(A, p, Cons(x,env));
env ∈ list(A); p ∈ formula; arity(p) ≤ succ(length(env))|]
==> {x∈A. P(x)} ∈ DPow(A)"
⟨proof⟩
```

lemma DPowD:

```
"X ∈ DPow(A)
==> X ⊆ A &
(∃ env ∈ list(A).
∃ p ∈ formula. arity(p) ≤ succ(length(env)) &
X = {x∈A. sats(A, p, Cons(x,env))})"
⟨proof⟩
```

lemmas DPow_imp_subset = DPowD [THEN conjunct1]

```
lemma "[| p ∈ formula; env ∈ list(A); arity(p) ≤ succ(length(env))
|]
==> {x∈A. sats(A, p, Cons(x,env))} ∈ DPow(A)"
⟨proof⟩
```

lemma DPow_subset_Pow: "DPow(A) ⊆ Pow(A)"
 ⟨proof⟩

lemma empty_in_DPow: "0 ∈ DPow(A)"
 ⟨proof⟩

lemma Compl_in_DPow: "X ∈ DPow(A) ==> (A-X) ∈ DPow(A)"
 ⟨proof⟩

lemma Int_in_DPow: "[| X ∈ DPow(A); Y ∈ DPow(A) |] ==> X ∩ Y ∈ DPow(A)"
 ⟨proof⟩

lemma Un_in_DPow: "[| X ∈ DPow(A); Y ∈ DPow(A) |] ==> X ∪ Y ∈ DPow(A)"
 ⟨proof⟩

lemma singleton_in_DPow: "a ∈ A ==> {a} ∈ DPow(A)"
 ⟨proof⟩

lemma *cons_in_DPow*: "[| a ∈ A; X ∈ DPow(A) |] ==> cons(a,X) ∈ DPow(A)"
 <proof>

lemma *Fin_into_DPow*: "X ∈ Fin(A) ==> X ∈ DPow(A)"
 <proof>

DPow is not monotonic. For example, let *A* be some non-constructible set of natural numbers, and let *B* be *nat*. Then $A \subseteq B$ and obviously $A \in DPow(A)$ but $A \notin DPow(B)$.

lemma *Finite_Pow_subset_Pow*: "Finite(A) ==> Pow(A) ⊆ DPow(A)"
 <proof>

lemma *Finite_DPow_eq_Pow*: "Finite(A) ==> DPow(A) = Pow(A)"
 <proof>

1.7 Internalized Formulas for the Ordinals

The *sats* theorems below differ from the usual form in that they include an element of absoluteness. That is, they relate internalized formulas to real concepts such as the subset relation, rather than to the relativized concepts defined in theory *Relative*. This lets us prove the theorem as *Ords_in_DPow* without first having to instantiate the locale *M_trivial*. Note that the present theory does not even take *Relative* as a parent.

1.7.1 The subset relation

definition

subset_fm :: "[i,i]=>i" where
 "subset_fm(x,y) == Forall(Implies(Member(0,succ(x)), Member(0,succ(y))))"

lemma *subset_type* [TC]: "[| x ∈ nat; y ∈ nat |] ==> subset_fm(x,y) ∈ formula"
 <proof>

lemma *arity_subset_fm* [simp]:
 "[| x ∈ nat; y ∈ nat |] ==> arity(subset_fm(x,y)) = succ(x) ∪ succ(y)"
 <proof>

lemma *sats_subset_fm* [simp]:
 "[| x < length(env); y ∈ nat; env ∈ list(A); Transset(A) |]
 ==> sats(A, subset_fm(x,y), env) ⟷ nth(x,env) ⊆ nth(y,env)"
 <proof>

1.7.2 Transitive sets

definition

```

transset_fm :: "i=>i" where
  "transset_fm(x) == Forall(Implies(Member(0,succ(x)), subset_fm(0,succ(x))))"

lemma transset_type [TC]: "x ∈ nat ==> transset_fm(x) ∈ formula"
⟨proof⟩

lemma arity_transset_fm [simp]:
  "x ∈ nat ==> arity(transset_fm(x)) = succ(x)"
⟨proof⟩

lemma sats_transset_fm [simp]:
  "[|x < length(env); env ∈ list(A); Transset(A)|]
  ==> sats(A, transset_fm(x), env) ⟷ Transset(nth(x,env))"
⟨proof⟩

```

1.7.3 Ordinals

definition

```

ordinal_fm :: "i=>i" where
  "ordinal_fm(x) ==
    And(transset_fm(x), Forall(Implies(Member(0,succ(x)), transset_fm(0))))"

```

```

lemma ordinal_type [TC]: "x ∈ nat ==> ordinal_fm(x) ∈ formula"
⟨proof⟩

```

```

lemma arity_ordinal_fm [simp]:
  "x ∈ nat ==> arity(ordinal_fm(x)) = succ(x)"
⟨proof⟩

```

```

lemma sats_ordinal_fm:
  "[|x < length(env); env ∈ list(A); Transset(A)|]
  ==> sats(A, ordinal_fm(x), env) ⟷ Ord(nth(x,env))"
⟨proof⟩

```

The subset consisting of the ordinals is definable. Essential lemma for *Ord_in_Lset*. This result is the objective of the present subsection.

```

theorem Ords_in_DPow: "Transset(A) ==> {x ∈ A. Ord(x)} ∈ DPow(A)"
⟨proof⟩

```

1.8 Constant Lset: Levels of the Constructible Universe

definition

```

Lset :: "i=>i" where
  "Lset(i) == transrec(i, %x f. ⋃ y∈x. DPow(f'y))"

```

definition

```

L :: "i=>o" where — Kunen's definition VI 1.5, page 167
  "L(x) == ∃ i. Ord(i) & x ∈ Lset(i)"

```

NOT SUITABLE FOR REWRITING – RECURSIVE!

lemma *Lset*: " $Lset(i) = (\bigcup_{j \in i} DPow(Lset(j)))$ "
 $\langle proof \rangle$

lemma *LsetI*: " $[|y \in x; A \in DPow(Lset(y))|] \implies A \in Lset(x)$ "
 $\langle proof \rangle$

lemma *LsetD*: " $A \in Lset(x) \implies \exists y \in x. A \in DPow(Lset(y))$ "
 $\langle proof \rangle$

1.8.1 Transitivity

lemma *elem_subset_in_DPow*: " $[|X \in A; X \subseteq A|] \implies X \in DPow(A)$ "
 $\langle proof \rangle$

lemma *Transset_subset_DPow*: " $Transset(A) \implies A \subseteq DPow(A)$ "
 $\langle proof \rangle$

lemma *Transset_DPow*: " $Transset(A) \implies Transset(DPow(A))$ "
 $\langle proof \rangle$

Kunen's VI 1.6 (a)

lemma *Transset_Lset*: " $Transset(Lset(i))$ "
 $\langle proof \rangle$

lemma *mem_Lset_imp_subset_Lset*: " $a \in Lset(i) \implies a \subseteq Lset(i)$ "
 $\langle proof \rangle$

1.8.2 Monotonicity

Kunen's VI 1.6 (b)

lemma *Lset_mono* [rule_format]:
 $"\forall j. i \leq j \longrightarrow Lset(i) \subseteq Lset(j)"$
 $\langle proof \rangle$

This version lets us remove the premise $Ord(i)$ sometimes.

lemma *Lset_mono_mem* [rule_format]:
 $"\forall j. i \in j \longrightarrow Lset(i) \subseteq Lset(j)"$
 $\langle proof \rangle$

Useful with Reflection to bump up the ordinal

lemma *subset_Lset_ltD*: " $[|A \subseteq Lset(i); i < j|] \implies A \subseteq Lset(j)$ "
 $\langle proof \rangle$

1.8.3 0, successor and limit equations for Lset

lemma *Lset_0* [simp]: " $Lset(0) = 0$ "
 $\langle proof \rangle$

lemma *Lset_succ_subset1*: " $DPow(Lset(i)) \subseteq Lset(succ(i))$ "
 $\langle proof \rangle$

lemma *Lset_succ_subset2*: " $Lset(succ(i)) \subseteq DPow(Lset(i))$ "
 $\langle proof \rangle$

lemma *Lset_succ*: " $Lset(succ(i)) = DPow(Lset(i))$ "
 $\langle proof \rangle$

lemma *Lset_Union [simp]*: " $Lset(\bigcup (X)) = (\bigcup_{y \in X}. Lset(y))$ "
 $\langle proof \rangle$

1.8.4 Lset applied to Limit ordinals

lemma *Limit_Lset_eq*:
" $Limit(i) \implies Lset(i) = (\bigcup_{y \in i}. Lset(y))$ "
 $\langle proof \rangle$

lemma *lt_LsetI*: " $[| a \in Lset(j); j < i |] \implies a \in Lset(i)$ "
 $\langle proof \rangle$

lemma *Limit_LsetE*:
" $[| a \in Lset(i); \neg R \implies Limit(i);$
 $!!x. [| x < i; a \in Lset(x) |] \implies R$
 $|] \implies R$ "
 $\langle proof \rangle$

1.8.5 Basic closure properties

lemma *zero_in_Lset*: " $y \in x \implies 0 \in Lset(x)$ "
 $\langle proof \rangle$

lemma *notin_Lset*: " $x \notin Lset(x)$ "
 $\langle proof \rangle$

1.9 Constructible Ordinals: Kunen's VI 1.9 (b)

lemma *Ords_of_Lset_eq*: " $Ord(i) \implies \{x \in Lset(i). Ord(x)\} = i$ "
 $\langle proof \rangle$

lemma *Ord_subset_Lset*: " $Ord(i) \implies i \subseteq Lset(i)$ "
 $\langle proof \rangle$

lemma *Ord_in_Lset*: " $Ord(i) \implies i \in Lset(succ(i))$ "
 $\langle proof \rangle$

lemma *Ord_in_L*: " $Ord(i) \implies L(i)$ "
 $\langle proof \rangle$

1.9.1 Unions

lemma *Union_in_Lset*:
 $"X \in Lset(i) \implies \bigcup (X) \in Lset(succ(i))"$
 $\langle proof \rangle$

theorem *Union_in_L*: $"L(X) \implies L(\bigcup (X))"$
 $\langle proof \rangle$

1.9.2 Finite sets and ordered pairs

lemma *singleton_in_Lset*: $"a \in Lset(i) \implies \{a\} \in Lset(succ(i))"$
 $\langle proof \rangle$

lemma *doubleton_in_Lset*:
 $"[| a \in Lset(i); b \in Lset(i) |] \implies \{a, b\} \in Lset(succ(i))"$
 $\langle proof \rangle$

lemma *Pair_in_Lset*:
 $"[| a \in Lset(i); b \in Lset(i); Ord(i) |] \implies \langle a, b \rangle \in Lset(succ(succ(i)))"$
 $\langle proof \rangle$

lemmas *Lset_UnI1* = *Un_upper1* [THEN *Lset_mono* [THEN *subsetD*]]

lemmas *Lset_UnI2* = *Un_upper2* [THEN *Lset_mono* [THEN *subsetD*]]

Hard work is finding a single $j \in i$ such that $\{a, b\} \subseteq Lset(j)$

lemma *doubleton_in_LLimit*:
 $"[| a \in Lset(i); b \in Lset(i); Limit(i) |] \implies \{a, b\} \in Lset(i)"$
 $\langle proof \rangle$

theorem *doubleton_in_L*: $"[| L(a); L(b) |] \implies L(\{a, b\})"$
 $\langle proof \rangle$

lemma *Pair_in_LLimit*:
 $"[| a \in Lset(i); b \in Lset(i); Limit(i) |] \implies \langle a, b \rangle \in Lset(i)"$

Infer that a, b occur at ordinals $x, x_a < i$.

$\langle proof \rangle$

The rank function for the constructible universe

definition

$lrank :: "i \Rightarrow i"$ **where** — Kunen's definition VI 1.7
 $"lrank(x) == \mu i. x \in Lset(succ(i))"$

lemma *L_I*: $"[| x \in Lset(i); Ord(i) |] \implies L(x)"$
 $\langle proof \rangle$

lemma *L_D*: $"L(x) \implies \exists i. Ord(i) \ \& \ x \in Lset(i)"$
 $\langle proof \rangle$

lemma *Ord_lrank [simp]: "Ord(lrank(a))"*
 $\langle proof \rangle$

lemma *Lset_lrank_lt [rule_format]: "Ord(i) ==> x ∈ Lset(i) → lrank(x) < i"*
 $\langle proof \rangle$

Kunen's VI 1.8. The proof is much harder than the text would suggest. For a start, it needs the previous lemma, which is proved by induction.

lemma *Lset_iff_lrank_lt: "Ord(i) ==> x ∈ Lset(i) ↔ L(x) & lrank(x) < i"*
 $\langle proof \rangle$

lemma *Lset_succ_lrank_iff [simp]: "x ∈ Lset(succ(lrank(x))) ↔ L(x)"*
 $\langle proof \rangle$

Kunen's VI 1.9 (a)

lemma *lrank_of_Ord: "Ord(i) ==> lrank(i) = i"*
 $\langle proof \rangle$

This is $\text{lrank}(\text{lrank}(a)) = \text{lrank}(a)$

declare *Ord_lrank [THEN lrank_of_Ord, simp]*

Kunen's VI 1.10

lemma *Lset_in_Lset_succ: "Lset(i) ∈ Lset(succ(i))"*
 $\langle proof \rangle$

lemma *lrank_Lset: "Ord(i) ==> lrank(Lset(i)) = i"*
 $\langle proof \rangle$

Kunen's VI 1.11

lemma *Lset_subset_Vset: "Ord(i) ==> Lset(i) ⊆ Vset(i)"*
 $\langle proof \rangle$

Kunen's VI 1.12

lemma *Lset_subset_Vset': "i ∈ nat ==> Lset(i) = Vset(i)"*
 $\langle proof \rangle$

Every set of constructible sets is included in some *Lset*

lemma *subset_Lset:*
 $"(\forall x \in A. L(x)) ==> \exists i. \text{Ord}(i) \ \& \ A \subseteq Lset(i)"$
 $\langle proof \rangle$

lemma *subset_LsetE:*
 $"[\forall x \in A. L(x);$
 $\quad !!i. [\text{Ord}(i); A \subseteq Lset(i)] ==> P]$
 $==> P"$
 $\langle proof \rangle$

1.9.3 For L to satisfy the Powerset axiom

```
lemma LPow_env_typing:
  "[| y ∈ Lset(i); Ord(i); y ⊆ X |]
   ==> ∃ z ∈ Pow(X). y ∈ Lset(succ(lrank(z)))"
⟨proof⟩
```

```
lemma LPow_in_Lset:
  "[| X ∈ Lset(i); Ord(i) |] ==> ∃ j. Ord(j) & {y ∈ Pow(X). L(y)} ∈
Lset(j)"
⟨proof⟩
```

```
theorem LPow_in_L: "L(X) ==> L({y ∈ Pow(X). L(y)})"
⟨proof⟩
```

1.10 Eliminating arity from the Definition of Lset

```
lemma nth_zero_eq_0: "n ∈ nat ==> nth(n, [0]) = 0"
⟨proof⟩
```

```
lemma sats_app_0_iff [rule_format]:
  "[| p ∈ formula; 0 ∈ A |]
   ==> ∀ env ∈ list(A). sats(A, p, env@[0]) ⟷ sats(A, p, env)"
⟨proof⟩
```

```
lemma sats_app_zeroes_iff:
  "[| p ∈ formula; 0 ∈ A; env ∈ list(A); n ∈ nat |]
   ==> sats(A, p, env @ repeat(0, n)) ⟷ sats(A, p, env)"
⟨proof⟩
```

```
lemma exists_bigger_env:
  "[| p ∈ formula; 0 ∈ A; env ∈ list(A) |]
   ==> ∃ env' ∈ list(A). arity(p) ≤ succ(length(env')) &
      (∀ a ∈ A. sats(A, p, Cons(a, env')) ⟷ sats(A, p, Cons(a, env)))"
⟨proof⟩
```

A simpler version of DPow: no arity check!

definition

```
DPow' :: "i => i" where
  "DPow'(A) == {X ∈ Pow(A).
    ∃ env ∈ list(A). ∃ p ∈ formula.
      X = {x ∈ A. sats(A, p, Cons(x, env))}}"
```

```
lemma DPow_subset_DPow': "DPow(A) ⊆ DPow'(A)"
⟨proof⟩
```

```
lemma DPow'_0: "DPow'(0) = {0}"
⟨proof⟩
```

```
lemma DPow'_subset_DPow: "0 ∈ A ==> DPow'(A) ⊆ DPow(A)"
```

<proof>

lemma *DPow_eq_DPow'*: "Transset(A) ==> DPow(A) = DPow'(A)"
<proof>

And thus we can relativize *Lset* without bothering with *arity* and *length*

lemma *Lset_eq_transrec_DPow'*: "Lset(i) = transrec(i, %x f. $\bigcup_{y \in x} \text{DPow}'(f'y)$)"
<proof>

With this rule we can specify *p* later and don't worry about arities at all!

lemma *DPow_LsetI* [*rule_format*]:
"[/ $\forall x \in \text{Lset}(i). P(x) \longleftrightarrow \text{sats}(\text{Lset}(i), p, \text{Cons}(x, \text{env}))$;
 $\text{env} \in \text{list}(\text{Lset}(i)); p \in \text{formula}$]/
 ==> $\{x \in \text{Lset}(i). P(x)\} \in \text{DPow}(\text{Lset}(i))$ "
<proof>

end

2 Relativization and Absoluteness

theory *Relative* imports *ZF* begin

2.1 Relativized versions of standard set-theoretic concepts

definition

empty :: "[*i*=>*o*,*i*] => *o*" where
 "*empty*(*M*,*z*) == $\forall x[M]. x \notin z$ "

definition

subset :: "[*i*=>*o*,*i*,*i*] => *o*" where
 "*subset*(*M*,*A*,*B*) == $\forall x[M]. x \in A \longrightarrow x \in B$ "

definition

upair :: "[*i*=>*o*,*i*,*i*,*i*] => *o*" where
 "*upair*(*M*,*a*,*b*,*z*) == $a \in z \ \& \ b \in z \ \& \ (\forall x[M]. x \in z \longrightarrow x = a \mid x = b)$ "

definition

pair :: "[*i*=>*o*,*i*,*i*,*i*] => *o*" where
 "*pair*(*M*,*a*,*b*,*z*) == $\exists x[M]. \text{upair}(M, a, a, x) \ \& \ (\exists y[M]. \text{upair}(M, a, b, y) \ \& \ \text{upair}(M, x, y, z))$ "

definition

union :: "[*i*=>*o*,*i*,*i*,*i*] => *o*" where
 "*union*(*M*,*a*,*b*,*z*) == $\forall x[M]. x \in z \longleftrightarrow x \in a \mid x \in b$ "

definition

is_cons :: "[*i*=>*o*,*i*,*i*,*i*] => *o*" where

"is_cons(M,a,b,z) == $\exists x[M]. \text{upair}(M,a,a,x) \ \& \ \text{union}(M,x,b,z)$ "

definition

successor :: "[i=>o,i,i] => o" where
 "successor(M,a,z) == is_cons(M,a,a,z)"

definition

number1 :: "[i=>o,i] => o" where
 "number1(M,a) == $\exists x[M]. \text{empty}(M,x) \ \& \ \text{successor}(M,x,a)$ "

definition

number2 :: "[i=>o,i] => o" where
 "number2(M,a) == $\exists x[M]. \text{number1}(M,x) \ \& \ \text{successor}(M,x,a)$ "

definition

number3 :: "[i=>o,i] => o" where
 "number3(M,a) == $\exists x[M]. \text{number2}(M,x) \ \& \ \text{successor}(M,x,a)$ "

definition

powerset :: "[i=>o,i,i] => o" where
 "powerset(M,A,z) == $\forall x[M]. x \in z \longleftrightarrow \text{subset}(M,x,A)$ "

definition

is_Collect :: "[i=>o,i,i=>o,i] => o" where
 "is_Collect(M,A,P,z) == $\forall x[M]. x \in z \longleftrightarrow x \in A \ \& \ P(x)$ "

definition

is_Replace :: "[i=>o,i,[i,i]=>o,i] => o" where
 "is_Replace(M,A,P,z) == $\forall u[M]. u \in z \longleftrightarrow (\exists x[M]. x \in A \ \& \ P(x,u))$ "

definition

inter :: "[i=>o,i,i,i] => o" where
 "inter(M,a,b,z) == $\forall x[M]. x \in z \longleftrightarrow x \in a \ \& \ x \in b$ "

definition

setdiff :: "[i=>o,i,i,i] => o" where
 "setdiff(M,a,b,z) == $\forall x[M]. x \in z \longleftrightarrow x \in a \ \& \ x \notin b$ "

definition

big_union :: "[i=>o,i,i] => o" where
 "big_union(M,A,z) == $\forall x[M]. x \in z \longleftrightarrow (\exists y[M]. y \in A \ \& \ x \in y)$ "

definition

big_inter :: "[i=>o,i,i] => o" where
 "big_inter(M,A,z) ==
 (A=0 $\longrightarrow$ z=0) &
 (A $\neq$ 0 $\longrightarrow$ ($\forall x[M]. x \in z \longleftrightarrow (\forall y[M]. y \in A \longrightarrow x \in y)$))"

definition

```

cartprod :: "[i=>o,i,i,i] => o" where
  "cartprod(M,A,B,z) ==
     $\forall u[M]. u \in z \longleftrightarrow (\exists x[M]. x \in A \ \& \ (\exists y[M]. y \in B \ \& \ \text{pair}(M,x,y,u)))"$ 

```

definition

```

is_sum :: "[i=>o,i,i,i] => o" where
  "is_sum(M,A,B,Z) ==
     $\exists A0[M]. \exists n1[M]. \exists s1[M]. \exists B1[M].$ 
    number1(M,n1) & cartprod(M,n1,A,A0) & upair(M,n1,n1,s1) &
    cartprod(M,s1,B,B1) & union(M,A0,B1,Z)"

```

definition

```

is_Inl :: "[i=>o,i,i] => o" where
  "is_Inl(M,a,z) ==  $\exists \text{zero}[M]. \text{empty}(M,\text{zero}) \ \& \ \text{pair}(M,\text{zero},a,z)"$ 

```

definition

```

is_Inr :: "[i=>o,i,i] => o" where
  "is_Inr(M,a,z) ==  $\exists n1[M]. \text{number1}(M,n1) \ \& \ \text{pair}(M,n1,a,z)"$ 

```

definition

```

is_converse :: "[i=>o,i,i] => o" where
  "is_converse(M,r,z) ==
     $\forall x[M]. x \in z \longleftrightarrow$ 
     $(\exists w[M]. w \in r \ \& \ (\exists u[M]. \exists v[M]. \text{pair}(M,u,v,w) \ \& \ \text{pair}(M,v,u,x)))"$ 

```

definition

```

pre_image :: "[i=>o,i,i,i] => o" where
  "pre_image(M,r,A,z) ==
     $\forall x[M]. x \in z \longleftrightarrow (\exists w[M]. w \in r \ \& \ (\exists y[M]. y \in A \ \& \ \text{pair}(M,x,y,w)))"$ 

```

definition

```

is_domain :: "[i=>o,i,i] => o" where
  "is_domain(M,r,z) ==
     $\forall x[M]. x \in z \longleftrightarrow (\exists w[M]. w \in r \ \& \ (\exists y[M]. \text{pair}(M,x,y,w)))"$ 

```

definition

```

image :: "[i=>o,i,i,i] => o" where
  "image(M,r,A,z) ==
     $\forall y[M]. y \in z \longleftrightarrow (\exists w[M]. w \in r \ \& \ (\exists x[M]. x \in A \ \& \ \text{pair}(M,x,y,w)))"$ 

```

definition

```

is_range :: "[i=>o,i,i] => o" where
  — the cleaner  $\exists r'[M]. \text{is\_converse}(M, r, r') \wedge \text{is\_domain}(M, r', z)$ 
  unfortunately needs an instance of separation in order to prove  $M(\text{converse}(r))$ .
  "is_range(M,r,z) ==
     $\forall y[M]. y \in z \longleftrightarrow (\exists w[M]. w \in r \ \& \ (\exists x[M]. \text{pair}(M,x,y,w)))"$ 

```

definition

```

is_field :: "[i=>o,i,i] => o" where

```

```

"is_field(M,r,z) ==
  ∃ dr[M]. ∃ rr[M]. is_domain(M,r,dr) & is_range(M,r,rr) &
    union(M,dr,rr,z)"

```

definition

```

is_relation :: "[i=>o,i] => o" where
  "is_relation(M,r) ==
    (∀ z[M]. z ∈ r → (∃ x[M]. ∃ y[M]. pair(M,x,y,z)))"

```

definition

```

is_function :: "[i=>o,i] => o" where
  "is_function(M,r) ==
    ∀ x[M]. ∀ y[M]. ∀ y'[M]. ∀ p[M]. ∀ p'[M].
      pair(M,x,y,p) → pair(M,x,y',p') → p ∈ r → p' ∈ r → y=y'"

```

definition

```

fun_apply :: "[i=>o,i,i,i] => o" where
  "fun_apply(M,f,x,y) ==
    (∃ xs[M]. ∃ fxs[M].
      upair(M,x,x,xs) & image(M,f,xs,fxs) & big_union(M,fxs,y))"

```

definition

```

typed_function :: "[i=>o,i,i,i] => o" where
  "typed_function(M,A,B,r) ==
    is_function(M,r) & is_relation(M,r) & is_domain(M,r,A) &
    (∀ u[M]. u ∈ r → (∀ x[M]. ∀ y[M]. pair(M,x,y,u) → y ∈ B))"

```

definition

```

is_funspace :: "[i=>o,i,i,i] => o" where
  "is_funspace(M,A,B,F) ==
    ∀ f[M]. f ∈ F ↔ typed_function(M,A,B,f)"

```

definition

```

composition :: "[i=>o,i,i,i] => o" where
  "composition(M,r,s,t) ==
    ∀ p[M]. p ∈ t ↔
      (∃ x[M]. ∃ y[M]. ∃ z[M]. ∃ xy[M]. ∃ yz[M].
        pair(M,x,z,p) & pair(M,x,y,xy) & pair(M,y,z,yz) &
        xy ∈ s & yz ∈ r)"

```

definition

```

injection :: "[i=>o,i,i,i] => o" where
  "injection(M,A,B,f) ==
    typed_function(M,A,B,f) &
    (∀ x[M]. ∀ x'[M]. ∀ y[M]. ∀ p[M]. ∀ p'[M].
      pair(M,x,y,p) → pair(M,x',y,p') → p ∈ f → p' ∈ f → x=x')"

```

definition

```

surjection :: "[i=>o,i,i,i] => o" where

```

```

"surjection(M,A,B,f) ==
  typed_function(M,A,B,f) &
  ( $\forall y[M]. y \in B \longrightarrow (\exists x[M]. x \in A \ \& \ fun\_apply(M,f,x,y))$ )"

```

definition

```

bijection :: "[i=>o,i,i,i] => o" where
  "bijection(M,A,B,f) == injection(M,A,B,f) & surjection(M,A,B,f)"

```

definition

```

restriction :: "[i=>o,i,i,i] => o" where
  "restriction(M,r,A,z) ==
     $\forall x[M]. x \in z \longleftrightarrow (x \in r \ \& \ (\exists u[M]. u \in A \ \& \ (\exists v[M]. pair(M,u,v,x))))$ "

```

definition

```

transitive_set :: "[i=>o,i] => o" where
  "transitive_set(M,a) ==  $\forall x[M]. x \in a \longrightarrow subset(M,x,a)$ "

```

definition

```

ordinal :: "[i=>o,i] => o" where
  — an ordinal is a transitive set of transitive sets
  "ordinal(M,a) == transitive_set(M,a) & ( $\forall x[M]. x \in a \longrightarrow transitive\_set(M,x)$ )"

```

definition

```

limit_ordinal :: "[i=>o,i] => o" where
  — a limit ordinal is a non-empty, successor-closed ordinal
  "limit_ordinal(M,a) ==
    ordinal(M,a) &  $\sim empty(M,a)$  &
    ( $\forall x[M]. x \in a \longrightarrow (\exists y[M]. y \in a \ \& \ successor(M,x,y))$ )"

```

definition

```

successor_ordinal :: "[i=>o,i] => o" where
  — a successor ordinal is any ordinal that is neither empty nor limit
  "successor_ordinal(M,a) ==
    ordinal(M,a) &  $\sim empty(M,a)$  &  $\sim limit\_ordinal(M,a)$ "

```

definition

```

finite_ordinal :: "[i=>o,i] => o" where
  — an ordinal is finite if neither it nor any of its elements are limit
  "finite_ordinal(M,a) ==
    ordinal(M,a) &  $\sim limit\_ordinal(M,a)$  &
    ( $\forall x[M]. x \in a \longrightarrow \sim limit\_ordinal(M,x)$ )"

```

definition

```

omega :: "[i=>o,i] => o" where
  — omega is a limit ordinal none of whose elements are limit
  "omega(M,a) == limit_ordinal(M,a) & ( $\forall x[M]. x \in a \longrightarrow \sim limit\_ordinal(M,x)$ )"

```

definition

```

is_quasinat :: "[i=>o,i] => o" where

```

```
"is_quasinat(M,z) == empty(M,z) | ( $\exists m[M]. \text{successor}(M,m,z)$ )"
```

definition

```
is_nat_case :: "[i=>o, i, [i,i]=>o, i, i] => o" where
  "is_nat_case(M, a, is_b, k, z) ==
    (empty(M,k)  $\longrightarrow$  z=a) &
    ( $\forall m[M]. \text{successor}(M,m,k) \longrightarrow \text{is}_b(m,z)$ ) &
    (is_quasinat(M,k) | empty(M,z))"
```

definition

```
relation1 :: "[i=>o, [i,i]=>o, i=>i] => o" where
  "relation1(M,is_f,f) ==  $\forall x[M]. \forall y[M]. \text{is}_f(x,y) \longleftrightarrow y = f(x)$ "
```

definition

```
Relation1 :: "[i=>o, i, [i,i]=>o, i=>i] => o" where
  — as above, but typed
  "Relation1(M,A,is_f,f) ==
     $\forall x[M]. \forall y[M]. x \in A \longrightarrow \text{is}_f(x,y) \longleftrightarrow y = f(x)$ "
```

definition

```
relation2 :: "[i=>o, [i,i,i]=>o, [i,i]=>i] => o" where
  "relation2(M,is_f,f) ==  $\forall x[M]. \forall y[M]. \forall z[M]. \text{is}_f(x,y,z) \longleftrightarrow z = f(x,y)$ "
```

definition

```
Relation2 :: "[i=>o, i, i, [i,i,i]=>o, [i,i]=>i] => o" where
  "Relation2(M,A,B,is_f,f) ==
     $\forall x[M]. \forall y[M]. \forall z[M]. x \in A \longrightarrow y \in B \longrightarrow \text{is}_f(x,y,z) \longleftrightarrow z = f(x,y)$ "
```

definition

```
relation3 :: "[i=>o, [i,i,i,i]=>o, [i,i,i]=>i] => o" where
  "relation3(M,is_f,f) ==
     $\forall x[M]. \forall y[M]. \forall z[M]. \forall u[M]. \text{is}_f(x,y,z,u) \longleftrightarrow u = f(x,y,z)$ "
```

definition

```
Relation3 :: "[i=>o, i, i, i, [i,i,i,i]=>o, [i,i,i]=>i] => o" where
  "Relation3(M,A,B,C,is_f,f) ==
     $\forall x[M]. \forall y[M]. \forall z[M]. \forall u[M].$ 
     $x \in A \longrightarrow y \in B \longrightarrow z \in C \longrightarrow \text{is}_f(x,y,z,u) \longleftrightarrow u = f(x,y,z)$ "
```

definition

```
relation4 :: "[i=>o, [i,i,i,i,i]=>o, [i,i,i,i]=>i] => o" where
  "relation4(M,is_f,f) ==
     $\forall u[M]. \forall x[M]. \forall y[M]. \forall z[M]. \forall a[M]. \text{is}_f(u,x,y,z,a) \longleftrightarrow a = f(u,x,y,z)$ "
```

Useful when absoluteness reasoning has replaced the predicates by terms

lemma triv_Relation1:

```
"Relation1(M, A,  $\lambda x y. y = f(x), f$ )"
<proof>
```

lemma *triv_Relation2*:
 "Relation2(*M*, *A*, *B*, $\lambda x y a. a = f(x,y), f$)"
 <proof>

2.2 The relativized ZF axioms

definition

extensionality :: "(*i=>o*) => *o*" where
 "extensionality(*M*) ==
 $\forall x[M]. \forall y[M]. (\forall z[M]. z \in x \longleftrightarrow z \in y) \longrightarrow x=y$ "

definition

separation :: "[*i=>o*, *i=>o*] => *o*" where
 — The formula *P* should only involve parameters belonging to *M* and all its quantifiers must be relativized to *M*. We do not have separation as a scheme; every instance that we need must be assumed (and later proved) separately.
 "separation(*M*,*P*) ==
 $\forall z[M]. \exists y[M]. \forall x[M]. x \in y \longleftrightarrow x \in z \ \& \ P(x)$ "

definition

upair_ax :: "(*i=>o*) => *o*" where
 "upair_ax(*M*) == $\forall x[M]. \forall y[M]. \exists z[M]. \text{upair}(M,x,y,z)$ "

definition

Union_ax :: "(*i=>o*) => *o*" where
 "Union_ax(*M*) == $\forall x[M]. \exists z[M]. \text{big_union}(M,x,z)$ "

definition

power_ax :: "(*i=>o*) => *o*" where
 "power_ax(*M*) == $\forall x[M]. \exists z[M]. \text{powerset}(M,x,z)$ "

definition

univalent :: "[*i=>o*, *i*, [*i,i*]=>*o*] => *o*" where
 "univalent(*M*,*A*,*P*) ==
 $\forall x[M]. x \in A \longrightarrow (\forall y[M]. \forall z[M]. P(x,y) \ \& \ P(x,z) \longrightarrow y=z)$ "

definition

replacement :: "[*i=>o*, [*i,i*]=>*o*] => *o*" where
 "replacement(*M*,*P*) ==
 $\forall A[M]. \text{univalent}(M,A,P) \longrightarrow$
 $(\exists Y[M]. \forall b[M]. (\exists x[M]. x \in A \ \& \ P(x,b)) \longrightarrow b \in Y)$ "

definition

strong_replacement :: "[*i=>o*, [*i,i*]=>*o*] => *o*" where
 "strong_replacement(*M*,*P*) ==
 $\forall A[M]. \text{univalent}(M,A,P) \longrightarrow$
 $(\exists Y[M]. \forall b[M]. b \in Y \longleftrightarrow (\exists x[M]. x \in A \ \& \ P(x,b)))$ "

definition

```
foundation_ax :: "(i=>o) => o" where
  "foundation_ax(M) ==
     $\forall x[M]. (\exists y[M]. y \in x) \longrightarrow (\exists y[M]. y \in x \ \& \ \sim(\exists z[M]. z \in x \ \& \ z \in y))"$ 
```

2.3 A trivial consistency proof for V_ω

We prove that V_ω (or *univ* in Isabelle) satisfies some ZF axioms. Kunen, Theorem IV 3.13, page 123.

```
lemma univ0_downwards_mem: "[| y ∈ x; x ∈ univ(0) |] ==> y ∈ univ(0)"
  <proof>
```

```
lemma univ0_Ball_abs [simp]:
  "A ∈ univ(0) ==> ( $\forall x \in A. x \in univ(0) \longrightarrow P(x)$ )  $\longleftrightarrow$  ( $\forall x \in A. P(x)$ )"
  <proof>
```

```
lemma univ0_Bex_abs [simp]:
  "A ∈ univ(0) ==> ( $\exists x \in A. x \in univ(0) \ \& \ P(x)$ )  $\longleftrightarrow$  ( $\exists x \in A. P(x)$ )"
  <proof>
```

Congruence rule for separation: can assume the variable is in M

```
lemma separation_cong [cong]:
  "(!!x. M(x) ==> P(x)  $\longleftrightarrow$  P'(x))
  ==> separation(M, %x. P(x))  $\longleftrightarrow$  separation(M, %x. P'(x))"
  <proof>
```

```
lemma univalent_cong [cong]:
  "[| A=A'; !!x y. [| x ∈ A; M(x); M(y) |] ==> P(x,y)  $\longleftrightarrow$  P'(x,y) |]
  ==> univalent(M, A, %x y. P(x,y))  $\longleftrightarrow$  univalent(M, A', %x y. P'(x,y))"
  <proof>
```

```
lemma univalent_triv [intro,simp]:
  "univalent(M, A,  $\lambda x y. y = f(x)$ )"
  <proof>
```

```
lemma univalent_conjI2 [intro,simp]:
  "univalent(M,A,Q) ==> univalent(M, A,  $\lambda x y. P(x,y) \ \& \ Q(x,y)$ )"
  <proof>
```

Congruence rule for replacement

```
lemma strong_replacement_cong [cong]:
  "[| !!x y. [| M(x); M(y) |] ==> P(x,y)  $\longleftrightarrow$  P'(x,y) |]
  ==> strong_replacement(M, %x y. P(x,y))  $\longleftrightarrow$ 
    strong_replacement(M, %x y. P'(x,y))"
  <proof>
```

The extensionality axiom

```
lemma "extensionality( $\lambda x. x \in univ(0)$ )"
```

<proof>

The separation axiom requires some lemmas

lemma *Collect_in_Vfrom*:
" [| X ∈ Vfrom(A,j); Transset(A) |] ==> Collect(X,P) ∈ Vfrom(A,
succ(j)) "
<proof>

lemma *Collect_in_VLimit*:
" [| X ∈ Vfrom(A,i); Limit(i); Transset(A) |]
==> Collect(X,P) ∈ Vfrom(A,i) "
<proof>

lemma *Collect_in_univ*:
" [| X ∈ univ(A); Transset(A) |] ==> Collect(X,P) ∈ univ(A) "
<proof>

lemma "separation($\lambda x. x \in \text{univ}(0), P$) "
<proof>

Unordered pairing axiom

lemma "upair_ax($\lambda x. x \in \text{univ}(0)$) "
<proof>

Union axiom

lemma "Union_ax($\lambda x. x \in \text{univ}(0)$) "
<proof>

Powerset axiom

lemma *Pow_in_univ*:
" [| X ∈ univ(A); Transset(A) |] ==> Pow(X) ∈ univ(A) "
<proof>

lemma "power_ax($\lambda x. x \in \text{univ}(0)$) "
<proof>

Foundation axiom

lemma "foundation_ax($\lambda x. x \in \text{univ}(0)$) "
<proof>

lemma "replacement($\lambda x. x \in \text{univ}(0), P$) "
<proof>

no idea: maybe prove by induction on the rank of A?

Still missing: Replacement, Choice

2.4 Lemmas Needed to Reduce Some Set Constructions to Instances of Separation

lemma *image_iff_Collect*: "r -'' A = {y ∈ ⋃ (⋃ (r)). ∃ p ∈ r. ∃ x ∈ A. p = <x,y>}"
 ⟨proof⟩

lemma *vimage_iff_Collect*:
 "r -'' A = {x ∈ ⋃ (⋃ (r)). ∃ p ∈ r. ∃ y ∈ A. p = <x,y>}"
 ⟨proof⟩

These two lemmas lets us prove *domain_closed* and *range_closed* without new instances of separation

lemma *domain_eq_vimage*: "domain(r) = r -'' Union(Union(r))"
 ⟨proof⟩

lemma *range_eq_image*: "range(r) = r -'' Union(Union(r))"
 ⟨proof⟩

lemma *replacementD*:
 "[| replacement(M,P); M(A); univalent(M,A,P) |]
 ==> ∃ Y[M]. (∀ b[M]. ((∃ x[M]. x ∈ A & P(x,b)) → b ∈ Y))"
 ⟨proof⟩

lemma *strong_replacementD*:
 "[| strong_replacement(M,P); M(A); univalent(M,A,P) |]
 ==> ∃ Y[M]. (∀ b[M]. (b ∈ Y ↔ (∃ x[M]. x ∈ A & P(x,b))))"
 ⟨proof⟩

lemma *separationD*:
 "[| separation(M,P); M(z) |] ==> ∃ y[M]. ∀ x[M]. x ∈ y ↔ x ∈ z & P(x)"
 ⟨proof⟩

More constants, for order types

definition

order_isomorphism :: "[i=>o,i,i,i,i,i] => o" where
 "order_isomorphism(M,A,r,B,s,f) ==
 bijection(M,A,B,f) &
 (∀ x[M]. x ∈ A → (∀ y[M]. y ∈ A →
 (∀ p[M]. ∀ fx[M]. ∀ fy[M]. ∀ q[M].
 pair(M,x,y,p) → fun_apply(M,f,x,fx) → fun_apply(M,f,y,fy)
 →
 pair(M,fx,fy,q) → (p ∈ r ↔ q ∈ s))))"

definition

pred_set :: "[i=>o,i,i,i,i,i] => o" where
 "pred_set(M,A,x,r,B) ==
 ∀ y[M]. y ∈ B ↔ (∃ p[M]. p ∈ r & y ∈ A & pair(M,y,x,p))"

definition

```
membership :: "[i=>o,i,i] => o" where — membership relation
"membership(M,A,r) ==
  
$$\forall p[M]. p \in r \iff (\exists x[M]. x \in A \ \& \ (\exists y[M]. y \in A \ \& \ x \in y \ \& \ \text{pair}(M,x,y,p)))"$$

```

2.5 Introducing a Transitive Class Model

The class M is assumed to be transitive and inhabited

```
locale M_trans =
  fixes M
  assumes transM: "[| y∈x; M(x) |] ==> M(y)"
  and M_inhabited: "∃x . M(x)"
```

```
lemma (in M_trans) nonempty [simp]: "M(0)"
<proof>
```

The class M is assumed to be transitive and to satisfy some relativized ZF axioms

```
locale M_trivial = M_trans +
  assumes upair_ax: "upair_ax(M)"
  and Union_ax: "Union_ax(M)"
```

```
lemma (in M_trans) rall_abs [simp]:
  
$$M(A) \implies (\forall x[M]. x \in A \longrightarrow P(x)) \iff (\forall x \in A. P(x))$$

<proof>
```

```
lemma (in M_trans) rex_abs [simp]:
  
$$M(A) \implies (\exists x[M]. x \in A \ \& \ P(x)) \iff (\exists x \in A. P(x))$$

<proof>
```

```
lemma (in M_trans) ball_iff_equiv:
  
$$M(A) \implies (\forall x[M]. (x \in A \iff P(x))) \iff$$


$$(\forall x \in A. P(x)) \ \& \ (\forall x. P(x) \longrightarrow M(x) \longrightarrow x \in A)$$

<proof>
```

Simplifies proofs of equalities when there's an iff-equality available for rewriting, universally quantified over M. But it's not the only way to prove such equalities: its premises $M(A)$ and $M(B)$ can be too strong.

```
lemma (in M_trans) M_equalityI:
  
$$"[| \text{!!}x. M(x) \implies x \in A \iff x \in B; M(A); M(B) |] \implies A=B"$$

<proof>
```

2.5.1 Trivial Absoluteness Proofs: Empty Set, Pairs, etc.

```
lemma (in M_trans) empty_abs [simp]:
  
$$M(z) \implies \text{empty}(M,z) \iff z=0$$

<proof>
```

```

lemma (in M_trans) subset_abs [simp]:
  "M(A) ==> subset(M,A,B) <=> A ⊆ B"
<proof>

lemma (in M_trans) upair_abs [simp]:
  "M(z) ==> upair(M,a,b,z) <=> z={a,b}"
<proof>

lemma (in M_trivial) upair_in_MI [intro!]:
  " M(a) & M(b) ==> M({a,b}) "
<proof>

lemma (in M_trans) upair_in_MD [dest!]:
  "M({a,b}) ==> M(a) & M(b)"
<proof>

lemma (in M_trivial) upair_in_M_iff [simp]:
  "M({a,b}) <=> M(a) & M(b)"
<proof>

lemma (in M_trivial) singleton_in_MI [intro!]:
  "M(a) ==> M({a})"
<proof>

lemma (in M_trans) singleton_in_MD [dest!]:
  "M({a}) ==> M(a)"
<proof>

lemma (in M_trivial) singleton_in_M_iff [simp]:
  "M({a}) <=> M(a)"
<proof>

lemma (in M_trans) pair_abs [simp]:
  "M(z) ==> pair(M,a,b,z) <=> z=<a,b>"
<proof>

lemma (in M_trans) pair_in_MD [dest!]:
  "M(<a,b>) ==> M(a) & M(b)"
<proof>

lemma (in M_trivial) pair_in_MI [intro!]:
  "M(a) & M(b) ==> M(<a,b>)"
<proof>

lemma (in M_trivial) pair_in_M_iff [simp]:
  "M(<a,b>) <=> M(a) & M(b)"
<proof>

lemma (in M_trans) pair_components_in_M:

```

"[| <x,y> ∈ A; M(A) |] ==> M(x) & M(y)"
 <proof>

lemma (in M_trivial) cartprod_abs [simp]:
 "[| M(A); M(B); M(z) |] ==> cartprod(M,A,B,z) <=> z = A*B"
 <proof>

2.5.2 Absoluteness for Unions and Intersections

lemma (in M_trans) union_abs [simp]:
 "[| M(a); M(b); M(z) |] ==> union(M,a,b,z) <=> z = a ∪ b"
 <proof>

lemma (in M_trans) inter_abs [simp]:
 "[| M(a); M(b); M(z) |] ==> inter(M,a,b,z) <=> z = a ∩ b"
 <proof>

lemma (in M_trans) setdiff_abs [simp]:
 "[| M(a); M(b); M(z) |] ==> setdiff(M,a,b,z) <=> z = a-b"
 <proof>

lemma (in M_trans) Union_abs [simp]:
 "[| M(A); M(z) |] ==> big_union(M,A,z) <=> z = ∪ (A)"
 <proof>

lemma (in M_trivial) Union_closed [intro,simp]:
 "M(A) ==> M(∪ (A))"
 <proof>

lemma (in M_trivial) Un_closed [intro,simp]:
 "[| M(A); M(B) |] ==> M(A ∪ B)"
 <proof>

lemma (in M_trivial) cons_closed [intro,simp]:
 "[| M(a); M(A) |] ==> M(cons(a,A))"
 <proof>

lemma (in M_trivial) cons_abs [simp]:
 "[| M(b); M(z) |] ==> is_cons(M,a,b,z) <=> z = cons(a,b)"
 <proof>

lemma (in M_trivial) successor_abs [simp]:
 "[| M(a); M(z) |] ==> successor(M,a,z) <=> z = succ(a)"
 <proof>

lemma (in M_trans) succ_in_MD [dest!]:
 "M(succ(a)) ==> M(a)"
 <proof>

```
lemma (in M_trivial) succ_in_MI [intro!]:
  "M(a)  $\implies$  M(succ(a))"
  <proof>
```

```
lemma (in M_trivial) succ_in_M_iff [simp]:
  "M(succ(a))  $\longleftrightarrow$  M(a)"
  <proof>
```

2.5.3 Absoluteness for Separation and Replacement

```
lemma (in M_trans) separation_closed [intro,simp]:
  "[| separation(M,P); M(A) |]  $\implies$  M(Collect(A,P))"
  <proof>
```

```
lemma separation_iff:
  "separation(M,P)  $\longleftrightarrow$  ( $\forall z[M]. \exists y[M]. \text{is\_Collect}(M,z,P,y)$ )"
  <proof>
```

```
lemma (in M_trans) Collect_abs [simp]:
  "[| M(A); M(z) |]  $\implies$   $\text{is\_Collect}(M,A,P,z) \longleftrightarrow z = \text{Collect}(A,P)$ "
  <proof>
```

2.5.4 The Operator *is_Replace*

```
lemma is_Replace_cong [cong]:
  "[| A=A';
    !!x y. [| M(x); M(y) |]  $\implies$   $P(x,y) \longleftrightarrow P'(x,y)$ ;
    z=z' |]
   $\implies$   $\text{is\_Replace}(M, A, \%x y. P(x,y), z) \longleftrightarrow$ 
   $\text{is\_Replace}(M, A', \%x y. P'(x,y), z')$ "
  <proof>
```

```
lemma (in M_trans) univalent_Replace_iff:
  "[| M(A); univalent(M,A,P);
    !!x y. [| x $\in$ A; P(x,y) |]  $\implies$  M(y) |]
   $\implies$   $u \in \text{Replace}(A,P) \longleftrightarrow (\exists x. x \in A \ \& \ P(x,u))$ "
  <proof>
```

```
lemma (in M_trans) strong_replacement_closed [intro,simp]:
  "[| strong_replacement(M,P); M(A); univalent(M,A,P);
    !!x y. [| x $\in$ A; P(x,y) |]  $\implies$  M(y) |]  $\implies$  M(Replace(A,P))"
  <proof>
```

```
lemma (in M_trans) Replace_abs:
  "[| M(A); M(z); univalent(M,A,P);
    !!x y. [| x $\in$ A; P(x,y) |]  $\implies$  M(y) |]
   $\implies$   $\text{is\_Replace}(M,A,P,z) \longleftrightarrow z = \text{Replace}(A,P)$ "
  <proof>
```

```

lemma (in M_trans) RepFun_closed:
  "[| strong_replacement(M,  $\lambda x y. y = f(x)$ );  $M(A)$ ;  $\forall x \in A. M(f(x))$  |]
    ==>  $M(\text{RepFun}(A, f))$ "
  <proof>

```

```

lemma Replace_conj_eq: " $\{y . x \in A, x \in A \ \& \ y=f(x)\} = \{y . x \in A, y=f(x)\}$ "
  <proof>

```

Better than RepFun_closed when having the formula $x \in A$ makes relativization easier.

```

lemma (in M_trans) RepFun_closed2:
  "[| strong_replacement(M,  $\lambda x y. x \in A \ \& \ y = f(x)$ );  $M(A)$ ;  $\forall x \in A. M(f(x))$  |]
    ==>  $M(\text{RepFun}(A, \lambda x. f(x)))$ "
  <proof>

```

2.5.5 Absoluteness for Lambda

definition

```

is_lambda :: "[i=>o, i, [i,i]=>o, i] => o" where
  "is_lambda(M, A, is_b, z) ==
     $\forall p[M]. p \in z \longleftrightarrow$ 
     $(\exists u[M]. \exists v[M]. u \in A \ \& \ \text{pair}(M, u, v, p) \ \& \ \text{is}_b(u, v))$ "

```

```

lemma (in M_trivial) lam_closed:
  "[| strong_replacement(M,  $\lambda x y. y = \langle x, b(x) \rangle$ );  $M(A)$ ;  $\forall x \in A. M(b(x))$  |]
    ==>  $M(\lambda x \in A. b(x))$ "
  <proof>

```

Better than lam_closed: has the formula $x \in A$

```

lemma (in M_trivial) lam_closed2:
  "[| strong_replacement(M,  $\lambda x y. x \in A \ \& \ y = \langle x, b(x) \rangle$ );
     $M(A)$ ;  $\forall m[M]. m \in A \longrightarrow M(b(m))$  |] ==>  $M(\text{Lambda}(A, b))$ "
  <proof>

```

```

lemma (in M_trivial) lambda_abs2:
  "[| Relation1(M, A, is_b, b);  $M(A)$ ;  $\forall m[M]. m \in A \longrightarrow M(b(m))$ ;  $M(z)$  |]
    ==>  $\text{is\_lambda}(M, A, \text{is}_b, z) \longleftrightarrow z = \text{Lambda}(A, b)$ "
  <proof>

```

```

lemma is_lambda_cong [cong]:
  "[|  $A=A'$ ;  $z=z'$ ;
     $\forall x y. [| x \in A; M(x); M(y) |] ==> \text{is}_b(x, y) \longleftrightarrow \text{is}_{b'}(x, y)$  |]
    ==>  $\text{is\_lambda}(M, A, \lambda x y. \text{is}_b(x, y), z) \longleftrightarrow$ 
     $\text{is\_lambda}(M, A', \lambda x y. \text{is}_{b'}(x, y), z')$ "
  <proof>

```

```

lemma (in M_trans) image_abs [simp]:
  "[| M(r); M(A); M(z) |] ==> image(M,r,A,z) <=> z = r`A"
<proof>

```

2.5.6 Relativization of Powerset

What about Pow_abs ? Powerset is NOT absolute! This result is one direction of absoluteness.

```

lemma (in M_trans) powerset_Pow:
  "powerset(M, x, Pow(x))"
<proof>

```

But we can't prove that the powerset in M includes the real powerset.

```

lemma (in M_trans) powerset_imp_subset_Pow:
  "[| powerset(M,x,y); M(y) |] ==> y ⊆ Pow(x)"
<proof>

```

```

lemma (in M_trans) powerset_abs:
  assumes
    "M(y)"
  shows
    "powerset(M,x,y) <=> y = {a∈Pow(x) . M(a)}"
<proof>

```

2.5.7 Absoluteness for the Natural Numbers

```

lemma (in M_trivial) nat_into_M [intro]:
  "n ∈ nat ==> M(n)"
<proof>

```

```

lemma (in M_trans) nat_case_closed [intro,simp]:
  "[| M(k); M(a); ∀ m[M]. M(b(m)) |] ==> M(nat_case(a,b,k))"
<proof>

```

```

lemma (in M_trivial) quasinat_abs [simp]:
  "M(z) ==> is_quasinat(M,z) <=> quasinat(z)"
<proof>

```

```

lemma (in M_trivial) nat_case_abs [simp]:
  "[| relation1(M,is_b,b); M(k); M(z) |]
  ==> is_nat_case(M,a,is_b,k,z) <=> z = nat_case(a,b,k)"
<proof>

```

```

lemma is_nat_case_cong:
  "[| a = a'; k = k'; z = z'; M(z');
  !!x y. [| M(x); M(y) |] ==> is_b(x,y) <=> is_b'(x,y) |]

```

```

      ==> is_nat_case(M, a, is_b, k, z) <=> is_nat_case(M, a', is_b',
k', z')"
<proof>

```

2.6 Absoluteness for Ordinals

These results constitute Theorem IV 5.1 of Kunen (page 126).

```

lemma (in M_trans) lt_closed:
  "[| j<i; M(i) |] ==> M(j)"
<proof>

```

```

lemma (in M_trans) transitive_set_abs [simp]:
  "M(a) ==> transitive_set(M,a) <=> Transset(a)"
<proof>

```

```

lemma (in M_trans) ordinal_abs [simp]:
  "M(a) ==> ordinal(M,a) <=> Ord(a)"
<proof>

```

```

lemma (in M_trivial) limit_ordinal_abs [simp]:
  "M(a) ==> limit_ordinal(M,a) <=> Limit(a)"
<proof>

```

```

lemma (in M_trivial) successor_ordinal_abs [simp]:
  "M(a) ==> successor_ordinal(M,a) <=> Ord(a) & (∃ b[M]. a = succ(b))"
<proof>

```

```

lemma finite_Ord_is_nat:
  "[| Ord(a); ~ Limit(a); ∀ x∈a. ~ Limit(x) |] ==> a ∈ nat"
<proof>

```

```

lemma (in M_trivial) finite_ordinal_abs [simp]:
  "M(a) ==> finite_ordinal(M,a) <=> a ∈ nat"
<proof>

```

```

lemma Limit_non_Limit_implies_nat:
  "[| Limit(a); ∀ x∈a. ~ Limit(x) |] ==> a = nat"
<proof>

```

```

lemma (in M_trivial) omega_abs [simp]:
  "M(a) ==> omega(M,a) <=> a = nat"
<proof>

```

```

lemma (in M_trivial) number1_abs [simp]:
  "M(a) ==> number1(M,a) <=> a = 1"
<proof>

```

```

lemma (in M_trivial) number2_abs [simp]:
  "M(a) ==> number2(M,a) <=> a = succ(1)"

```

$\langle proof \rangle$

```
lemma (in M_trivial) number3_abs [simp]:
  "M(a) ==> number3(M,a)  $\longleftrightarrow$  a = succ(succ(1))"
 $\langle proof \rangle$ 
```

Kunen continued to 20...

2.7 Some instances of separation and strong replacement

```
locale M_basic = M_trivial +
assumes Inter_separation:
  "M(A) ==> separation(M,  $\lambda x. \forall y[M]. y \in A \longrightarrow x \in y$ )"
and Diff_separation:
  "M(B) ==> separation(M,  $\lambda x. x \notin B$ )"
and cartprod_separation:
  "[| M(A); M(B) |]
  ==> separation(M,  $\lambda z. \exists x[M]. x \in A \ \& \ (\exists y[M]. y \in B \ \& \ \text{pair}(M,x,y,z))$ )"
and image_separation:
  "[| M(A); M(r) |]
  ==> separation(M,  $\lambda y. \exists p[M]. p \in r \ \& \ (\exists x[M]. x \in A \ \& \ \text{pair}(M,x,y,p))$ )"
and converse_separation:
  "M(r) ==> separation(M,
     $\lambda z. \exists p[M]. p \in r \ \& \ (\exists x[M]. \exists y[M]. \text{pair}(M,x,y,p) \ \& \ \text{pair}(M,y,x,z))$ )"
and restrict_separation:
  "M(A) ==> separation(M,  $\lambda z. \exists x[M]. x \in A \ \& \ (\exists y[M]. \text{pair}(M,x,y,z))$ )"
and comp_separation:
  "[| M(r); M(s) |]
  ==> separation(M,  $\lambda xz. \exists x[M]. \exists y[M]. \exists z[M]. \exists xy[M]. \exists yz[M].$ 
     $\text{pair}(M,x,z,xz) \ \& \ \text{pair}(M,x,y,xy) \ \& \ \text{pair}(M,y,z,yz) \ \&$ 
     $xy \in s \ \& \ yz \in r$ )"
and pred_separation:
  "[| M(r); M(x) |] ==> separation(M,  $\lambda y. \exists p[M]. p \in r \ \& \ \text{pair}(M,y,x,p)$ )"
and Memrel_separation:
  "separation(M,  $\lambda z. \exists x[M]. \exists y[M]. \text{pair}(M,x,y,z) \ \& \ x \in y$ )"
and funspace_succ_replacement:
  "M(n) ==>
    strong_replacement(M,  $\lambda p z. \exists f[M]. \exists b[M]. \exists nb[M]. \exists cnbf[M].$ 
       $\text{pair}(M,f,b,p) \ \& \ \text{pair}(M,n,b,nb) \ \& \ \text{is\_cons}(M,nb,f,cnbf)$ 
    &
      upair(M,cnbf,cnbf,z))"
and is_recfun_separation:
  — for well-founded recursion: used to prove is_recfun_equal
  "[| M(r); M(f); M(g); M(a); M(b) |]
  ==> separation(M,
     $\lambda x. \exists xa[M]. \exists xb[M].$ 
       $\text{pair}(M,x,a,xa) \ \& \ xa \in r \ \& \ \text{pair}(M,x,b,xb) \ \& \ xb \in r \ \&$ 
       $(\exists fx[M]. \exists gx[M]. \text{fun\_apply}(M,f,x,fx) \ \& \ \text{fun\_apply}(M,g,x,gx))$ 
    &
```

```

                                fx ≠ gx))"
and power_ax:                  "power_ax(M)"

lemma (in M_trivial) cartprod_iff_lemma:
  "[| M(C);  ∀u[M]. u ∈ C ⟷ (∃x∈A. ∃y∈B. u = {{x}, {x,y}});
    powerset(M, A ∪ B, p1); powerset(M, p1, p2); M(p2) |]
  ==> C = {u ∈ p2 . ∃x∈A. ∃y∈B. u = {{x}, {x,y}}}"
⟨proof⟩

lemma (in M_basic) cartprod_iff:
  "[| M(A); M(B); M(C) |]
  ==> cartprod(M,A,B,C) ⟷
    (∃p1[M]. ∃p2[M]. powerset(M,A ∪ B,p1) & powerset(M,p1,p2) &
     C = {z ∈ p2. ∃x∈A. ∃y∈B. z = <x,y>})"
⟨proof⟩

lemma (in M_basic) cartprod_closed_lemma:
  "[| M(A); M(B) |] ==> ∃C[M]. cartprod(M,A,B,C)"
⟨proof⟩

All the lemmas above are necessary because Powerset is not absolute. I
should have used Replacement instead!

lemma (in M_basic) cartprod_closed [intro,simp]:
  "[| M(A); M(B) |] ==> M(A*B)"
⟨proof⟩

lemma (in M_basic) sum_closed [intro,simp]:
  "[| M(A); M(B) |] ==> M(A+B)"
⟨proof⟩

lemma (in M_basic) sum_abs [simp]:
  "[| M(A); M(B); M(Z) |] ==> is_sum(M,A,B,Z) ⟷ (Z = A+B)"
⟨proof⟩

lemma (in M_trivial) Inl_in_M_iff [iff]:
  "M(Inl(a)) ⟷ M(a)"
⟨proof⟩

lemma (in M_trivial) Inl_abs [simp]:
  "M(Z) ==> is_Inl(M,a,Z) ⟷ (Z = Inl(a))"
⟨proof⟩

lemma (in M_trivial) Inr_in_M_iff [iff]:
  "M(Inr(a)) ⟷ M(a)"
⟨proof⟩

lemma (in M_trivial) Inr_abs [simp]:
  "M(Z) ==> is_Inr(M,a,Z) ⟷ (Z = Inr(a))"
⟨proof⟩

```

2.7.1 converse of a relation

```
lemma (in M_basic) M_converse_iff:
  "M(r) ==>
    converse(r) =
    {z ∈ ⋃ (⋃ (r)) * ⋃ (⋃ (r)).
      ∃ p ∈ r. ∃ x[M]. ∃ y[M]. p = ⟨x,y⟩ & z = ⟨y,x⟩}"
⟨proof⟩
```

```
lemma (in M_basic) converse_closed [intro,simp]:
  "M(r) ==> M(converse(r))"
⟨proof⟩
```

```
lemma (in M_basic) converse_abs [simp]:
  "[| M(r); M(z) |] ==> is_converse(M,r,z) ⟷ z = converse(r)"
⟨proof⟩
```

2.7.2 image, preimage, domain, range

```
lemma (in M_basic) image_closed [intro,simp]:
  "[| M(A); M(r) |] ==> M(r-‘A)"
⟨proof⟩
```

```
lemma (in M_basic) vimage_abs [simp]:
  "[| M(r); M(A); M(z) |] ==> pre_image(M,r,A,z) ⟷ z = r-‘A"
⟨proof⟩
```

```
lemma (in M_basic) vimage_closed [intro,simp]:
  "[| M(A); M(r) |] ==> M(r-‘A)"
⟨proof⟩
```

2.7.3 Domain, range and field

```
lemma (in M_trans) domain_abs [simp]:
  "[| M(r); M(z) |] ==> is_domain(M,r,z) ⟷ z = domain(r)"
⟨proof⟩
```

```
lemma (in M_basic) domain_closed [intro,simp]:
  "M(r) ==> M(domain(r))"
⟨proof⟩
```

```
lemma (in M_trans) range_abs [simp]:
  "[| M(r); M(z) |] ==> is_range(M,r,z) ⟷ z = range(r)"
⟨proof⟩
```

```
lemma (in M_basic) range_closed [intro,simp]:
  "M(r) ==> M(range(r))"
⟨proof⟩
```

```
lemma (in M_basic) field_abs [simp]:
```

"[| M(r); M(z) |] ==> is_field(M,r,z) $\longleftrightarrow$ z = field(r)"
 <proof>

lemma (in M_basic) field_closed [intro,simp]:
 "M(r) ==> M(field(r))"
 <proof>

2.7.4 Relations, functions and application

lemma (in M_trans) relation_abs [simp]:
 "M(r) ==> is_relation(M,r) $\longleftrightarrow$ relation(r)"
 <proof>

lemma (in M_trivial) function_abs [simp]:
 "M(r) ==> is_function(M,r) $\longleftrightarrow$ function(r)"
 <proof>

lemma (in M_basic) apply_closed [intro,simp]:
 "[| M(f); M(a) |] ==> M(f'a)"
 <proof>

lemma (in M_basic) apply_abs [simp]:
 "[| M(f); M(x); M(y) |] ==> fun_apply(M,f,x,y) $\longleftrightarrow$ f'x = y"
 <proof>

lemma (in M_trivial) typed_function_abs [simp]:
 "[| M(A); M(f) |] ==> typed_function(M,A,B,f) $\longleftrightarrow$ f $\in$ A $\rightarrow$ B"
 <proof>

lemma (in M_basic) injection_abs [simp]:
 "[| M(A); M(f) |] ==> injection(M,A,B,f) $\longleftrightarrow$ f $\in$ inj(A,B)"
 <proof>

lemma (in M_basic) surjection_abs [simp]:
 "[| M(A); M(B); M(f) |] ==> surjection(M,A,B,f) $\longleftrightarrow$ f $\in$ surj(A,B)"
 <proof>

lemma (in M_basic) bijection_abs [simp]:
 "[| M(A); M(B); M(f) |] ==> bijection(M,A,B,f) $\longleftrightarrow$ f $\in$ bij(A,B)"
 <proof>

2.7.5 Composition of relations

lemma (in M_basic) M_comp_iff:
 "[| M(r); M(s) |]
 ==> r O s =
 {xz $\in$ domain(s) * range(r).
 $\exists x[M]. \exists y[M]. \exists z[M]. xz = \langle x,z \rangle$ & $\langle x,y \rangle \in s$ & $\langle y,z \rangle \in r$ }"
 <proof>

```

lemma (in M_basic) comp_closed [intro,simp]:
  "[| M(r); M(s) |] ==> M(r 0 s)"
<proof>

lemma (in M_basic) composition_abs [simp]:
  "[| M(r); M(s); M(t) |] ==> composition(M,r,s,t) <=> t = r 0 s"
<proof>

no longer needed

lemma (in M_basic) restriction_is_function:
  "[| restriction(M,f,A,z); function(f); M(f); M(A); M(z) |]
  ==> function(z)"
<proof>

lemma (in M_trans) restriction_abs [simp]:
  "[| M(f); M(A); M(z) |]
  ==> restriction(M,f,A,z) <=> z = restrict(f,A)"
<proof>

lemma (in M_trans) M_restrict_iff:
  "M(r) ==> restrict(r,A) = {z ∈ r . ∃x∈A. ∃y[M]. z = ⟨x, y⟩}"
<proof>

lemma (in M_basic) restrict_closed [intro,simp]:
  "[| M(A); M(r) |] ==> M(restrict(r,A))"
<proof>

lemma (in M_trans) Inter_abs [simp]:
  "[| M(A); M(z) |] ==> big_inter(M,A,z) <=> z = ⋂ (A)"
<proof>

lemma (in M_basic) Inter_closed [intro,simp]:
  "M(A) ==> M(⋂ (A))"
<proof>

lemma (in M_basic) Int_closed [intro,simp]:
  "[| M(A); M(B) |] ==> M(A ∩ B)"
<proof>

lemma (in M_basic) Diff_closed [intro,simp]:
  "[| M(A); M(B) |] ==> M(A-B)"
<proof>

```

2.7.6 Some Facts About Separation Axioms

```

lemma (in M_basic) separation_conj:
  "[| separation(M,P); separation(M,Q) |] ==> separation(M, λz. P(z)
  & Q(z))"

```

$\langle proof \rangle$

lemma *Collect_Un_Collect_eq*:

"Collect(A,P) $\cup$ Collect(A,Q) = Collect(A, $\%x. P(x) \mid Q(x)$)"

$\langle proof \rangle$

lemma *Diff_Collect_eq*:

"A - Collect(A,P) = Collect(A, $\%x. \sim P(x)$)"

$\langle proof \rangle$

lemma (in *M_trans*) *Collect_rall_eq*:

"M(Y) $\implies$ Collect(A, $\%x. \forall y[M]. y \in Y \longrightarrow P(x,y)$) =
(if Y=0 then A else ($\bigcap_{y \in Y. \{x \in A. P(x,y)\}}$))"

$\langle proof \rangle$

lemma (in *M_basic*) *separation_disj*:

"[|separation(M,P); separation(M,Q)|] $\implies$ separation(M, $\lambda z. P(z) \mid Q(z)$)"

$\langle proof \rangle$

lemma (in *M_basic*) *separation_neg*:

"separation(M,P) $\implies$ separation(M, $\lambda z. \sim P(z)$)"

$\langle proof \rangle$

lemma (in *M_basic*) *separation_imp*:

"[|separation(M,P); separation(M,Q)|]
 $\implies$ separation(M, $\lambda z. P(z) \longrightarrow Q(z)$)"

$\langle proof \rangle$

This result is a hint of how little can be done without the Reflection Theorem. The quantifier has to be bounded by a set. We also need another instance of Separation!

lemma (in *M_basic*) *separation_rall*:

"[|M(Y); $\forall y[M].$ separation(M, $\lambda x. P(x,y)$);
 $\forall z[M].$ strong_replacement(M, $\lambda x y. y = \{u \in z . P(u,x)\}$)|]
 $\implies$ separation(M, $\lambda x. \forall y[M]. y \in Y \longrightarrow P(x,y)$)"

$\langle proof \rangle$

2.7.7 Functions and function space

The assumption $M(A \rightarrow B)$ is unusual, but essential: in all but trivial cases, $A \rightarrow B$ cannot be expected to belong to M .

lemma (in *M_trivial*) *is_funspace_abs* [simp]:

"[|M(A); M(B); M(F); M(A $\rightarrow$ B)|] $\implies$ is_funspace(M,A,B,F) $\longleftrightarrow$ F = A $\rightarrow$ B"

$\langle proof \rangle$

```

lemma (in M_basic) succ_fun_eq2:
  "[|M(B); M(n->B)|] ==>
    succ(n) -> B =
    ⋃ {z. p ∈ (n->B)*B, ∃ f[M]. ∃ b[M]. p = <f,b> & z = {cons(<n,b>,
f)}}}"
<proof>

```

```

lemma (in M_basic) funspace_succ:
  "[|M(n); M(B); M(n->B)|] ==> M(succ(n) -> B)"
<proof>

```

M contains all finite function spaces. Needed to prove the absoluteness of transitive closure. See the definition of `rtranc1_alt` in `WF_absolute.thy`.

```

lemma (in M_basic) finite_funspace_closed [intro,simp]:
  "[|n∈nat; M(B)|] ==> M(n->B)"
<proof>

```

2.8 Relativization and Absoluteness for Boolean Operators

definition

```

is_bool_of_o :: "[i=>o, o, i] => o" where
  "is_bool_of_o(M,P,z) == (P & number1(M,z)) | (~P & empty(M,z))"

```

definition

```

is_not :: "[i=>o, i, i] => o" where
  "is_not(M,a,z) == (number1(M,a) & empty(M,z)) |
    (~number1(M,a) & number1(M,z))"

```

definition

```

is_and :: "[i=>o, i, i, i] => o" where
  "is_and(M,a,b,z) == (number1(M,a) & z=b) |
    (~number1(M,a) & empty(M,z))"

```

definition

```

is_or :: "[i=>o, i, i, i] => o" where
  "is_or(M,a,b,z) == (number1(M,a) & number1(M,z)) |
    (~number1(M,a) & z=b)"

```

```

lemma (in M_trivial) bool_of_o_abs [simp]:
  "M(z) ==> is_bool_of_o(M,P,z) ⟷ z = bool_of_o(P)"
<proof>

```

```

lemma (in M_trivial) not_abs [simp]:
  "[| M(a); M(z)|] ==> is_not(M,a,z) ⟷ z = not(a)"
<proof>

```

```

lemma (in M_trivial) and_abs [simp]:
  "[| M(a); M(b); M(z)|] ==> is_and(M,a,b,z) ⟷ z = a and b"

```

<proof>

lemma (in *M_trivial*) *or_abs [simp]*:
" [| *M(a)*; *M(b)*; *M(z)* |] ==> *is_or(M,a,b,z)* $\longleftrightarrow$ *z = a or b* "
<proof>

lemma (in *M_trivial*) *bool_of_o_closed [intro,simp]*:
"*M(bool_of_o(P))*"
<proof>

lemma (in *M_trivial*) *and_closed [intro,simp]*:
" [| *M(p)*; *M(q)* |] ==> *M(p and q)* "
<proof>

lemma (in *M_trivial*) *or_closed [intro,simp]*:
" [| *M(p)*; *M(q)* |] ==> *M(p or q)* "
<proof>

lemma (in *M_trivial*) *not_closed [intro,simp]*:
"*M(p)* ==> *M(not(p))* "
<proof>

2.9 Relativization and Absoluteness for List Operators

definition

is_Nil :: "[*i*=>*o*, *i*] => *o*" where
— because *[]* $\equiv$ *Inl(0)*
"*is_Nil(M,xs)* == $\exists$ *zero[M]*. *empty(M,zero)* & *is_Inl(M,zero,xs)* "

definition

is_Cons :: "[*i*=>*o*,*i*,*i*,*i*] => *o*" where
— because *Cons(a, l)* $\equiv$ *Inr(<a, l>)*
"*is_Cons(M,a,l,Z)* == $\exists$ *p[M]*. *pair(M,a,l,p)* & *is_Inr(M,p,Z)* "

lemma (in *M_trivial*) *Nil_in_M [intro,simp]*: "*M(Nil)*"
<proof>

lemma (in *M_trivial*) *Nil_abs [simp]*: "*M(Z)* ==> *is_Nil(M,Z)* $\longleftrightarrow$ (*Z = Nil*) "
<proof>

lemma (in *M_trivial*) *Cons_in_M_iff [iff]*: "*M(Cons(a,l))* $\longleftrightarrow$ *M(a)* & *M(l)* "
<proof>

lemma (in *M_trivial*) *Cons_abs [simp]*:
" [| *M(a)*; *M(l)*; *M(Z)* |] ==> *is_Cons(M,a,l,Z)* $\longleftrightarrow$ (*Z = Cons(a,l)*) "
<proof>

definition

```

quaselist :: "i => o" where
  "quaselist(xs) == xs=Nil | ( $\exists x\ l. xs = Cons(x,l)$ )"

```

definition

```

is_quaselist :: "[i=>o, i] => o" where
  "is_quaselist(M,z) == is_Nil(M,z) | ( $\exists x[M]. \exists l[M]. is\_Cons(M,x,l,z)$ )"

```

definition

```

list_case' :: "[i, [i,i]=>i, i] => i" where
  — A version of list_case that's always defined.
  "list_case'(a,b,xs) ==
    if quaselist(xs) then list_case(a,b,xs) else 0"

```

definition

```

is_list_case :: "[i=>o, i, [i,i,i]=>o, i, i] => o" where
  — Returns 0 for non-lists
  "is_list_case(M, a, is_b, xs, z) ==
    (is_Nil(M,xs)  $\longrightarrow$  z=a) &
    ( $\forall x[M]. \forall l[M]. is\_Cons(M,x,l,xs) \longrightarrow is\_b(x,l,z)$ ) &
    (is_quaselist(M,xs) | empty(M,z))"

```

definition

```

hd' :: "i => i" where
  — A version of hd that's always defined.
  "hd'(xs) == if quaselist(xs) then hd(xs) else 0"

```

definition

```

tl' :: "i => i" where
  — A version of tl that's always defined.
  "tl'(xs) == if quaselist(xs) then tl(xs) else 0"

```

definition

```

is_hd :: "[i=>o, i, i] => o" where
  — hd([]) = 0 no constraints if not a list. Avoiding implication prevents the
  simplifier's looping.
  "is_hd(M,xs,H) ==
    (is_Nil(M,xs)  $\longrightarrow$  empty(M,H)) &
    ( $\forall x[M]. \forall l[M]. \sim is\_Cons(M,x,l,xs) \mid H=x$ ) &
    (is_quaselist(M,xs) | empty(M,H))"

```

definition

```

is_tl :: "[i=>o, i, i] => o" where
  — tl([]) = []; see comments about is_hd
  "is_tl(M,xs,T) ==
    (is_Nil(M,xs)  $\longrightarrow$  T=xs) &
    ( $\forall x[M]. \forall l[M]. \sim is\_Cons(M,x,l,xs) \mid T=l$ ) &

```

(is_quaselist(M,xs) | empty(M,T))"

2.9.1 quaselist: For Case-Splitting with list_case'

lemma [iff]: "quaselist(Nil)"
 <proof>

lemma [iff]: "quaselist(Cons(x,l))"
 <proof>

lemma list_imp_quaselist: "l ∈ list(A) ==> quaselist(l)"
 <proof>

2.9.2 list_case', the Modified Version of list_case

lemma list_case'_Nil [simp]: "list_case'(a,b,Nil) = a"
 <proof>

lemma list_case'_Cons [simp]: "list_case'(a,b,Cons(x,l)) = b(x,l)"
 <proof>

lemma non_list_case: "~ quaselist(x) ==> list_case'(a,b,x) = 0"
 <proof>

lemma list_case'_eq_list_case [simp]:
 "xs ∈ list(A) ==> list_case'(a,b,xs) = list_case(a,b,xs)"
 <proof>

lemma (in M_basic) list_case'_closed [intro,simp]:
 "[| M(k); M(a); ∀ x[M]. ∀ y[M]. M(b(x,y)) |] ==> M(list_case'(a,b,k))"
 <proof>

lemma (in M_trivial) quaselist_abs [simp]:
 "M(z) ==> is_quaselist(M,z) ⟷ quaselist(z)"
 <proof>

lemma (in M_trivial) list_case_abs [simp]:
 "[| relation2(M,is_b,b); M(k); M(z) |]
 ==> is_list_case(M,a,is_b,k,z) ⟷ z = list_case'(a,b,k)"
 <proof>

2.9.3 The Modified Operators hd' and tl'

lemma (in M_trivial) is_hd_Nil: "is_hd(M,[],Z) ⟷ empty(M,Z)"
 <proof>

lemma (in M_trivial) is_hd_Cons:
 "[| M(a); M(l) |] ==> is_hd(M,Cons(a,l),Z) ⟷ Z = a"
 <proof>

```

lemma (in M_trivial) hd_abs [simp]:
  "[|M(x); M(y)|] ==> is_hd(M,x,y) <=> y = hd'(x)"
<proof>

lemma (in M_trivial) is_tl_Nil: "is_tl(M, [], Z) <=> Z = []"
<proof>

lemma (in M_trivial) is_tl_Cons:
  "[|M(a); M(l)|] ==> is_tl(M, Cons(a, l), Z) <=> Z = l"
<proof>

lemma (in M_trivial) tl_abs [simp]:
  "[|M(x); M(y)|] ==> is_tl(M, x, y) <=> y = tl'(x)"
<proof>

lemma (in M_trivial) relation1_tl: "relation1(M, is_tl(M), tl')"
<proof>

lemma hd'_Nil: "hd'([]) = 0"
<proof>

lemma hd'_Cons: "hd'(Cons(a, l)) = a"
<proof>

lemma tl'_Nil: "tl'([]) = []"
<proof>

lemma tl'_Cons: "tl'(Cons(a, l)) = l"
<proof>

lemma iterates_tl_Nil: "n ∈ nat ==> tl'^n ([]) = []"
<proof>

lemma (in M_basic) tl'_closed: "M(x) ==> M(tl'(x))"
<proof>

end

```

3 Relativized Wellorderings

theory *Wellorderings* **imports** *Relative* **begin**

We define functions analogous to *ordermap ordertype* but without using recursion. Instead, there is a direct appeal to Replacement. This will be the basis for a version relativized to some class *M*. The main result is Theorem I 7.6 in Kunen, page 17.

3.1 Wellorderings

definition

$irreflexive :: "[i=>o,i,i]=>o"$ where
 $irreflexive(M,A,r) == \forall x[M]. x \in A \longrightarrow \langle x,x \rangle \notin r$

definition

$transitive_rel :: "[i=>o,i,i]=>o"$ where
 $transitive_rel(M,A,r) ==$
 $\forall x[M]. x \in A \longrightarrow (\forall y[M]. y \in A \longrightarrow (\forall z[M]. z \in A \longrightarrow$
 $\langle x,y \rangle \in r \longrightarrow \langle y,z \rangle \in r \longrightarrow \langle x,z \rangle \in r))$

definition

$linear_rel :: "[i=>o,i,i]=>o"$ where
 $linear_rel(M,A,r) ==$
 $\forall x[M]. x \in A \longrightarrow (\forall y[M]. y \in A \longrightarrow \langle x,y \rangle \in r \mid x=y \mid \langle y,x \rangle \in r)$

definition

$wellfounded :: "[i=>o,i,i]=>o"$ where
 — EVERY non-empty set has an r -minimal element
 $wellfounded(M,r) ==$
 $\forall x[M]. x \neq 0 \longrightarrow (\exists y[M]. y \in x \ \& \ \sim(\exists z[M]. z \in x \ \& \ \langle z,y \rangle \in r))$

definition

$wellfounded_on :: "[i=>o,i,i]=>o"$ where
 — every non-empty SUBSET OF A has an r -minimal element
 $wellfounded_on(M,A,r) ==$
 $\forall x[M]. x \neq 0 \longrightarrow x \subseteq A \longrightarrow (\exists y[M]. y \in x \ \& \ \sim(\exists z[M]. z \in x \ \& \ \langle z,y \rangle \in r))$

definition

$wellordered :: "[i=>o,i,i]=>o"$ where
 — linear and wellfounded on A
 $wellordered(M,A,r) ==$
 $transitive_rel(M,A,r) \ \& \ linear_rel(M,A,r) \ \& \ wellfounded_on(M,A,r)$

3.1.1 Trivial absoluteness proofs

lemma (in M_basic) $irreflexive_abs [simp]:$
 $M(A) ==> irreflexive(M,A,r) \longleftrightarrow irrefl(A,r)$
 $\langle proof \rangle$

lemma (in M_basic) $transitive_rel_abs [simp]:$
 $M(A) ==> transitive_rel(M,A,r) \longleftrightarrow trans[A](r)$
 $\langle proof \rangle$

lemma (in M_basic) $linear_rel_abs [simp]:$
 $M(A) ==> linear_rel(M,A,r) \longleftrightarrow linear(A,r)$
 $\langle proof \rangle$

lemma (in M_basic) $wellordered_is_trans_on:$

"[| wellordered(M,A,r); M(A) |] ==> trans[A](r)"
 <proof>

lemma (in M_basic) wellordered_is_linear:
 "[| wellordered(M,A,r); M(A) |] ==> linear(A,r)"
 <proof>

lemma (in M_basic) wellordered_is_wellfounded_on:
 "[| wellordered(M,A,r); M(A) |] ==> wellfounded_on(M,A,r)"
 <proof>

lemma (in M_basic) wellfounded_imp_wellfounded_on:
 "[| wellfounded(M,r); M(A) |] ==> wellfounded_on(M,A,r)"
 <proof>

lemma (in M_basic) wellfounded_on_subset_A:
 "[| wellfounded_on(M,A,r); B<=A |] ==> wellfounded_on(M,B,r)"
 <proof>

3.1.2 Well-founded relations

lemma (in M_basic) wellfounded_on_iff_wellfounded:
 "wellfounded_on(M,A,r) $\longleftrightarrow$ wellfounded(M, r $\cap$ A*A)"
 <proof>

lemma (in M_basic) wellfounded_on_imp_wellfounded:
 "[| wellfounded_on(M,A,r); r $\subseteq$ A*A |] ==> wellfounded(M,r)"
 <proof>

lemma (in M_basic) wellfounded_on_field_imp_wellfounded:
 "wellfounded_on(M, field(r), r) ==> wellfounded(M,r)"
 <proof>

lemma (in M_basic) wellfounded_iff_wellfounded_on_field:
 "M(r) ==> wellfounded(M,r) $\longleftrightarrow$ wellfounded_on(M, field(r), r)"
 <proof>

lemma (in M_basic) wellfounded_induct:
 "[| wellfounded(M,r); M(a); M(r); separation(M, $\lambda x. \sim P(x)$);
 $\forall x. M(x) \ \& \ (\forall y. \langle y,x \rangle \in r \longrightarrow P(y)) \longrightarrow P(x)$ |]
 ==> P(a)"
 <proof>

lemma (in M_basic) wellfounded_on_induct:
 "[| a $\in$ A; wellfounded_on(M,A,r); M(A);
 separation(M, $\lambda x. x \in A \longrightarrow \sim P(x)$);
 $\forall x \in A. M(x) \ \& \ (\forall y \in A. \langle y,x \rangle \in r \longrightarrow P(y)) \longrightarrow P(x)$ |]
 ==> P(a)"

<proof>

3.1.3 Kunen's lemma IV 3.14, page 123

```
lemma (in M_basic) linear_imp_relativized:
  "linear(A,r) ==> linear_rel(M,A,r)"
<proof>
```

```
lemma (in M_basic) trans_on_imp_relativized:
  "trans[A](r) ==> transitive_rel(M,A,r)"
<proof>
```

```
lemma (in M_basic) wf_on_imp_relativized:
  "wf[A](r) ==> wellfounded_on(M,A,r)"
<proof>
```

```
lemma (in M_basic) wf_imp_relativized:
  "wf(r) ==> wellfounded(M,r)"
<proof>
```

```
lemma (in M_basic) well_ord_imp_relativized:
  "well_ord(A,r) ==> wellordered(M,A,r)"
<proof>
```

The property being well founded (and hence of being well ordered) is not absolute: the set that doesn't contain a minimal element may not exist in the class M . However, every set that is well founded in a transitive model M is well founded (page 124).

3.2 Relativized versions of order-isomorphisms and order types

```
lemma (in M_basic) order_isomorphism_abs [simp]:
  "[| M(A); M(B); M(f) |]
  ==> order_isomorphism(M,A,r,B,s,f) <=> f ∈ ord_iso(A,r,B,s)"
<proof>
```

```
lemma (in M_trans) pred_set_abs [simp]:
  "[| M(r); M(B) |] ==> pred_set(M,A,x,r,B) <=> B = Order.pred(A,x,r)"
<proof>
```

```
lemma (in M_basic) pred_closed [intro,simp]:
  "[| M(A); M(r); M(x) |] ==> M(Order.pred(A, x, r))"
<proof>
```

```
lemma (in M_basic) membership_abs [simp]:
  "[| M(r); M(A) |] ==> membership(M,A,r) <=> r = Memrel(A)"
<proof>
```

```

lemma (in M_basic) M_Memrel_iff:
  "M(A)  $\implies$  Memrel(A) = {z  $\in$  A*A.  $\exists$  x[M].  $\exists$  y[M]. z = <x,y> & x  $\in$  y}"
<proof>

```

```

lemma (in M_basic) Memrel_closed [intro,simp]:
  "M(A)  $\implies$  M(Memrel(A))"
<proof>

```

3.3 Main results of Kunen, Chapter 1 section 6

Subset properties– proved outside the locale

```

lemma linear_rel_subset:
  "[linear_rel(M, A, r); B  $\subseteq$  A]  $\implies$  linear_rel(M, B, r)"
<proof>

```

```

lemma transitive_rel_subset:
  "[transitive_rel(M, A, r); B  $\subseteq$  A]  $\implies$  transitive_rel(M, B, r)"
<proof>

```

```

lemma wellfounded_on_subset:
  "[wellfounded_on(M, A, r); B  $\subseteq$  A]  $\implies$  wellfounded_on(M, B, r)"
<proof>

```

```

lemma wellordered_subset:
  "[wellordered(M, A, r); B  $\subseteq$  A]  $\implies$  wellordered(M, B, r)"
<proof>

```

```

lemma (in M_basic) wellfounded_on_asym:
  "[| wellfounded_on(M,A,r); <a,x> $\in$ r; a $\in$ A; x $\in$ A; M(A) |]  $\implies$  <x,a> $\notin$ r"
<proof>

```

```

lemma (in M_basic) wellordered_asym:
  "[| wellordered(M,A,r); <a,x> $\in$ r; a $\in$ A; x $\in$ A; M(A) |]  $\implies$  <x,a> $\notin$ r"
<proof>

```

end

4 Relativized Well-Founded Recursion

theory WFreq imports Wellorderings begin

4.1 General Lemmas

```

lemma apply_recfun2:
  "[| is_recfun(r,a,H,f); <x,i>:f |]  $\implies$  i = H(x, restrict(f,r-“{x}”))"
<proof>

```

Expresses *is_recfun* as a recursion equation

```

lemma is_recfun_iff_equation:
  "is_recfun(r,a,H,f)  $\longleftrightarrow$ 
    f  $\in$  r -'' {a}  $\rightarrow$  range(f) &
    ( $\forall$ x  $\in$  r-'' {a}. f'x = H(x, restrict(f, r-'' {x})))"
  <proof>

lemma is_recfun_imp_in_r: "[| is_recfun(r,a,H,f); <x,i>  $\in$  f |] ==> <x,
a>  $\in$  r"
  <proof>

lemma trans_Int_eq:
  "[| trans(r); <y,x>  $\in$  r |] ==> r -'' {x}  $\cap$  r -'' {y} = r -'' {y}"
  <proof>

lemma is_recfun_restrict_idem:
  "is_recfun(r,a,H,f) ==> restrict(f, r -'' {a}) = f"
  <proof>

lemma is_recfun_cong_lemma:
  "[| is_recfun(r,a,H,f); r = r'; a = a'; f = f';
    !!x g. [| <x,a'>  $\in$  r'; relation(g); domain(g)  $\subseteq$  r' -'' {x} |]
    ==> H(x,g) = H'(x,g) |]
    ==> is_recfun(r',a',H',f')"
  <proof>

```

For `is_recfun` we need only pay attention to functions whose domains are initial segments of `r`.

```

lemma is_recfun_cong:
  "[| r = r'; a = a'; f = f';
    !!x g. [| <x,a'>  $\in$  r'; relation(g); domain(g)  $\subseteq$  r' -'' {x} |]
    ==> H(x,g) = H'(x,g) |]
    ==> is_recfun(r,a,H,f)  $\longleftrightarrow$  is_recfun(r',a',H',f')"
  <proof>

```

4.2 Reworking of the Recursion Theory Within M

```

lemma (in M_basic) is_recfun_separation':
  "[| f  $\in$  r -'' {a}  $\rightarrow$  range(f); g  $\in$  r -'' {b}  $\rightarrow$  range(g);
    M(r); M(f); M(g); M(a); M(b) |]
    ==> separation(M,  $\lambda$ x.  $\neg$  (<x, a>  $\in$  r  $\longrightarrow$  <x, b>  $\in$  r  $\longrightarrow$  f'x = g'x))"
  <proof>

```

Stated using `trans(r)` rather than `transitive_rel(M, A, r)` because the latter rewrites to the former anyway, by `transitive_rel_abs`. As always, theorems should be expressed in simplified form. The last three M -premises are redundant because of `M(r)`, but without them we'd have to undertake more work to set up the induction formula.

```

lemma (in M_basic) is_recfun_equal [rule_format]:

```

```

    "[| is_recfun(r,a,H,f); is_recfun(r,b,H,g);
      wellfounded(M,r); trans(r);
      M(f); M(g); M(r); M(x); M(a); M(b) |]
    ==> <x,a> ∈ r ⟶ <x,b> ∈ r ⟶ f'x=g'x"
  <proof>

```

```

lemma (in M_basic) is_recfun_cut:
  "[| is_recfun(r,a,H,f); is_recfun(r,b,H,g);
    wellfounded(M,r); trans(r);
    M(f); M(g); M(r); <b,a> ∈ r |]
  ==> restrict(f, r-''{b}) = g"
  <proof>

```

```

lemma (in M_basic) is_recfun_functional:
  "[| is_recfun(r,a,H,f); is_recfun(r,a,H,g);
    wellfounded(M,r); trans(r); M(f); M(g); M(r) |] ==> f=g"
  <proof>

```

Tells us that `is_recfun` can (in principle) be relativized.

```

lemma (in M_basic) is_recfun_relativize:
  "[| M(r); M(f); ∀ x[M]. ∀ g[M]. function(g) ⟶ M(H(x,g)) |]
  ==> is_recfun(r,a,H,f) ⟷
    (∀ z[M]. z ∈ f ⟷
      (∃ x[M]. <x,a> ∈ r & z = <x, H(x, restrict(f, r-''{x}))>))"
  <proof>

```

```

lemma (in M_basic) is_recfun_restrict:
  "[| wellfounded(M,r); trans(r); is_recfun(r,x,H,f); <y,x> ∈ r;
    M(r); M(f);
    ∀ x[M]. ∀ g[M]. function(g) ⟶ M(H(x,g)) |]
  ==> is_recfun(r, y, H, restrict(f, r-''{y}))"
  <proof>

```

```

lemma (in M_basic) restrict_Y_lemma:
  "[| wellfounded(M,r); trans(r); M(r);
    ∀ x[M]. ∀ g[M]. function(g) ⟶ M(H(x,g)); M(Y);
    ∀ b[M].
      b ∈ Y ⟷
        (∃ x[M]. <x,a1> ∈ r &
          (∃ y[M]. b = <x,y> & (∃ g[M]. is_recfun(r,x,H,g) ∧ y = H(x,g)))));
    <x,a1> ∈ r; is_recfun(r,x,H,f); M(f) |]
  ==> restrict(Y, r-''{x}) = f"
  <proof>

```

For typical applications of Replacement for recursive definitions

```

lemma (in M_basic) univalent_is_recfun:
  "[| wellfounded(M,r); trans(r); M(r) |]
  ==> univalent (M, A, λx p.
    ∃ y[M]. p = <x,y> & (∃ f[M]. is_recfun(r,x,H,f) & y = H(x,f)))"

```

<proof>

Proof of the inductive step for *exists_is_recfun*, since we must prove two versions.

lemma (in *M_basic*) *exists_is_recfun_indstep*:
 "[$\forall y. \langle y, a1 \rangle \in r \longrightarrow (\exists f[M]. \text{is_recfun}(r, y, H, f));$
 $\text{wellfounded}(M, r); \text{trans}(r); M(r); M(a1);$
 $\text{strong_replacement}(M, \lambda x z.$
 $\quad \exists y[M]. \exists g[M]. \text{pair}(M, x, y, z) \ \& \ \text{is_recfun}(r, x, H, g) \ \& \ y =$
 $H(x, g));$
 $\quad \forall x[M]. \forall g[M]. \text{function}(g) \longrightarrow M(H(x, g)) \mid]$
 $\implies \exists f[M]. \text{is_recfun}(r, a1, H, f)"]$
<proof>

Relativized version, when we have the (currently weaker) premise *wellfounded*(*M*, *r*)

lemma (in *M_basic*) *wellfounded_exists_is_recfun*:
 "[$\text{wellfounded}(M, r); \text{trans}(r);$
 $\text{separation}(M, \lambda x. \sim (\exists f[M]. \text{is_recfun}(r, x, H, f)));$
 $\text{strong_replacement}(M, \lambda x z.$
 $\quad \exists y[M]. \exists g[M]. \text{pair}(M, x, y, z) \ \& \ \text{is_recfun}(r, x, H, g) \ \& \ y = H(x, g));$
 $M(r); M(a);$
 $\quad \forall x[M]. \forall g[M]. \text{function}(g) \longrightarrow M(H(x, g)) \mid]$
 $\implies \exists f[M]. \text{is_recfun}(r, a, H, f)"]$
<proof>

lemma (in *M_basic*) *wf_exists_is_recfun [rule_format]*:
 "[$\text{wf}(r); \text{trans}(r); M(r);$
 $\text{strong_replacement}(M, \lambda x z.$
 $\quad \exists y[M]. \exists g[M]. \text{pair}(M, x, y, z) \ \& \ \text{is_recfun}(r, x, H, g) \ \& \ y = H(x, g));$
 $\quad \forall x[M]. \forall g[M]. \text{function}(g) \longrightarrow M(H(x, g)) \mid]$
 $\implies M(a) \longrightarrow (\exists f[M]. \text{is_recfun}(r, a, H, f))"]$
<proof>

4.3 Relativization of the ZF Predicate *is_recfun*

definition

M_is_recfun :: "[$i \Rightarrow o, [i, i, i] \Rightarrow o, i, i, i] \Rightarrow o$ " where
 $M_is_recfun(M, MH, r, a, f) ==$
 $\forall z[M]. z \in f \longleftrightarrow$
 $(\exists x[M]. \exists y[M]. \exists xa[M]. \exists sx[M]. \exists r_sx[M]. \exists f_r_sx[M].$
 $\text{pair}(M, x, y, z) \ \& \ \text{pair}(M, x, a, xa) \ \& \ \text{upair}(M, x, x, sx) \ \&$
 $\text{pre_image}(M, r, sx, r_sx) \ \& \ \text{restriction}(M, f, r_sx, f_r_sx) \ \&$
 $xa \in r \ \& \ MH(x, f_r_sx, y))"$

definition

is_wfrec :: "[$i \Rightarrow o, [i, i, i] \Rightarrow o, i, i, i] \Rightarrow o$ " where

```
"is_wfrec(M,MH,r,a,z) ==
  ∃ f[M]. M_is_recfun(M,MH,r,a,f) & MH(a,f,z)"
```

definition

```
wfrec_replacement :: "[i=>o, [i,i,i]=>o, i] => o" where
  "wfrec_replacement(M,MH,r) ==
    strong_replacement(M,
      λx z. ∃ y[M]. pair(M,x,y,z) & is_wfrec(M,MH,r,x,y))"
```

lemma (in M_basic) is_recfun_abs:

```
"[| ∃ x[M]. ∃ g[M]. function(g) ⟶ M(H(x,g)); M(r); M(a); M(f);
    relation2(M,MH,H) |]
  ==> M_is_recfun(M,MH,r,a,f) ⟷ is_recfun(r,a,H,f)"
⟨proof⟩
```

lemma M_is_recfun_cong [cong]:

```
"[| r = r'; a = a'; f = f';
  !!x g y. [| M(x); M(g); M(y) |] ==> MH(x,g,y) ⟷ MH'(x,g,y) |]
  ==> M_is_recfun(M,MH,r,a,f) ⟷ M_is_recfun(M,MH',r',a',f')"
⟨proof⟩
```

lemma (in M_basic) is_wfrec_abs:

```
"[| ∃ x[M]. ∃ g[M]. function(g) ⟶ M(H(x,g));
    relation2(M,MH,H); M(r); M(a); M(z) |]
  ==> is_wfrec(M,MH,r,a,z) ⟷
    (∃ g[M]. is_recfun(r,a,H,g) & z = H(a,g))"
⟨proof⟩
```

Relating wfrec_replacement to native constructs

lemma (in M_basic) wfrec_replacement':

```
"[| wfrec_replacement(M,MH,r);
  ∃ x[M]. ∃ g[M]. function(g) ⟶ M(H(x,g));
  relation2(M,MH,H); M(r) |]
  ==> strong_replacement(M, λx z. ∃ y[M].
    pair(M,x,y,z) & (∃ g[M]. is_recfun(r,x,H,g) & y = H(x,g)))"
⟨proof⟩
```

lemma wfrec_replacement_cong [cong]:

```
"[| !!x y z. [| M(x); M(y); M(z) |] ==> MH(x,y,z) ⟷ MH'(x,y,z);
  r=r' |]
  ==> wfrec_replacement(M, %x y. MH(x,y), r) ⟷
    wfrec_replacement(M, %x y. MH'(x,y), r')"
⟨proof⟩
```

end

5 Absoluteness of Well-Founded Recursion

theory *WF_absolute* imports *WFrec* begin

5.1 Transitive closure without fixedpoints

definition

```
rtrancl_alt :: "[i,i]=>i" where
  "rtrancl_alt(A,r) ==
    {p ∈ A*A. ∃n∈nat. ∃f ∈ succ(n) -> A.
      (∃x y. p = <x,y> & f'0 = x & f'n = y) &
      (∀i∈n. <f'i, f'succ(i)> ∈ r)}"
```

lemma *alt_rtrancl_lemma1* [rule_format]:

```
"n ∈ nat
==> ∀f ∈ succ(n) -> field(r).
  (∀i∈n. <f'i, f' succ(i)> ∈ r) → <f'0, f'n> ∈ r^*"
⟨proof⟩
```

lemma *rtrancl_alt_subset_rtrancl*: "rtrancl_alt(field(r),r) ⊆ r^*"

⟨proof⟩

lemma *rtrancl_subset_rtrancl_alt*: "r^* ⊆ rtrancl_alt(field(r),r)"

⟨proof⟩

lemma *rtrancl_alt_eq_rtrancl*: "rtrancl_alt(field(r),r) = r^*"

⟨proof⟩

definition

```
rtran_closure_mem :: "[i=>o,i,i,i] => o" where
  — The property of belonging to rtran_closure(r)
  "rtran_closure_mem(M,A,r,p) ==
    ∃nnat[M]. ∃n[M]. ∃n'[M].
      omega(M,nnat) & n∈nnat & successor(M,n,n') &
      (∃f[M]. typed_function(M,n',A,f) &
      (∃x[M]. ∃y[M]. ∃zero[M]. pair(M,x,y,p) & empty(M,zero)
&
      fun_apply(M,f,zero,x) & fun_apply(M,f,n,y)) &
      (∀j[M]. j∈n →
      (∃fj[M]. ∃sj[M]. ∃fsj[M]. ∃ffp[M].
      fun_apply(M,f,j,fj) & successor(M,j,sj) &
      fun_apply(M,f,sj,fsj) & pair(M,fj,fsj,ffp) & ffp
∈ r))))"
```

definition

```
rtran_closure :: "[i=>o,i,i] => o" where
  "rtran_closure(M,r,s) ==
    ∀A[M]. is_field(M,r,A) →
    (∀p[M]. p ∈ s ↔ rtran_closure_mem(M,A,r,p))"
```

definition

```

tran_closure :: "[i=>o,i,i] => o" where
  "tran_closure(M,r,t) ==
     $\exists s[M]. \text{rtran\_closure}(M,r,s) \ \& \ \text{composition}(M,r,s,t)"$ 

```

locale $M_tranc1 = M_basic +$

assumes $\text{rtranc1_separation}$:

$"[| M(r); M(A) |] ==> \text{separation}(M, \text{rtran_closure_mem}(M,A,r))"$

and $\text{wellfounded_tranc1_separation}$:

$"[| M(r); M(Z) |] ==>$

$\text{separation}(M, \lambda x.$

$\exists w[M]. \exists wx[M]. \exists rp[M].$

$w \in Z \ \& \ \text{pair}(M,w,x,wx) \ \& \ \text{tran_closure}(M,r,rp) \ \& \ wx \in rp)"$

and $M_nat \text{ [iff] } : "M(\text{nat})"$

lemma (in M_tranc1) $\text{rtran_closure_mem_iff}$:

$"[| M(A); M(r); M(p) |]$

$==> \text{rtran_closure_mem}(M,A,r,p) \longleftrightarrow$

$(\exists n[M]. n \in \text{nat} \ \&$

$(\exists f[M]. f \in \text{succ}(n) \rightarrow A \ \&$

$(\exists x[M]. \exists y[M]. p = \langle x,y \rangle \ \& \ f'0 = x \ \& \ f'n = y) \ \&$

$(\forall i \in n. \langle f'i, f'\text{succ}(i) \rangle \in r))"$

$\langle \text{proof} \rangle$

lemma (in M_tranc1) $\text{rtran_closure_rtranc1}$:

$"M(r) ==> \text{rtran_closure}(M,r,\text{rtranc1}(r))"$

$\langle \text{proof} \rangle$

lemma (in M_tranc1) rtranc1_closed [intro,simp]:

$"M(r) ==> M(\text{rtranc1}(r))"$

$\langle \text{proof} \rangle$

lemma (in M_tranc1) rtranc1_abs [simp]:

$"[| M(r); M(z) |] ==> \text{rtran_closure}(M,r,z) \longleftrightarrow z = \text{rtranc1}(r)"$

$\langle \text{proof} \rangle$

lemma (in M_tranc1) tranc1_closed [intro,simp]:

$"M(r) ==> M(\text{tranc1}(r))"$

$\langle \text{proof} \rangle$

lemma (in M_tranc1) tranc1_abs [simp]:

$"[| M(r); M(z) |] ==> \text{tran_closure}(M,r,z) \longleftrightarrow z = \text{tranc1}(r)"$

$\langle \text{proof} \rangle$

lemma (in M_tranc1) $\text{wellfounded_tranc1_separation'}$:

$"[| M(r); M(Z) |] ==> \text{separation}(M, \lambda x. \exists w[M]. w \in Z \ \& \ \langle w,x \rangle \in$

$r^+)"$

$\langle \text{proof} \rangle$

Alternative proof of `wf_on_trancl`; inspiration for the relativized version.
Original version is on theory `WF`.

```
lemma "[| wf[A](r); r-''A ⊆ A |] ==> wf[A](r^+)"
<proof>
```

```
lemma (in M_trancl) wellfounded_on_trancl:
  "[| wellfounded_on(M,A,r); r-''A ⊆ A; M(r); M(A) |]
    ==> wellfounded_on(M,A,r^+)"
<proof>
```

```
lemma (in M_trancl) wellfounded_trancl:
  "[| wellfounded(M,r); M(r) |] ==> wellfounded(M,r^+)"
<proof>
```

Absoluteness for wfrec-defined functions.

```
lemma (in M_trancl) wfrec_relativize:
  "[| wf(r); M(a); M(r);
    strong_replacement(M, λx z. ∃ y[M]. ∃ g[M].
      pair(M,x,y,z) &
      is_recfun(r^+, x, λx f. H(x, restrict(f, r -'' {x})), g) &
      y = H(x, restrict(g, r -'' {x}))) |]
    ∀ x[M]. ∀ g[M]. function(g) ⟶ M(H(x,g)) |]
    ==> wfrec(r,a,H) = z ⟷
      (∃ f[M]. is_recfun(r^+, a, λx f. H(x, restrict(f, r -'' {x})), f)
    &
      z = H(a, restrict(f, r -'' {a})))"
<proof>
```

Assuming `r` is transitive simplifies the occurrences of `H`. The premise `relation(r)` is necessary before we can replace `r^+` by `r`.

```
theorem (in M_trancl) trans_wfrec_relativize:
  "[| wf(r); trans(r); relation(r); M(r); M(a);
    wfrec_replacement(M,MH,r); relation2(M,MH,H);
    ∀ x[M]. ∀ g[M]. function(g) ⟶ M(H(x,g)) |]
    ==> wfrec(r,a,H) = z ⟷ (∃ f[M]. is_recfun(r,a,H,f) & z = H(a,f))"
<proof>
```

```
theorem (in M_trancl) trans_wfrec_abs:
  "[| wf(r); trans(r); relation(r); M(r); M(a); M(z);
    wfrec_replacement(M,MH,r); relation2(M,MH,H);
    ∀ x[M]. ∀ g[M]. function(g) ⟶ M(H(x,g)) |]
    ==> is_wfrec(M,MH,r,a,z) ⟷ z=wfrec(r,a,H)"
<proof>
```

```
lemma (in M_trancl) trans_eq_pair_wfrec_iff:
  "[| wf(r); trans(r); relation(r); M(r); M(y);
```

```

wfrec_replacement(M,MH,r); relation2(M,MH,H);
∀ x[M]. ∀ g[M]. function(g) → M(H(x,g)) |]
==> y = <x, wfrec(r, x, H)> ↔
(∃ f[M]. is_recfun(r,x,H,f) & y = <x, H(x,f)>)
<proof>

```

5.2 M is closed under well-founded recursion

Lemma with the awkward premise mentioning *wfrec*.

```

lemma (in M_trancl) wfrec_closed_lemma [rule_format]:
  "[|wf(r); M(r);
    strong_replacement(M, λx y. y = <x, wfrec(r, x, H)>);
    ∀ x[M]. ∀ g[M]. function(g) → M(H(x,g)) |]
  ==> M(a) → M(wfrec(r,a,H))"
<proof>

```

Eliminates one instance of replacement.

```

lemma (in M_trancl) wfrec_replacement_iff:
  "strong_replacement(M, λx z.
    ∃ y[M]. pair(M,x,y,z) & (∃ g[M]. is_recfun(r,x,H,g) & y = H(x,g)))
  ↔
  strong_replacement(M,
    λx y. ∃ f[M]. is_recfun(r,x,H,f) & y = <x, H(x,f)>)"
<proof>

```

Useful version for transitive relations

```

theorem (in M_trancl) trans_wfrec_closed:
  "[|wf(r); trans(r); relation(r); M(r); M(a);
    wfrec_replacement(M,MH,r); relation2(M,MH,H);
    ∀ x[M]. ∀ g[M]. function(g) → M(H(x,g)) |]
  ==> M(wfrec(r,a,H))"
<proof>

```

5.3 Absoluteness without assuming transitivity

```

lemma (in M_trancl) eq_pair_wfrec_iff:
  "[|wf(r); M(r); M(y);
    strong_replacement(M, λx z. ∃ y[M]. ∃ g[M].
      pair(M,x,y,z) &
      is_recfun(r^+, x, λx f. H(x, restrict(f, r - '{x})), g) &
      y = H(x, restrict(g, r - '{x})));
    ∀ x[M]. ∀ g[M]. function(g) → M(H(x,g)) |]
  ==> y = <x, wfrec(r, x, H)> ↔
    (∃ f[M]. is_recfun(r^+, x, λx f. H(x, restrict(f, r - '{x})), f)
  &
    y = <x, H(x, restrict(f, r - '{x})))>)"
<proof>

```

Full version not assuming transitivity, but maybe not very useful.

```

theorem (in M_trancl) wfrec_closed:
  "[|wf(r); M(r); M(a);
    wfrec_replacement(M,MH,r^+);
    relation2(M,MH, λx f. H(x, restrict(f, r -'' {x})));
    ∀x[M]. ∀g[M]. function(g) → M(H(x,g)) |]
  ==> M(wfrec(r,a,H))"
⟨proof⟩

end

```

6 Absoluteness Properties for Recursive Datatypes

```

theory Datatype_absolute imports Formula WF_absolute begin

```

6.1 The lfp of a continuous function can be expressed as a union

definition

```

directed :: "i=>o" where
  "directed(A) == A≠0 & (∀x∈A. ∀y∈A. x ∪ y ∈ A)"

```

definition

```

contin :: "(i=>i) => o" where
  "contin(h) == (∀A. directed(A) → h(⋃A) = (⋃X∈A. h(X)))"

```

```

lemma bnd_mono_iterates_subset: "[|bnd_mono(D, h); n ∈ nat|] ==> h^n
(0) ⊆ D"
⟨proof⟩

```

```

lemma bnd_mono_increasing [rule_format]:
  "[|i ∈ nat; j ∈ nat; bnd_mono(D,h)|] ==> i ≤ j → h^i(0) ⊆ h^j(0)"
⟨proof⟩

```

```

lemma directed_iterates: "bnd_mono(D,h) ==> directed({h^n (0). n∈nat})"
⟨proof⟩

```

```

lemma contin_iterates_eq:
  "[|bnd_mono(D, h); contin(h)|]
  ==> h(⋃n∈nat. h^n (0)) = (⋃n∈nat. h^n (0))"
⟨proof⟩

```

```

lemma lfp_subset_Union:
  "[|bnd_mono(D, h); contin(h)|] ==> lfp(D,h) ⊆ (⋃n∈nat. h^n(0))"
⟨proof⟩

```

```

lemma Union_subset_lfp:
  "bnd_mono(D,h) ==> (⋃n∈nat. h^n(0)) ⊆ lfp(D,h)"
⟨proof⟩

```

lemma *lfp_eq_Union*:
 "[|bnd_mono(D, h); contin(h)|] ==> lfp(D,h) = ($\bigcup_{n \in \text{nat.}} h^n(0)$)"
 <proof>

6.1.1 Some Standard Datatype Constructions Preserve Continuity

lemma *contin_imp_mono*: "[|X ⊆ Y; contin(F)|] ==> F(X) ⊆ F(Y)"
 <proof>

lemma *sum_contin*: "[|contin(F); contin(G)|] ==> contin(λX. F(X) + G(X))"
 <proof>

lemma *prod_contin*: "[|contin(F); contin(G)|] ==> contin(λX. F(X) * G(X))"
 <proof>

lemma *const_contin*: "contin(λX. A)"
 <proof>

lemma *id_contin*: "contin(λX. X)"
 <proof>

6.2 Absoluteness for "Iterates"

definition

iterates_MH :: "[i=>o, [i,i]=>o, i, i, i, i] => o" where
 "iterates_MH(M, isF, v, n, g, z) ==
 is_nat_case(M, v, λm u. ∃ gm [M]. fun_apply(M, g, m, gm) & isF(gm, u),
 n, z)"

definition

is_iterates :: "[i=>o, [i,i]=>o, i, i, i] => o" where
 "is_iterates(M, isF, v, n, Z) ==
 ∃ sn [M]. ∃ msn [M]. successor(M, n, sn) & membership(M, sn, msn) &
 is_wfrec(M, iterates_MH(M, isF, v), msn, n, Z)"

definition

iterates_replacement :: "[i=>o, [i,i]=>o, i] => o" where
 "iterates_replacement(M, isF, v) ==
 ∀ n [M]. n ∈ nat →
 wfrec_replacement(M, iterates_MH(M, isF, v), Memrel(succ(n)))"

lemma (in *M_basic*) *iterates_MH_abs*:
 "[| relation1(M, isF, F); M(n); M(g); M(z) |]
 ==> iterates_MH(M, isF, v, n, g, z) ↔ z = nat_case(v, λm. F(g'm), n)"
 <proof>

lemma (in *M_trancl*) *iterates_imp_wfrec_replacement*:

```

"[/relation1(M,isF,F); n ∈ nat; iterates_replacement(M,isF,v) |]
==> wfrec_replacement(M, λn f z. z = nat_case(v, λm. F(f'm), n),
                        Memrel(succ(n)))"
<proof>

```

```

theorem (in M_trancl) iterates_abs:
  "[/ iterates_replacement(M,isF,v); relation1(M,isF,F);
   n ∈ nat; M(v); M(z); ∀x[M]. M(F(x)) |]
  ==> is_iterates(M,isF,v,n,z) <=> z = iterates(F,n,v)"
<proof>

```

```

lemma (in M_trancl) iterates_closed [intro,simp]:
  "[/ iterates_replacement(M,isF,v); relation1(M,isF,F);
   n ∈ nat; M(v); ∀x[M]. M(F(x)) |]
  ==> M(iterates(F,n,v))"
<proof>

```

6.3 lists without univ

```

lemmas datatype_univs = Inl_in_univ Inr_in_univ
                        Pair_in_univ nat_into_univ A_into_univ

```

```

lemma list_fun_bnd_mono: "bnd_mono(univ(A), λX. {0} + A*X)"
<proof>

```

```

lemma list_fun_contin: "contin(λX. {0} + A*X)"
<proof>

```

Re-expresses lists using sum and product

```

lemma list_eq_lfp2: "list(A) = lfp(univ(A), λX. {0} + A*X)"
<proof>

```

Re-expresses lists using "iterates", no univ.

```

lemma list_eq_Union:
  "list(A) = (⋃n∈nat. (λX. {0} + A*X) ^ n (0))"
<proof>

```

definition

```

is_list_functor :: "[i=>o,i,i,i] => o" where
  "is_list_functor(M,A,X,Z) ==
   ∃n1[M]. ∃AX[M].
     number1(M,n1) & cartprod(M,A,X,AX) & is_sum(M,n1,AX,Z)"

```

```

lemma (in M_basic) list_functor_abs [simp]:
  "[/ M(A); M(X); M(Z) |] ==> is_list_functor(M,A,X,Z) <=> (Z = {0}
+ A*X)"
<proof>

```

6.4 formulas without univ

lemma *formula_fun_bnd_mono*:
 "bnd_mono(univ(0), $\lambda X. ((\text{nat} * \text{nat}) + (\text{nat} * \text{nat})) + (X * X + X)$)"
 $\langle \text{proof} \rangle$

lemma *formula_fun_contin*:
 "contin($\lambda X. ((\text{nat} * \text{nat}) + (\text{nat} * \text{nat})) + (X * X + X)$)"
 $\langle \text{proof} \rangle$

Re-expresses formulas using sum and product

lemma *formula_eq_lfp2*:
 "formula = lfp(univ(0), $\lambda X. ((\text{nat} * \text{nat}) + (\text{nat} * \text{nat})) + (X * X + X)$)"
 $\langle \text{proof} \rangle$

Re-expresses formulas using "iterates", no univ.

lemma *formula_eq_Union*:
 "formula =
 $(\bigcup_{n \in \text{nat}. } (\lambda X. ((\text{nat} * \text{nat}) + (\text{nat} * \text{nat})) + (X * X + X)) \wedge n (0))$ "
 $\langle \text{proof} \rangle$

definition

is_formula_functor :: "[$i \Rightarrow o, i, i$] $\Rightarrow o$ " where
 "is_formula_functor(M, X, Z) ==
 $\exists \text{nat}'[M]. \exists \text{natnat}[M]. \exists \text{natnatsum}[M]. \exists XX[M]. \exists X3[M].$
 $\text{omega}(M, \text{nat}')$ & $\text{cartprod}(M, \text{nat}', \text{nat}', \text{natnat})$ &
 $\text{is_sum}(M, \text{natnat}, \text{natnat}, \text{natnatsum})$ &
 $\text{cartprod}(M, X, X, XX)$ & $\text{is_sum}(M, XX, X, X3)$ &
 $\text{is_sum}(M, \text{natnatsum}, X3, Z)$ "

lemma (in *M_trancl*) *formula_functor_abs* [simp]:
 "[$| M(X); M(Z) |$]
 $\Rightarrow \text{is_formula_functor}(M, X, Z) \longleftrightarrow$
 $Z = ((\text{nat} * \text{nat}) + (\text{nat} * \text{nat})) + (X * X + X)$ "
 $\langle \text{proof} \rangle$

6.5 M Contains the List and Formula Datatypes

definition

list_N :: "[i, i] $\Rightarrow i$ " where
 "list_N(A, n) == ($\lambda X. \{0\} + A * X$) $^n (0)$ "

lemma *Nil_in_list_N* [simp]: " $[] \in \text{list_N}(A, \text{succ}(n))$ "
 $\langle \text{proof} \rangle$

lemma *Cons_in_list_N* [simp]:
 " $\text{Cons}(a, l) \in \text{list_N}(A, \text{succ}(n)) \longleftrightarrow a \in A \ \& \ l \in \text{list_N}(A, n)$ "
 $\langle \text{proof} \rangle$

These two aren't simprules because they reveal the underlying list representation.

```
lemma list_N_0: "list_N(A,0) = 0"
<proof>
```

```
lemma list_N_succ: "list_N(A,succ(n)) = {0} + A * (list_N(A,n))"
<proof>
```

```
lemma list_N_imp_list:
  "[| l ∈ list_N(A,n); n ∈ nat |] ==> l ∈ list(A)"
<proof>
```

```
lemma list_N_imp_length_lt [rule_format]:
  "n ∈ nat ==> ∀ l ∈ list_N(A,n). length(l) < n"
<proof>
```

```
lemma list_imp_list_N [rule_format]:
  "l ∈ list(A) ==> ∀ n ∈ nat. length(l) < n → l ∈ list_N(A, n)"
<proof>
```

```
lemma list_N_imp_eq_length:
  "[| n ∈ nat; l ∉ list_N(A, n); l ∈ list_N(A, succ(n)) |]
  ==> n = length(l)"
<proof>
```

Express `list_rec` without using `rank` or `Vset`, neither of which is absolute.

```
lemma (in M_trivial) list_rec_eq:
  "l ∈ list(A) ==>
    list_rec(a,g,l) =
      transrec (succ(length(l)),
        λx h. Lambda (list(A),
          list_case' (a,
            λa l. g(a, l, h ' succ(length(l)) ' l)))) '
  l"
<proof>
```

definition

```
is_list_N :: "[i=>o,i,i,i] => o" where
  "is_list_N(M,A,n,Z) ==
    ∃ zero[M]. empty(M,zero) &
      is_iterates(M, is_list_functor(M,A), zero, n, Z)"
```

definition

```
mem_list :: "[i=>o,i,i] => o" where
  "mem_list(M,A,l) ==
    ∃ n[M]. ∃ listn[M].
      finite_ordinal(M,n) & is_list_N(M,A,n,listn) & l ∈ listn"
```

definition

```

is_list :: "[i=>o,i,i] => o" where
  "is_list(M,A,Z) ==  $\forall l[M]. l \in Z \longleftrightarrow \text{mem\_list}(M,A,l)$ "

```

6.5.1 Towards Absoluteness of *formula_rec*

```

consts  depth :: "i=>i"
primrec
  "depth(Member(x,y)) = 0"
  "depth(Equal(x,y))  = 0"
  "depth(Nand(p,q)) = succ(depth(p)  $\cup$  depth(q))"
  "depth(Forall(p)) = succ(depth(p))"

```

```

lemma depth_type [TC]: "p  $\in$  formula ==> depth(p)  $\in$  nat"
<proof>

```

definition

```

formula_N :: "i => i" where
  "formula_N(n) == ( $\lambda X. ((\text{nat} * \text{nat}) + (\text{nat} * \text{nat})) + (X * X + X)$ )  $^n$  (0)"

```

```

lemma Member_in_formula_N [simp]:
  "Member(x,y)  $\in$  formula_N(succ(n))  $\longleftrightarrow$  x  $\in$  nat & y  $\in$  nat"
<proof>

```

```

lemma Equal_in_formula_N [simp]:
  "Equal(x,y)  $\in$  formula_N(succ(n))  $\longleftrightarrow$  x  $\in$  nat & y  $\in$  nat"
<proof>

```

```

lemma Nand_in_formula_N [simp]:
  "Nand(x,y)  $\in$  formula_N(succ(n))  $\longleftrightarrow$  x  $\in$  formula_N(n) & y  $\in$  formula_N(n)"
<proof>

```

```

lemma Forall_in_formula_N [simp]:
  "Forall(x)  $\in$  formula_N(succ(n))  $\longleftrightarrow$  x  $\in$  formula_N(n)"
<proof>

```

These two aren't simprules because they reveal the underlying formula representation.

```

lemma formula_N_0: "formula_N(0) = 0"
<proof>

```

```

lemma formula_N_succ:
  "formula_N(succ(n)) =
    ((nat*nat) + (nat*nat)) + (formula_N(n) * formula_N(n) + formula_N(n))"
<proof>

```

```

lemma formula_N_imp_formula:
  "[| p  $\in$  formula_N(n); n  $\in$  nat |] ==> p  $\in$  formula"
<proof>

```

```

lemma formula_N_imp_depth_lt [rule_format]:
  "n ∈ nat ==> ∀ p ∈ formula_N(n). depth(p) < n"
⟨proof⟩

lemma formula_imp_formula_N [rule_format]:
  "p ∈ formula ==> ∀ n ∈ nat. depth(p) < n → p ∈ formula_N(n)"
⟨proof⟩

lemma formula_N_imp_eq_depth:
  "[| n ∈ nat; p ∉ formula_N(n); p ∈ formula_N(succ(n)) |]
  ==> n = depth(p)"
⟨proof⟩

```

This result and the next are unused.

```

lemma formula_N_mono [rule_format]:
  "[| m ∈ nat; n ∈ nat |] ==> m ≤ n → formula_N(m) ⊆ formula_N(n)"
⟨proof⟩

lemma formula_N_distrib:
  "[| m ∈ nat; n ∈ nat |] ==> formula_N(m ∪ n) = formula_N(m) ∪ formula_N(n)"
⟨proof⟩

```

definition

```

is_formula_N :: "[i=>o,i,i] => o" where
  "is_formula_N(M,n,Z) ==
    ∃ zero[M]. empty(M,zero) &
      is_iterates(M, is_formula_functor(M), zero, n, Z)"

```

definition

```

mem_formula :: "[i=>o,i] => o" where
  "mem_formula(M,p) ==
    ∃ n[M]. ∃ formn[M].
      finite_ordinal(M,n) & is_formula_N(M,n,formn) & p ∈ formn"

```

definition

```

is_formula :: "[i=>o,i] => o" where
  "is_formula(M,Z) == ∀ p[M]. p ∈ Z ↔ mem_formula(M,p)"

```

```

locale M_datatypes = M_tranc1 +
assumes list_replacement1:
  "M(A) ==> iterates_replacement(M, is_list_functor(M,A), 0)"
and list_replacement2:
  "M(A) ==> strong_replacement(M,
    λn y. n ∈ nat & is_iterates(M, is_list_functor(M,A), 0, n, y))"
and formula_replacement1:
  "iterates_replacement(M, is_formula_functor(M), 0)"
and formula_replacement2:

```

```

"strong_replacement(M,
  λn y. n∈nat & is_iterates(M, is_formula_functor(M), 0, n, y))"
and nth_replacement:
"M(1) ==> iterates_replacement(M, %1 t. is_tl(M,1,t), 1)"

```

6.5.2 Absoluteness of the List Construction

```

lemma (in M_datatypes) list_replacement2':
  "M(A) ==> strong_replacement(M, λn y. n∈nat & y = (λX. {0} + A * X)^n
  (0))"
<proof>

```

```

lemma (in M_datatypes) list_closed [intro,simp]:
  "M(A) ==> M(list(A))"
<proof>

```

WARNING: use only with `dest:` or with variables fixed!

```

lemmas (in M_datatypes) list_into_M = transM [OF _ list_closed]

```

```

lemma (in M_datatypes) list_N_abs [simp]:
  "[|M(A); n∈nat; M(Z)|]
  ==> is_list_N(M,A,n,Z) ⟷ Z = list_N(A,n)"
<proof>

```

```

lemma (in M_datatypes) list_N_closed [intro,simp]:
  "[|M(A); n∈nat|] ==> M(list_N(A,n))"
<proof>

```

```

lemma (in M_datatypes) mem_list_abs [simp]:
  "M(A) ==> mem_list(M,A,1) ⟷ 1 ∈ list(A)"
<proof>

```

```

lemma (in M_datatypes) list_abs [simp]:
  "[|M(A); M(Z)|] ==> is_list(M,A,Z) ⟷ Z = list(A)"
<proof>

```

6.5.3 Absoluteness of Formulas

```

lemma (in M_datatypes) formula_replacement2':
  "strong_replacement(M, λn y. n∈nat & y = (λX. ((nat*nat) + (nat*nat))
  + (X*X + X))^n (0))"
<proof>

```

```

lemma (in M_datatypes) formula_closed [intro,simp]:
  "M(formula)"
<proof>

```

```

lemmas (in M_datatypes) formula_into_M = transM [OF _ formula_closed]

```

```

lemma (in M_datatypes) formula_N_abs [simp]:

```

```

      "[|n∈nat; M(Z)|]
      ==> is_formula_N(M,n,Z) <=> Z = formula_N(n)"
⟨proof⟩

lemma (in M_datatypes) formula_N_closed [intro,simp]:
  "n∈nat ==> M(formula_N(n))"
⟨proof⟩

lemma (in M_datatypes) mem_formula_abs [simp]:
  "mem_formula(M,l) <=> l ∈ formula"
⟨proof⟩

lemma (in M_datatypes) formula_abs [simp]:
  "[|M(Z)|] ==> is_formula(M,Z) <=> Z = formula"
⟨proof⟩

```

6.6 Absoluteness for ε -Closure: the *eclose* Operator

Re-expresses *eclose* using "iterates"

```

lemma eclose_eq_Union:
  "eclose(A) = (⋃ n∈nat. Union^n (A))"
⟨proof⟩

```

definition

```

is_eclose_n :: "[i=>o,i,i,i] => o" where
  "is_eclose_n(M,A,n,Z) == is_iterates(M, big_union(M), A, n, Z)"

```

definition

```

mem_eclose :: "[i=>o,i,i] => o" where
  "mem_eclose(M,A,l) ==
    ∃ n[M]. ∃ eclosen[M].
      finite_ordinal(M,n) & is_eclose_n(M,A,n,eclosen) & l ∈ eclosen"

```

definition

```

is_eclose :: "[i=>o,i,i] => o" where
  "is_eclose(M,A,Z) == ∀ u[M]. u ∈ Z <=> mem_eclose(M,A,u)"

```

locale *M_eclose* = *M_datatypes* +

assumes *eclose_replacement1*:

```

  "M(A) ==> iterates_replacement(M, big_union(M), A)"

```

and *eclose_replacement2*:

```

  "M(A) ==> strong_replacement(M,
    λn y. n∈nat & is_iterates(M, big_union(M), A, n, y))"

```

lemma (in *M_eclose*) *eclose_replacement2'*:

```

  "M(A) ==> strong_replacement(M, λn y. n∈nat & y = Union^n (A))"

```

⟨proof⟩

```

lemma (in M_eclose) eclose_closed [intro,simp]:
  "M(A) ==> M(eclose(A))"
<proof>

lemma (in M_eclose) is_eclose_n_abs [simp]:
  "[|M(A); n∈nat; M(Z)|] ==> is_eclose_n(M,A,n,Z) <=> Z = Union^n
(A)"
<proof>

lemma (in M_eclose) mem_eclose_abs [simp]:
  "M(A) ==> mem_eclose(M,A,l) <=> l ∈ eclose(A)"
<proof>

lemma (in M_eclose) eclose_abs [simp]:
  "[|M(A); M(Z)|] ==> is_eclose(M,A,Z) <=> Z = eclose(A)"
<proof>

```

6.7 Absoluteness for transrec

$\text{transrec}(a, H) \equiv \text{wfrec}(\text{Memrel}(\text{eclose}(\{a\})), a, H)$

definition

```

is_transrec :: "[i=>o, [i,i,i]=>o, i, i] => o" where
  "is_transrec(M,MH,a,z) ==
    ∃ sa[M]. ∃ esa[M]. ∃ mesa[M].
      upair(M,a,a,sa) & is_eclose(M,sa,esa) & membership(M,esa,mesa)
  &
    is_wfrec(M,MH,mesa,a,z)"

```

definition

```

transrec_replacement :: "[i=>o, [i,i,i]=>o, i] => o" where
  "transrec_replacement(M,MH,a) ==
    ∃ sa[M]. ∃ esa[M]. ∃ mesa[M].
      upair(M,a,a,sa) & is_eclose(M,sa,esa) & membership(M,esa,mesa)
  &
    wfrec_replacement(M,MH,mesa)"

```

The condition $\text{Ord}(i)$ lets us use the simpler trans_wfrec_abs rather than trans_wfrec_abs , which I haven't even proved yet.

theorem (in M_eclose) transrec_abs :

```

"[|transrec_replacement(M,MH,i); relation2(M,MH,H);
  Ord(i); M(i); M(z);
  ∀ x[M]. ∀ g[M]. function(g) ⟶ M(H(x,g))|]
==> is_transrec(M,MH,i,z) <=> z = transrec(i,H)"
<proof>

```

theorem (in M_eclose) transrec_closed :

```

"[|transrec_replacement(M,MH,i); relation2(M,MH,H);

```

```

      Ord(i); M(i);
       $\forall x[M]. \forall g[M]. \text{function}(g) \longrightarrow M(H(x,g)) \mid \mid$ 
       $\implies M(\text{transrec}(i,H))$ 
    <proof>

```

Helps to prove instances of `transrec_replacement`

```

lemma (in M_eclose) transrec_replacementI:
  "[|M(a);
    strong_replacement (M,
       $\lambda x z. \exists y[M]. \text{pair}(M, x, y, z) \ \&$ 
       $\text{is\_wfrec}(M, MH, \text{Memrel}(\text{eclose}(\{a\})), x, y) \mid \mid$ 
     $\implies \text{transrec\_replacement}(M, MH, a)$ 
  "
  <proof>

```

6.8 Absoluteness for the List Operator `length`

But it is never used.

definition

```

is_length :: "[i=>o,i,i,i] => o" where
  "is_length(M,A,l,n) ==
     $\exists sn[M]. \exists list\_n[M]. \exists list\_sn[M].$ 
     $\text{is\_list\_N}(M,A,n,list\_n) \ \& \ l \notin list\_n \ \&$ 
     $\text{successor}(M,n,sn) \ \& \ \text{is\_list\_N}(M,A,sn,list\_sn) \ \& \ l \in list\_sn$ "

```

```

lemma (in M_datatypes) length_abs [simp]:
  "[|M(A); l ∈ list(A); n ∈ nat|]  $\implies \text{is\_length}(M,A,l,n) \longleftrightarrow n = \text{length}(l)$ "
  <proof>

```

Proof is trivial since `length` returns natural numbers.

```

lemma (in M_trivial) length_closed [intro,simp]:
  " $l \in list(A) \implies M(\text{length}(l))$ "
  <proof>

```

6.9 Absoluteness for the List Operator `nth`

```

lemma nth_eq_hd_iterates_tl [rule_format]:
  " $xs \in list(A) \implies \forall n \in nat. \text{nth}(n,xs) = \text{hd}' \ (tl'{}^n \ (xs))$ "
  <proof>

```

```

lemma (in M_basic) iterates_tl'_closed:
  "[|n ∈ nat; M(x)|]  $\implies M(\text{tl}'{}^n \ (x))$ "
  <proof>

```

Immediate by type-checking

```

lemma (in M_datatypes) nth_closed [intro,simp]:
  "[|xs ∈ list(A); n ∈ nat; M(A)|]  $\implies M(\text{nth}(n,xs))$ "
  <proof>

```

definition

```
is_nth :: "[i=>o,i,i,i] => o" where
  "is_nth(M,n,l,Z) ==
     $\exists X[M]. \text{is\_iterates}(M, \text{is\_tl}(M), l, n, X) \ \& \ \text{is\_hd}(M,X,Z)"$ 
```

lemma (in M_datatypes) nth_abs [simp]:

```
"[|M(A); n ∈ nat; l ∈ list(A); M(Z)|]
==> is_nth(M,n,l,Z) ⟷ Z = nth(n,l)"
```

⟨proof⟩

6.10 Relativization and Absoluteness for the *formula* Constructors

definition

```
is_Member :: "[i=>o,i,i,i] => o" where
  — because Member(x, y) ≡ Inl(Inl(⟨x, y⟩))
  "is_Member(M,x,y,Z) ==
     $\exists p[M]. \exists u[M]. \text{pair}(M,x,y,p) \ \& \ \text{is\_Inl}(M,p,u) \ \& \ \text{is\_Inl}(M,u,Z)"$ 
```

lemma (in M_trivial) Member_abs [simp]:

```
"[|M(x); M(y); M(Z)|] ==> is_Member(M,x,y,Z) ⟷ (Z = Member(x,y))"
```

⟨proof⟩

lemma (in M_trivial) Member_in_M_iff [iff]:

```
"M(Member(x,y)) ⟷ M(x) & M(y)"
```

⟨proof⟩

definition

```
is_Equal :: "[i=>o,i,i,i] => o" where
  — because Equal(x, y) ≡ Inl(Inr(⟨x, y⟩))
  "is_Equal(M,x,y,Z) ==
     $\exists p[M]. \exists u[M]. \text{pair}(M,x,y,p) \ \& \ \text{is\_Inr}(M,p,u) \ \& \ \text{is\_Inl}(M,u,Z)"$ 
```

lemma (in M_trivial) Equal_abs [simp]:

```
"[|M(x); M(y); M(Z)|] ==> is_Equal(M,x,y,Z) ⟷ (Z = Equal(x,y))"
```

⟨proof⟩

lemma (in M_trivial) Equal_in_M_iff [iff]: "M(Equal(x,y)) ⟷ M(x) & M(y)"

⟨proof⟩

definition

```
is_Nand :: "[i=>o,i,i,i] => o" where
  — because Nand(x, y) ≡ Inr(Inl(⟨x, y⟩))
  "is_Nand(M,x,y,Z) ==
     $\exists p[M]. \exists u[M]. \text{pair}(M,x,y,p) \ \& \ \text{is\_Inl}(M,p,u) \ \& \ \text{is\_Inr}(M,u,Z)"$ 
```

lemma (in M_trivial) Nand_abs [simp]:

"[|M(x); M(y); M(Z)|] ==> is_Nand(M,x,y,Z) <=> (Z = Nand(x,y))"
 <proof>

lemma (in M_trivial) Nand_in_M_iff [iff]: "M(Nand(x,y)) <=> M(x) & M(y)"
 <proof>

definition

is_Forall :: "[i=>o,i,i] => o" where
 — because Forall(x) ≡ Inr(Inr(p))
 "is_Forall(M,p,Z) == ∃u[M]. is_Inr(M,p,u) & is_Inr(M,u,Z)"

lemma (in M_trivial) Forall_abs [simp]:
 "[|M(x); M(Z)|] ==> is_Forall(M,x,Z) <=> (Z = Forall(x))"
 <proof>

lemma (in M_trivial) Forall_in_M_iff [iff]: "M(Forall(x)) <=> M(x)"
 <proof>

6.11 Absoluteness for formula_rec

definition

formula_rec_case :: "[[i,i]=>i, [i,i]=>i, [i,i,i,i]=>i, [i,i]=>i, i,
 i] => i" where
 — the instance of formula_case in formula_rec
 "formula_rec_case(a,b,c,d,h) ==
 formula_case (a, b,
 λu v. c(u, v, h ' succ(depth(u)) ' u,
 h ' succ(depth(v)) ' v),
 λu. d(u, h ' succ(depth(u)) ' u))"

Unfold *formula_rec* to *formula_rec_case*. Express *formula_rec* without using *rank* or *Vset*, neither of which is absolute.

lemma (in M_trivial) formula_rec_eq:
 "p ∈ formula ==>
 formula_rec(a,b,c,d,p) =
 transrec (succ(depth(p)),
 λx h. Lambda (formula, formula_rec_case(a,b,c,d,h))) ' p"
 <proof>

6.11.1 Absoluteness for the Formula Operator depth

definition

is_depth :: "[i=>o,i,i] => o" where
 "is_depth(M,p,n) ==
 ∃sn[M]. ∃formula_n[M]. ∃formula_sn[M].
 is_formula_N(M,n,formula_n) & p ∉ formula_n &
 successor(M,n,sn) & is_formula_N(M,sn,formula_sn) & p ∈ formula_sn"

```

lemma (in M_datatypes) depth_abs [simp]:
  "[| p ∈ formula; n ∈ nat |] ==> is_depth(M,p,n) ⟷ n = depth(p)"
⟨proof⟩

```

Proof is trivial since *depth* returns natural numbers.

```

lemma (in M_trivial) depth_closed [intro,simp]:
  "p ∈ formula ==> M(depth(p))"
⟨proof⟩

```

6.11.2 *is_formula_case*: relativization of *formula_case*

definition

```

is_formula_case ::
  "[i=>o, [i,i,i]=>o, [i,i,i]=>o, [i,i,i]=>o, [i,i]=>o, i, i] => o"
where
  — no constraint on non-formulas
  "is_formula_case(M, is_a, is_b, is_c, is_d, p, z) ==
    (∀ x[M]. ∀ y[M]. finite_ordinal(M,x) ⟶ finite_ordinal(M,y) ⟶
      is_Member(M,x,y,p) ⟶ is_a(x,y,z)) &
    (∀ x[M]. ∀ y[M]. finite_ordinal(M,x) ⟶ finite_ordinal(M,y) ⟶
      is_Equal(M,x,y,p) ⟶ is_b(x,y,z)) &
    (∀ x[M]. ∀ y[M]. mem_formula(M,x) ⟶ mem_formula(M,y) ⟶
      is_Nand(M,x,y,p) ⟶ is_c(x,y,z)) &
    (∀ x[M]. mem_formula(M,x) ⟶ is_Forall(M,x,p) ⟶ is_d(x,z))"

```

```

lemma (in M_datatypes) formula_case_abs [simp]:
  "[| Relation2(M,nat,nat,is_a,a); Relation2(M,nat,nat,is_b,b);
    Relation2(M,formula,formula,is_c,c); Relation1(M,formula,is_d,d);
    p ∈ formula; M(z) |]
  ==> is_formula_case(M,is_a,is_b,is_c,is_d,p,z) ⟷
    z = formula_case(a,b,c,d,p)"
⟨proof⟩

```

```

lemma (in M_datatypes) formula_case_closed [intro,simp]:
  "[| p ∈ formula;
    ∀ x[M]. ∀ y[M]. x∈nat ⟶ y∈nat ⟶ M(a(x,y));
    ∀ x[M]. ∀ y[M]. x∈nat ⟶ y∈nat ⟶ M(b(x,y));
    ∀ x[M]. ∀ y[M]. x∈formula ⟶ y∈formula ⟶ M(c(x,y));
    ∀ x[M]. x∈formula ⟶ M(d(x)) |] ==> M(formula_case(a,b,c,d,p))"
⟨proof⟩

```

6.11.3 Absoluteness for *formula_rec*: Final Results

definition

```

is_formula_rec :: "[i=>o, [i,i,i]=>o, i, i] => o" where
  — predicate to relativize the functional formula_rec
  "is_formula_rec(M,MH,p,z) ==
    ∃ dp[M]. ∃ i[M]. ∃ f[M]. finite_ordinal(M,dp) & is_depth(M,p,dp) &
      successor(M,dp,i) & fun_apply(M,f,p,z) & is_transrec(M,MH,i,f)"

```

Sufficient conditions to relativize the instance of *formula_case* in *formula_rec*

```

lemma (in M_datatypes) Relation1_formula_rec_case:
  "[/Relation2(M, nat, nat, is_a, a);
    Relation2(M, nat, nat, is_b, b);
    Relation2 (M, formula, formula,
      is_c, λu v. c(u, v, h'succ(depth(u))'u, h'succ(depth(v))'v));
    Relation1(M, formula,
      is_d, λu. d(u, h ' succ(depth(u)) ' u));
    M(h) |]
  ==> Relation1(M, formula,
    is_formula_case (M, is_a, is_b, is_c, is_d),
    formula_rec_case(a, b, c, d, h))"
<proof>

```

This locale packages the premises of the following theorems, which is the normal purpose of locales. It doesn't accumulate constraints on the class *M*, as in most of this development.

```

locale Formula_Rec = M_eclose +
  fixes a and is_a and b and is_b and c and is_c and d and is_d and
  MH
  defines
    "MH(u::i,f,z) ==
      ∀ fml[M]. is_formula(M,fml) ⟶
        is_lambda
          (M, fml, is_formula_case (M, is_a, is_b, is_c(f), is_d(f)), z)"

  assumes a_closed: "[|x∈nat; y∈nat|] ==> M(a(x,y))"
  and a_rel: "Relation2(M, nat, nat, is_a, a)"
  and b_closed: "[|x∈nat; y∈nat|] ==> M(b(x,y))"
  and b_rel: "Relation2(M, nat, nat, is_b, b)"
  and c_closed: "[|x ∈ formula; y ∈ formula; M(gx); M(gy)|]
    ==> M(c(x, y, gx, gy))"
  and c_rel:
    "M(f) ==>
      Relation2 (M, formula, formula, is_c(f),
        λu v. c(u, v, f ' succ(depth(u)) ' u, f ' succ(depth(v))
          ' v))"
  and d_closed: "[|x ∈ formula; M(gx)|] ==> M(d(x, gx))"
  and d_rel:
    "M(f) ==>
      Relation1(M, formula, is_d(f), λu. d(u, f ' succ(depth(u)) '
        u))"
  and fr_replace: "n ∈ nat ==> transrec_replacement(M,MH,n)"
  and fr_lam_replace:
    "M(g) ==>
      strong_replacement
        (M, λx y. x ∈ formula &
          y = ⟨x, formula_rec_case(a,b,c,d,g,x⟩)"

```

```

lemma (in Formula_Rec) formula_rec_case_closed:
  "[|M(g); p ∈ formula|] ==> M(formula_rec_case(a, b, c, d, g, p))"
  <proof>

lemma (in Formula_Rec) formula_rec_lam_closed:
  "M(g) ==> M(Lambda (formula, formula_rec_case(a,b,c,d,g)))"
  <proof>

lemma (in Formula_Rec) MH_rel2:
  "relation2 (M, MH,
    λx h. Lambda (formula, formula_rec_case(a,b,c,d,h)))"
  <proof>

lemma (in Formula_Rec) fr_transrec_closed:
  "n ∈ nat
    ==> M(transrec
      (n, λx h. Lambda(formula, formula_rec_case(a, b, c, d, h))))"
  <proof>

The main two results: formula_rec is absolute for M.

theorem (in Formula_Rec) formula_rec_closed:
  "p ∈ formula ==> M(formula_rec(a,b,c,d,p))"
  <proof>

theorem (in Formula_Rec) formula_rec_abs:
  "[| p ∈ formula; M(z)|]
    ==> is_formula_rec(M,MH,p,z) ⟷ z = formula_rec(a,b,c,d,p)"
  <proof>

end

```

7 Closed Unbounded Classes and Normal Functions

theory *Normal* imports ZF begin

One source is the book

Frank R. Drake. *Set Theory: An Introduction to Large Cardinals*. North-Holland, 1974.

7.1 Closed and Unbounded (c.u.) Classes of Ordinals

definition

Closed :: "(i=>o) => o" where
 "Closed(P) == $\forall I. I \neq 0 \longrightarrow (\forall i \in I. \text{Ord}(i) \wedge P(i)) \longrightarrow P(\bigcup (I))$ "

definition

```

Unbounded :: "(i=>o) => o" where
  "Unbounded(P) ==  $\forall i. \text{Ord}(i) \longrightarrow (\exists j. i < j \wedge P(j))"$ 

```

definition

```

Closed_Unbounded :: "(i=>o) => o" where
  "Closed_Unbounded(P) == Closed(P)  $\wedge$  Unbounded(P)"

```

7.1.1 Simple facts about c.u. classes

lemma *ClosedI*:

```

"[| !!I. [| I  $\neq$  0;  $\forall i \in I. \text{Ord}(i) \wedge P(i)$  |] ==> P( $\bigcup(I)$ ) |]
==> Closed(P)"

```

<proof>

lemma *ClosedD*:

```

"[| Closed(P); I  $\neq$  0; !!i. i  $\in$  I ==> Ord(i); !!i. i  $\in$  I ==> P(i) |]
==> P( $\bigcup(I)$ )"

```

<proof>

lemma *UnboundedD*:

```

"[| Unbounded(P); Ord(i) |] ==>  $\exists j. i < j \wedge P(j)$ "

```

<proof>

lemma *Closed_Unbounded_imp_Unbounded*: "Closed_Unbounded(C) ==> Unbounded(C)"

<proof>

The universal class, *V*, is closed and unbounded. A bit odd, since *C. U.* concerns only ordinals, but it's used below!

theorem *Closed_Unbounded_V* [simp]: "Closed_Unbounded($\lambda x. \text{True}$)"

<proof>

The class of ordinals, *Ord*, is closed and unbounded.

theorem *Closed_Unbounded_Ord* [simp]: "Closed_Unbounded(Ord)"

<proof>

The class of limit ordinals, *Limit*, is closed and unbounded.

theorem *Closed_Unbounded_Limit* [simp]: "Closed_Unbounded(Limit)"

<proof>

The class of cardinals, *Card*, is closed and unbounded.

theorem *Closed_Unbounded_Card* [simp]: "Closed_Unbounded(Card)"

<proof>

7.1.2 The intersection of any set-indexed family of c.u. classes is c.u.

The constructions below come from Kunen, *Set Theory*, page 78.

```

locale cub_family =
  fixes P and A
  fixes next_greater — the next ordinal satisfying class A
  fixes sup_greater — sup of those ordinals over all A
  assumes closed: "a ∈ A ==> Closed(P(a))"
    and unbounded: "a ∈ A ==> Unbounded(P(a))"
    and A_non0: "A ≠ 0"
  defines "next_greater(a,x) == μ y. x < y ∧ P(a,y)"
    and "sup_greater(x) == ⋃ a ∈ A. next_greater(a,x)"

```

Trivial that the intersection is closed.

```

lemma (in cub_family) Closed_INT: "Closed(λx. ∀ i ∈ A. P(i,x))"
  <proof>

```

All remaining effort goes to show that the intersection is unbounded.

```

lemma (in cub_family) Ord_sup_greater:
  "Ord(sup_greater(x))"
  <proof>

```

```

lemma (in cub_family) Ord_next_greater:
  "Ord(next_greater(a,x))"
  <proof>

```

`next_greater` works as expected: it returns a larger value and one that belongs to class $P(a)$.

```

lemma (in cub_family) next_greater_lemma:
  "[| Ord(x); a ∈ A |] ==> P(a, next_greater(a,x)) ∧ x < next_greater(a,x)"
  <proof>

```

```

lemma (in cub_family) next_greater_in_P:
  "[| Ord(x); a ∈ A |] ==> P(a, next_greater(a,x))"
  <proof>

```

```

lemma (in cub_family) next_greater_gt:
  "[| Ord(x); a ∈ A |] ==> x < next_greater(a,x)"
  <proof>

```

```

lemma (in cub_family) sup_greater_gt:
  "Ord(x) ==> x < sup_greater(x)"
  <proof>

```

```

lemma (in cub_family) next_greater_le_sup_greater:
  "a ∈ A ==> next_greater(a,x) ≤ sup_greater(x)"
  <proof>

```

```

lemma (in cub_family) omega_sup_greater_eq_UN:
  "[| Ord(x); a ∈ A |]
  ==> sup_greater^ω (x) =
    (⋃ n ∈ nat. next_greater(a, sup_greater^n (x)))"

```

<proof>

lemma (in cub_family) P_omega_sup_greater:
" [| Ord(x); a ∈ A |] ==> P(a, sup_greater^ω (x)) "
<proof>

lemma (in cub_family) omega_sup_greater_gt:
"Ord(x) ==> x < sup_greater^ω (x)"
<proof>

lemma (in cub_family) Unbounded_INT: "Unbounded(λx. ∀ a ∈ A. P(a, x))"
<proof>

lemma (in cub_family) Closed_Unbounded_INT:
"Closed_Unbounded(λx. ∀ a ∈ A. P(a, x))"
<proof>

theorem Closed_Unbounded_INT:
" (!! a. a ∈ A ==> Closed_Unbounded(P(a)))
==> Closed_Unbounded(λx. ∀ a ∈ A. P(a, x)) "
<proof>

lemma Int_iff_INT2:
"P(x) ∧ Q(x) ⟷ (∀ i ∈ 2. (i=0 ⟶ P(x)) ∧ (i=1 ⟶ Q(x))) "
<proof>

theorem Closed_Unbounded_Int:
" [| Closed_Unbounded(P); Closed_Unbounded(Q) |]
==> Closed_Unbounded(λx. P(x) ∧ Q(x)) "
<proof>

7.2 Normal Functions

definition
mono_le_subset :: "(i=>i) => o" where
"mono_le_subset(M) == ∀ i j. i ≤ j ⟶ M(i) ⊆ M(j)"

definition
mono_Ord :: "(i=>i) => o" where
"mono_Ord(F) == ∀ i j. i < j ⟶ F(i) < F(j)"

definition
cont_Ord :: "(i=>i) => o" where
"cont_Ord(F) == ∀ l. Limit(l) ⟶ F(l) = (⋃ i < l. F(i))"

definition
Normal :: "(i=>i) => o" where
"Normal(F) == mono_Ord(F) ∧ cont_Ord(F)"

7.2.1 Immediate properties of the definitions

```

lemma NormalI:
  "[!!!i j. i<j ==> F(i) < F(j);  !!l. Limit(l) ==> F(l) = (⋃ i<l.
  F(i))]"
  ==> Normal(F)
<proof>

lemma mono_Ord_imp_Ord: "[| Ord(i); mono_Ord(F) |] ==> Ord(F(i))"
<proof>

lemma mono_Ord_imp_mono: "[| i<j; mono_Ord(F) |] ==> F(i) < F(j)"
<proof>

lemma Normal_imp_Ord [simp]: "[| Normal(F); Ord(i) |] ==> Ord(F(i))"
<proof>

lemma Normal_imp_cont: "[| Normal(F); Limit(l) |] ==> F(l) = (⋃ i<l.
  F(i))"
<proof>

lemma Normal_imp_mono: "[| i<j; Normal(F) |] ==> F(i) < F(j)"
<proof>

lemma Normal_increasing:
  assumes i: "Ord(i)" and F: "Normal(F)" shows "i ≤ F(i)"
<proof>

```

7.2.2 The class of fixedpoints is closed and unbounded

The proof is from Drake, pages 113–114.

```

lemma mono_Ord_imp_le_subset: "mono_Ord(F) ==> mono_le_subset(F)"
<proof>

```

The following equation is taken for granted in any set theory text.

```

lemma cont_Ord_Union:
  "[| cont_Ord(F); mono_le_subset(F); X=0 → F(0)=0; ∀ x∈X. Ord(x)
  |]
  ==> F(⋃ (X)) = (⋃ y∈X. F(y))"
<proof>

lemma Normal_Union:
  "[| X≠0; ∀ x∈X. Ord(x); Normal(F) |] ==> F(⋃ (X)) = (⋃ y∈X. F(y))"
<proof>

lemma Normal_imp_fp_Closed: "Normal(F) ==> Closed(λi. F(i) = i)"
<proof>

```

```

lemma iterates_Normal_increasing:
  "[| n∈nat; x < F(x); Normal(F) |]
    ==> Fn (x) < F(succ(n)) (x)"
  <proof>

lemma Ord_iterates_Normal:
  "[| n∈nat; Normal(F); Ord(x) |] ==> Ord(Fn (x))"
  <proof>

THIS RESULT IS UNUSED

lemma iterates_omega_Limit:
  "[| Normal(F); x < F(x) |] ==> Limit(Fω (x))"
  <proof>

lemma iterates_omega_fixedpoint:
  "[| Normal(F); Ord(a) |] ==> F(Fω (a)) = Fω (a)"
  <proof>

lemma iterates_omega_increasing:
  "[| Normal(F); Ord(a) |] ==> a ≤ Fω (a)"
  <proof>

lemma Normal_imp_fp_Unbounded: "Normal(F) ==> Unbounded(λi. F(i) = i)"
  <proof>

theorem Normal_imp_fp_Closed_Unbounded:
  "Normal(F) ==> Closed_Unbounded(λi. F(i) = i)"
  <proof>

7.2.3 Function normalize

Function normalize maps a function F to a normal function that bounds
it above. The result is normal if and only if F is continuous: succ is not
bounded above by any normal function, by Normal_imp_fp_Unbounded.

definition
  normalize :: "[i=>i, i] => i" where
    "normalize(F,a) == transrec2(a, F(0), λx r. F(succ(x)) ∪ succ(r))"

lemma Ord_normalize [simp, intro]:
  "[| Ord(a); !!x. Ord(x) ==> Ord(F(x)) |] ==> Ord(normalize(F, a))"
  <proof>

lemma normalize_increasing:
  assumes ab: "a < b" and F: "!!x. Ord(x) ==> Ord(F(x))"
  shows "normalize(F,a) < normalize(F,b)"
  <proof>

```

```

theorem Normal_normalize:
  "(!!x. Ord(x) ==> Ord(F(x))) ==> Normal(normalize(F))"
  <proof>

theorem le_normalize:
  assumes a: "Ord(a)" and coF: "cont_Ord(F)" and F: "!!x. Ord(x) ==>
  Ord(F(x))"
  shows "F(a) ≤ normalize(F,a)"
  <proof>

```

7.3 The Alephs

This is the well-known transfinite enumeration of the cardinal numbers.

definition

```

Aleph :: "i => i"  (<\_> [90] 90) where
  "Aleph(a) == transrec2(a, nat, λx r. csucc(r))"

```

```

lemma Card_Aleph [simp, intro]:
  "Ord(a) ==> Card(Aleph(a))"
  <proof>

```

```

lemma Aleph_increasing:
  assumes ab: "a < b" shows "Aleph(a) < Aleph(b)"
  <proof>

```

```

theorem Normal_Aleph: "Normal(Aleph)"
  <proof>

```

end

8 The Reflection Theorem

theory Reflection **imports** Normal **begin**

```

lemma all_iff_not_ex_not: "(∀x. P(x)) ⟷ (¬ (∃x. ¬ P(x)))"
  <proof>

```

```

lemma ball_iff_not_bex_not: "(∀x∈A. P(x)) ⟷ (¬ (∃x∈A. ¬ P(x)))"
  <proof>

```

From the notes of A. S. Kechris, page 6, and from Andrzej Mostowski, *Constructible Sets with Applications*, North-Holland, 1969, page 23.

8.1 Basic Definitions

First part: the cumulative hierarchy defining the class M . To avoid handling multiple arguments, we assume that $Mset(1)$ is closed under ordered

pairing provided 1 is limit. Possibly this could be avoided: the induction hypothesis *Cl_reflects* (in locale *ex_reflection*) could be weakened to $\forall y \in \text{Mset}(a). \forall z \in \text{Mset}(a). P(\langle y, z \rangle) \longleftrightarrow Q(a, \langle y, z \rangle)$, removing most uses of *Pair_in_Mset*. But there isn't much point in doing so, since ultimately the *ex_reflection* proof is packaged up using the predicate *Reflects*.

```

locale reflection =
  fixes Mset and M and Reflects
  assumes Mset_mono_le : "mono_le_subset(Mset)"
    and Mset_cont      : "cont_Ord(Mset)"
    and Pair_in_Mset   : "[| x ∈ Mset(a); y ∈ Mset(a); Limit(a) |]
      ==> <x,y> ∈ Mset(a)"
  defines "M(x) == ∃ a. Ord(a) & x ∈ Mset(a)"
    and "Reflects(Cl,P,Q) == Closed_Unbounded(Cl) &
      (∀ a. Cl(a) → (∀ x ∈ Mset(a). P(x) ↔ Q(a,x)))"

  fixes F0 — ordinal for a specific value y
  fixes FF — sup over the whole level, y ∈ Mset(a)
  fixes ClEx — Reflecting ordinals for the formula ∃ z. P
  defines "F0(P,y) == μ b. (∃ z. M(z) & P(<y,z>)) →
    (∃ z ∈ Mset(b). P(<y,z>))"
    and "FF(P) == λ a. ⋃ y ∈ Mset(a). F0(P,y)"
    and "ClEx(P,a) == Limit(a) & normalize(FF(P),a) = a"

```

```

lemma (in reflection) Mset_mono: "i ≤ j ==> Mset(i) ⊆ Mset(j)"
  <proof>

```

Awkward: we need a version of *ClEx_def* as an equality at the level of classes, which do not really exist

```

lemma (in reflection) ClEx_eq:
  "ClEx(P) == λ a. Limit(a) & normalize(FF(P),a) = a"
  <proof>

```

8.2 Easy Cases of the Reflection Theorem

```

theorem (in reflection) Triv_reflection [intro]:
  "Reflects(Ord, P, λ a x. P(x))"
  <proof>

```

```

theorem (in reflection) Not_reflection [intro]:
  "Reflects(Cl,P,Q) ==> Reflects(Cl, λ x. ~P(x), λ a x. ~Q(a,x))"
  <proof>

```

```

theorem (in reflection) And_reflection [intro]:
  "[| Reflects(Cl,P,Q); Reflects(C',P',Q') |]
  ==> Reflects(λ a. Cl(a) & C'(a), λ x. P(x) & P'(x),
    λ a x. Q(a,x) & Q'(a,x))"
  <proof>

```

```

theorem (in reflection) Or_reflection [intro]:

```

```

"[/ Reflects(Cl,P,Q); Reflects(C',P',Q') [/]
==> Reflects( $\lambda a. Cl(a) \ \& \ C'(a), \ \lambda x. P(x) \mid P'(x),$ 
 $\lambda a \ x. Q(a,x) \mid Q'(a,x))$ )"
<proof>

```

```

theorem (in reflection) Imp_reflection [intro]:
"[/ Reflects(Cl,P,Q); Reflects(C',P',Q') [/]
==> Reflects( $\lambda a. Cl(a) \ \& \ C'(a),$ 
 $\lambda x. P(x) \longrightarrow P'(x),$ 
 $\lambda a \ x. Q(a,x) \longrightarrow Q'(a,x))$ )"
<proof>

```

```

theorem (in reflection) Iff_reflection [intro]:
"[/ Reflects(Cl,P,Q); Reflects(C',P',Q') [/]
==> Reflects( $\lambda a. Cl(a) \ \& \ C'(a),$ 
 $\lambda x. P(x) \longleftrightarrow P'(x),$ 
 $\lambda a \ x. Q(a,x) \longleftrightarrow Q'(a,x))$ )"
<proof>

```

8.3 Reflection for Existential Quantifiers

```

lemma (in reflection) F0_works:
"[/  $y \in Mset(a); Ord(a); M(z); P(<y,z>)$  [/] ==>  $\exists z \in Mset(F0(P,y)). P(<y,z>)$ "
<proof>

```

```

lemma (in reflection) Ord_F0 [intro,simp]: "Ord(F0(P,y))"
<proof>

```

```

lemma (in reflection) Ord_FF [intro,simp]: "Ord(FF(P,y))"
<proof>

```

```

lemma (in reflection) cont_Ord_FF: "cont_Ord(FF(P))"
<proof>

```

Recall that $F0$ depends upon $y \in Mset(a)$, while FF depends only upon a .

```

lemma (in reflection) FF_works:
"[/  $M(z); y \in Mset(a); P(<y,z>); Ord(a)$  [/] ==>  $\exists z \in Mset(FF(P,a)). P(<y,z>)$ "
<proof>

```

```

lemma (in reflection) FFN_works:
"[/  $M(z); y \in Mset(a); P(<y,z>); Ord(a)$  [/]
==>  $\exists z \in Mset(normalize(FF(P),a)). P(<y,z>)$ "
<proof>

```

Locale for the induction hypothesis

```

locale ex_reflection = reflection +
  fixes  $P$  — the original formula
  fixes  $Q$  — the reflected formula
  fixes  $Cl$  — the class of reflecting ordinals

```

assumes *Cl_reflects*: "[| *Cl*(*a*); *Ord*(*a*) |] ==> $\forall x \in \text{Mset}(a). P(x) \longleftrightarrow Q(a, x)$ "

lemma (in *ex_reflection*) *ClEx_downward*:
 "[| *M*(*z*); *y* ∈ *Mset*(*a*); *P*(<*y*, *z*>); *Cl*(*a*); *ClEx*(*P*, *a*) |]
 ==> $\exists z \in \text{Mset}(a). Q(a, \langle y, z \rangle)$ "
 <proof>

lemma (in *ex_reflection*) *ClEx_upward*:
 "[| *z* ∈ *Mset*(*a*); *y* ∈ *Mset*(*a*); *Q*(*a*, <*y*, *z*>); *Cl*(*a*); *ClEx*(*P*, *a*) |]
 ==> $\exists z. M(z) \ \& \ P(\langle y, z \rangle)$ "
 <proof>

Class *ClEx* indeed consists of reflecting ordinals...

lemma (in *ex_reflection*) *ZF_ClEx_iff*:
 "[| *y* ∈ *Mset*(*a*); *Cl*(*a*); *ClEx*(*P*, *a*) |]
 ==> $(\exists z. M(z) \ \& \ P(\langle y, z \rangle)) \longleftrightarrow (\exists z \in \text{Mset}(a). Q(a, \langle y, z \rangle))$ "
 <proof>

...and it is closed and unbounded

lemma (in *ex_reflection*) *ZF_Closed_Unbounded_ClEx*:
 "*Closed_Unbounded*(*ClEx*(*P*))"
 <proof>

The same two theorems, exported to locale *reflection*.

Class *ClEx* indeed consists of reflecting ordinals...

lemma (in *reflection*) *ClEx_iff*:
 "[| *y* ∈ *Mset*(*a*); *Cl*(*a*); *ClEx*(*P*, *a*);
 !!*a*. [| *Cl*(*a*); *Ord*(*a*) |] ==> $\forall x \in \text{Mset}(a). P(x) \longleftrightarrow Q(a, x)$ |]
 ==> $(\exists z. M(z) \ \& \ P(\langle y, z \rangle)) \longleftrightarrow (\exists z \in \text{Mset}(a). Q(a, \langle y, z \rangle))$ "
 <proof>

lemma (in *reflection*) *Closed_Unbounded_ClEx*:
 "(!!*a*. [| *Cl*(*a*); *Ord*(*a*) |] ==> $\forall x \in \text{Mset}(a). P(x) \longleftrightarrow Q(a, x)$)
 ==> *Closed_Unbounded*(*ClEx*(*P*))"
 <proof>

8.4 Packaging the Quantifier Reflection Rules

lemma (in *reflection*) *Ex_reflection_0*:
 "*Reflects*(*Cl*, *P0*, *Q0*)
 ==> *Reflects*($\lambda a. Cl(a) \ \& \ ClEx(P0, a),$
 $\lambda x. \exists z. M(z) \ \& \ P0(\langle x, z \rangle),$
 $\lambda a \ x. \exists z \in \text{Mset}(a). Q0(a, \langle x, z \rangle)$)"
 <proof>

```

lemma (in reflection) All_reflection_0:
  "Reflects(Cl,P0,Q0)
   ==> Reflects(λa. Cl(a) & ClEx(λx.~P0(x), a),
                λx. ∀z. M(z) → P0(<x,z>),
                λa x. ∀z∈Mset(a). Q0(a,<x,z>))"
⟨proof⟩

theorem (in reflection) Ex_reflection [intro]:
  "Reflects(Cl, λx. P(fst(x),snd(x)), λa x. Q(a,fst(x),snd(x)))
   ==> Reflects(λa. Cl(a) & ClEx(λx. P(fst(x),snd(x)), a),
                λx. ∃z. M(z) & P(x,z),
                λa x. ∃z∈Mset(a). Q(a,x,z))"
⟨proof⟩

theorem (in reflection) All_reflection [intro]:
  "Reflects(Cl, λx. P(fst(x),snd(x)), λa x. Q(a,fst(x),snd(x)))
   ==> Reflects(λa. Cl(a) & ClEx(λx. ~P(fst(x),snd(x)), a),
                λx. ∀z. M(z) → P(x,z),
                λa x. ∀z∈Mset(a). Q(a,x,z))"
⟨proof⟩

And again, this time using class-bounded quantifiers

theorem (in reflection) Rex_reflection [intro]:
  "Reflects(Cl, λx. P(fst(x),snd(x)), λa x. Q(a,fst(x),snd(x)))
   ==> Reflects(λa. Cl(a) & ClEx(λx. P(fst(x),snd(x)), a),
                λx. ∃z[M]. P(x,z),
                λa x. ∃z∈Mset(a). Q(a,x,z))"
⟨proof⟩

theorem (in reflection) Rall_reflection [intro]:
  "Reflects(Cl, λx. P(fst(x),snd(x)), λa x. Q(a,fst(x),snd(x)))
   ==> Reflects(λa. Cl(a) & ClEx(λx. ~P(fst(x),snd(x)), a),
                λx. ∀z[M]. P(x,z),
                λa x. ∀z∈Mset(a). Q(a,x,z))"
⟨proof⟩

```

No point considering bounded quantifiers, where reflection is trivial.

8.5 Simple Examples of Reflection

Example 1: reflecting a simple formula. The reflecting class is first given as the variable ?Cl and later retrieved from the final proof state.

```

schematic_goal (in reflection)
  "Reflects(?Cl,
            λx. ∃y. M(y) & x ∈ y,
            λa x. ∃y∈Mset(a). x ∈ y)"
⟨proof⟩

```

Problem here: there needs to be a conjunction (class intersection) in the class of reflecting ordinals. The $Ord(a)$ is redundant, though harmless.

lemma (in reflection)

"Reflects($\lambda a. Ord(a) \ \& \ C1Ex(\lambda x. fst(x) \in snd(x), a),$
 $\lambda x. \exists y. M(y) \ \& \ x \in y,$
 $\lambda a \ x. \exists y \in Mset(a). x \in y$)"

$\langle proof \rangle$

Example 2

schematic_goal (in reflection)

"Reflects(?Cl,
 $\lambda x. \exists y. M(y) \ \& \ (\forall z. M(z) \longrightarrow z \subseteq x \longrightarrow z \in y),$
 $\lambda a \ x. \exists y \in Mset(a). \forall z \in Mset(a). z \subseteq x \longrightarrow z \in y$)"

$\langle proof \rangle$

Example 2'. We give the reflecting class explicitly.

lemma (in reflection)

"Reflects
 $(\lambda a. (Ord(a) \ \& \ C1Ex(\lambda x. \sim (snd(x) \subseteq fst(fst(x)) \longrightarrow snd(x) \in snd(fst(x))),$
 $a)) \ \& \ C1Ex(\lambda x. \forall z. M(z) \longrightarrow z \subseteq fst(x) \longrightarrow z \in snd(x), a),$
 $\lambda x. \exists y. M(y) \ \& \ (\forall z. M(z) \longrightarrow z \subseteq x \longrightarrow z \in y),$
 $\lambda a \ x. \exists y \in Mset(a). \forall z \in Mset(a). z \subseteq x \longrightarrow z \in y$)"

$\langle proof \rangle$

Example 2". We expand the subset relation.

schematic_goal (in reflection)

"Reflects(?Cl,
 $\lambda x. \exists y. M(y) \ \& \ (\forall z. M(z) \longrightarrow (\forall w. M(w) \longrightarrow w \in z \longrightarrow w \in x) \longrightarrow z \in y),$
 $\lambda a \ x. \exists y \in Mset(a). \forall z \in Mset(a). (\forall w \in Mset(a). w \in z \longrightarrow w \in x) \longrightarrow z \in y$)"

$\langle proof \rangle$

Example 2'''. Single-step version, to reveal the reflecting class.

schematic_goal (in reflection)

"Reflects(?Cl,
 $\lambda x. \exists y. M(y) \ \& \ (\forall z. M(z) \longrightarrow z \subseteq x \longrightarrow z \in y),$
 $\lambda a \ x. \exists y \in Mset(a). \forall z \in Mset(a). z \subseteq x \longrightarrow z \in y$)"

$\langle proof \rangle$

Example 3. Warning: the following examples make sense only if P is quantifier-free, since it is not being relativized.

schematic_goal (in reflection)

"Reflects(?Cl,
 $\lambda x. \exists y. M(y) \ \& \ (\forall z. M(z) \longrightarrow z \in y \longleftrightarrow z \in x \ \& \ P(z)),$

$\lambda a \ x. \exists y \in \text{Mset}(a). \forall z \in \text{Mset}(a). z \in y \longleftrightarrow z \in x \ \& \ P(z))"$

<proof>

Example 3'

```
schematic_goal (in reflection)
  "Reflects(?Cl,
     $\lambda x. \exists y. M(y) \ \& \ y = \text{Collect}(x,P),$ 
     $\lambda a \ x. \exists y \in \text{Mset}(a). y = \text{Collect}(x,P))"$ 
<proof>
```

Example 3"

```
schematic_goal (in reflection)
  "Reflects(?Cl,
     $\lambda x. \exists y. M(y) \ \& \ y = \text{Replace}(x,P),$ 
     $\lambda a \ x. \exists y \in \text{Mset}(a). y = \text{Replace}(x,P))"$ 
<proof>
```

Example 4: Axiom of Choice. Possibly wrong, since Π needs to be relativized.

```
schematic_goal (in reflection)
  "Reflects(?Cl,
     $\lambda A. 0 \notin A \longrightarrow (\exists f. M(f) \ \& \ f \in (\prod X \in A. X)),$ 
     $\lambda a \ A. 0 \notin A \longrightarrow (\exists f \in \text{Mset}(a). f \in (\prod X \in A. X)))"$ 
<proof>
```

end

9 The meta-existential quantifier

theory *MetaExists* **imports** *ZF* **begin**

Allows quantification over any term. Used to quantify over classes. Yields a proposition rather than a FOL formula.

definition

```
ex :: "(( $\lambda a::\{ \}$ )  $\Rightarrow$  prop)  $\Rightarrow$  prop" (binder  $\langle \bigvee \rangle$  0) where
  "ex(P) == ( $\bigwedge Q. (\bigwedge x. \text{PROP } P(x) \Longrightarrow \text{PROP } Q) \Longrightarrow \text{PROP } Q)$ "
```

```
lemma meta_exI: "PROP P(x) ==> ( $\bigvee x. \text{PROP } P(x)$ )"
<proof>
```

```
lemma meta_exE: "[ $\bigvee x. \text{PROP } P(x); \bigwedge x. \text{PROP } P(x) \Longrightarrow \text{PROP } R$ ] ==> PROP R"
<proof>
```

end

10 The ZF Axioms (Except Separation) in L

theory *L_axioms* **imports** *Formula Relative Reflection MetaExists* **begin**

The class L satisfies the premises of locale $M_trivial$

lemma *transL*: " $[| y \in x; L(x) |] \implies L(y)$ "
 $\langle proof \rangle$

lemma *nonempty*: " $L(0)$ "
 $\langle proof \rangle$

theorem *upair_ax*: " $upair_ax(L)$ "
 $\langle proof \rangle$

theorem *Union_ax*: " $Union_ax(L)$ "
 $\langle proof \rangle$

theorem *power_ax*: " $power_ax(L)$ "
 $\langle proof \rangle$

We don't actually need L to satisfy the foundation axiom.

theorem *foundation_ax*: " $foundation_ax(L)$ "
 $\langle proof \rangle$

10.1 For L to satisfy Replacement

lemma *LReplace_in_Lset*:
 $[| X \in Lset(i); univalent(L, X, Q); Ord(i) |]$
 $\implies \exists j. Ord(j) \ \& \ Replace(X, \lambda x y. Q(x, y) \ \& \ L(y)) \subseteq Lset(j)$ "
 $\langle proof \rangle$

lemma *LReplace_in_L*:
 $[| L(X); univalent(L, X, Q) |]$
 $\implies \exists Y. L(Y) \ \& \ Replace(X, \lambda x y. Q(x, y) \ \& \ L(y)) \subseteq Y$ "
 $\langle proof \rangle$

theorem *replacement*: " $replacement(L, P)$ "
 $\langle proof \rangle$

lemma *strong_replacementI* [*rule_format*]:
 $[| \forall B[L]. separation(L, \lambda u. \exists x[L]. x \in B \ \& \ P(x, u)) |]$
 $\implies strong_replacement(L, P)$ "
 $\langle proof \rangle$

10.2 Instantiating the locale $M_trivial$

No instances of Separation yet.

lemma *Lset_mono_le*: " $mono_le_subset(Lset)$ "
 $\langle proof \rangle$

lemma *Lset_cont*: " $cont_Ord(Lset)$ "
 $\langle proof \rangle$

lemmas $L_nat = Ord_in_L [OF\ Ord_nat]$

theorem $M_trivial_L$: " $M_trivial(L)$ "
 $\langle proof \rangle$

interpretation L : $M_trivial\ L\ \langle proof \rangle$

10.3 Instantiation of the locale *reflection*

instances of locale constants

definition

$L_FO :: "[i=>o,i] => i"$ where
 $"L_FO(P,y) == \mu\ b.\ (\exists z.\ L(z) \wedge P(\langle y,z \rangle)) \longrightarrow (\exists z \in Lset(b).\ P(\langle y,z \rangle))"$

definition

$L_FF :: "[i=>o,i] => i"$ where
 $"L_FF(P) == \lambda a.\ \bigcup_{y \in Lset(a)} L_FO(P,y)"$

definition

$L_ClEx :: "[i=>o,i] => o"$ where
 $"L_ClEx(P) == \lambda a.\ Limit(a) \wedge normalize(L_FF(P),a) = a"$

We must use the meta-existential quantifier; otherwise the reflection terms become enormous!

definition

$L_Reflects :: "[i=>o,[i,i]=>o] => prop"$ ($\langle (3REFLECTS/ [_,/ _]) \rangle$) where
 $"REFLECTS[P,Q] == (\bigvee Cl.\ Closed_Unbounded(Cl) \ \& \ (\forall a.\ Cl(a) \longrightarrow (\forall x \in Lset(a).\ P(x) \longleftrightarrow Q(a,x))))"$

theorem $Triv_reflection$:

$"REFLECTS[P, \lambda a\ x.\ P(x)]"$
 $\langle proof \rangle$

theorem $Not_reflection$:

$"REFLECTS[P,Q] ==> REFLECTS[\lambda x.\ \sim P(x), \lambda a\ x.\ \sim Q(a,x)]"$
 $\langle proof \rangle$

theorem $And_reflection$:

$"[| REFLECTS[P,Q]; REFLECTS[P',Q'] |]"$
 $==> REFLECTS[\lambda x.\ P(x) \wedge P'(x), \lambda a\ x.\ Q(a,x) \wedge Q'(a,x)]"$
 $\langle proof \rangle$

theorem $Or_reflection$:

$"[| REFLECTS[P,Q]; REFLECTS[P',Q'] |]"$
 $==> REFLECTS[\lambda x.\ P(x) \vee P'(x), \lambda a\ x.\ Q(a,x) \vee Q'(a,x)]"$
 $\langle proof \rangle$

theorem *Imp_reflection*:
 "[| REFLECTS[P,Q]; REFLECTS[P',Q'] |]"
 ==> REFLECTS[$\lambda x. P(x) \longrightarrow P'(x), \lambda a x. Q(a,x) \longrightarrow Q'(a,x)$]"
 <proof>

theorem *Iff_reflection*:
 "[| REFLECTS[P,Q]; REFLECTS[P',Q'] |]"
 ==> REFLECTS[$\lambda x. P(x) \longleftrightarrow P'(x), \lambda a x. Q(a,x) \longleftrightarrow Q'(a,x)$]"
 <proof>

lemma *reflection_Lset*: "reflection(Lset)"
 <proof>

theorem *Ex_reflection*:
 "REFLECTS[$\lambda x. P(\text{fst}(x), \text{snd}(x)), \lambda a x. Q(a, \text{fst}(x), \text{snd}(x))$]"
 ==> REFLECTS[$\lambda x. \exists z. L(z) \wedge P(x,z), \lambda a x. \exists z \in \text{Lset}(a). Q(a,x,z)$]"
 <proof>

theorem *All_reflection*:
 "REFLECTS[$\lambda x. P(\text{fst}(x), \text{snd}(x)), \lambda a x. Q(a, \text{fst}(x), \text{snd}(x))$]"
 ==> REFLECTS[$\lambda x. \forall z. L(z) \longrightarrow P(x,z), \lambda a x. \forall z \in \text{Lset}(a). Q(a,x,z)$]"
 <proof>

theorem *Rex_reflection*:
 "REFLECTS[$\lambda x. P(\text{fst}(x), \text{snd}(x)), \lambda a x. Q(a, \text{fst}(x), \text{snd}(x))$]"
 ==> REFLECTS[$\lambda x. \exists z[L]. P(x,z), \lambda a x. \exists z \in \text{Lset}(a). Q(a,x,z)$]"
 <proof>

theorem *Rall_reflection*:
 "REFLECTS[$\lambda x. P(\text{fst}(x), \text{snd}(x)), \lambda a x. Q(a, \text{fst}(x), \text{snd}(x))$]"
 ==> REFLECTS[$\lambda x. \forall z[L]. P(x,z), \lambda a x. \forall z \in \text{Lset}(a). Q(a,x,z)$]"
 <proof>

This version handles an alternative form of the bounded quantifier in the second argument of *REFLECTS*.

theorem *Rex_reflection'*:
 "REFLECTS[$\lambda x. P(\text{fst}(x), \text{snd}(x)), \lambda a x. Q(a, \text{fst}(x), \text{snd}(x))$]"
 ==> REFLECTS[$\lambda x. \exists z[L]. P(x,z), \lambda a x. \exists z[\#\text{Lset}(a)]. Q(a,x,z)$]"
 <proof>

As above.

theorem *Rall_reflection'*:
 "REFLECTS[$\lambda x. P(\text{fst}(x), \text{snd}(x)), \lambda a x. Q(a, \text{fst}(x), \text{snd}(x))$]"
 ==> REFLECTS[$\lambda x. \forall z[L]. P(x,z), \lambda a x. \forall z[\#\text{Lset}(a)]. Q(a,x,z)$]"
 <proof>

```

lemmas FOL_reflections =
  Triv_reflection Not_reflection And_reflection Or_reflection
  Imp_reflection Iff_reflection Ex_reflection All_reflection
  Rex_reflection Rall_reflection Rex_reflection' Rall_reflection'

```

```

lemma ReflectsD:
  "[| REFLECTS[P,Q]; Ord(i) |]
  ==>  $\exists j. i < j \ \& \ (\forall x \in \text{Lset}(j). P(x) \longleftrightarrow Q(j,x))"$ 
<proof>

```

```

lemma ReflectsE:
  "[| REFLECTS[P,Q]; Ord(i);
  !!j. [| i < j;  $\forall x \in \text{Lset}(j). P(x) \longleftrightarrow Q(j,x)$  |] ==> R |]
  ==> R"
<proof>

```

```

lemma Collect_mem_eq: "{x ∈ A. x ∈ B} = A ∩ B"
<proof>

```

10.4 Internalized Formulas for some Set-Theoretic Concepts

10.4.1 Some numbers to help write de Bruijn indices

```

abbreviation
  digit3 :: i    (<3>) where "3 == succ(2)"

```

```

abbreviation
  digit4 :: i    (<4>) where "4 == succ(3)"

```

```

abbreviation
  digit5 :: i    (<5>) where "5 == succ(4)"

```

```

abbreviation
  digit6 :: i    (<6>) where "6 == succ(5)"

```

```

abbreviation
  digit7 :: i    (<7>) where "7 == succ(6)"

```

```

abbreviation
  digit8 :: i    (<8>) where "8 == succ(7)"

```

```

abbreviation
  digit9 :: i    (<9>) where "9 == succ(8)"

```

10.4.2 The Empty Set, Internalized

```

definition
  empty_fm :: "i=>i" where
    "empty_fm(x) == Forall(Neg(Member(0,succ(x))))"

```

```

lemma empty_type [TC]:
  "x ∈ nat ==> empty_fm(x) ∈ formula"
⟨proof⟩

lemma sats_empty_fm [simp]:
  "[| x ∈ nat; env ∈ list(A) |]
  ==> sats(A, empty_fm(x), env) ⟷ empty(##A, nth(x,env))"
⟨proof⟩

lemma empty_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; env ∈ list(A) |]
  ==> empty(##A, x) ⟷ sats(A, empty_fm(i), env)"
⟨proof⟩

theorem empty_reflection:
  "REFLECTS[λx. empty(L,f(x)),
    λi x. empty(##Lset(i),f(x))]"
⟨proof⟩

```

Not used. But maybe useful?

```

lemma Transset_sats_empty_fm_eq_0:
  "[| n ∈ nat; env ∈ list(A); Transset(A) |]
  ==> sats(A, empty_fm(n), env) ⟷ nth(n,env) = 0"
⟨proof⟩

```

10.4.3 Unordered Pairs, Internalized

```

definition
  upair_fm :: "[i,i,i]=>i" where
    "upair_fm(x,y,z) ==
      And(Member(x,z),
        And(Member(y,z),
          Forall(Implies(Member(0,succ(z)),
            Or(Equal(0,succ(x)), Equal(0,succ(y)))))))"

```

```

lemma upair_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> upair_fm(x,y,z) ∈ formula"
⟨proof⟩

```

```

lemma sats_upair_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, upair_fm(x,y,z), env) ⟷
    upair(##A, nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

```

```

lemma upair_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]

```

```

    ==> upair(##A, x, y, z) <=> sats(A, upair_fm(i,j,k), env)"
  <proof>

```

Useful? At least it refers to "real" unordered pairs

```

lemma sats_upair_fm2 [simp]:
  "[| x ∈ nat; y ∈ nat; z < length(env); env ∈ list(A); Transset(A) |]
  ==> sats(A, upair_fm(x,y,z), env) <=>
    nth(z,env) = {nth(x,env), nth(y,env)}"
  <proof>

```

```

theorem upair_reflection:
  "REFLECTS[λx. upair(L,f(x),g(x),h(x)),
    λi x. upair(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

10.4.4 Ordered pairs, Internalized

definition

```

  pair_fm :: "[i,i,i]=>i" where
    "pair_fm(x,y,z) ==
      Exists(And(upair_fm(succ(x),succ(x),0),
        Exists(And(upair_fm(succ(succ(x)),succ(succ(y)),0),
          upair_fm(1,0,succ(succ(z)))))))"

```

```

lemma pair_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> pair_fm(x,y,z) ∈ formula"
  <proof>

```

```

lemma sats_pair_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, pair_fm(x,y,z), env) <=>
    pair(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

```

```

lemma pair_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> pair(##A, x, y, z) <=> sats(A, pair_fm(i,j,k), env)"
  <proof>

```

```

theorem pair_reflection:
  "REFLECTS[λx. pair(L,f(x),g(x),h(x)),
    λi x. pair(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

10.4.5 Binary Unions, Internalized

definition

```

  union_fm :: "[i,i,i]=>i" where
    "union_fm(x,y,z) ==

```

```

    Forall(Iff(Member(0,succ(z)),
                Or(Member(0,succ(x)),Member(0,succ(y))))))"

lemma union_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> union_fm(x,y,z) ∈ formula"
  <proof>

lemma sats_union_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
  ==> sats(A, union_fm(x,y,z), env) ⟷
    union(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

lemma union_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
  ==> union(##A, x, y, z) ⟷ sats(A, union_fm(i,j,k), env)"
  <proof>

theorem union_reflection:
  "REFLECTS[λx. union(L,f(x),g(x),h(x)),
    λi x. union(##Lset(i),f(x),g(x),h(x))]"
  <proof>

10.4.6 Set “Cons,” Internalized

definition
  cons_fm :: "[i,i,i]=>i" where
    "cons_fm(x,y,z) ==
      Exists(And(upair_fm(succ(x),succ(x),0),
        union_fm(0,succ(y),succ(z))))"

lemma cons_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> cons_fm(x,y,z) ∈ formula"
  <proof>

lemma sats_cons_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
  ==> sats(A, cons_fm(x,y,z), env) ⟷
    is_cons(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

lemma cons_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
  ==> is_cons(##A, x, y, z) ⟷ sats(A, cons_fm(i,j,k), env)"
  <proof>

```

```

theorem cons_reflection:
  "REFLECTS[ $\lambda x. \text{is\_cons}(L, f(x), g(x), h(x)),$ 
     $\lambda i x. \text{is\_cons}(\#\#L\text{set}(i), f(x), g(x), h(x))$ ]"
  <proof>

```

10.4.7 Successor Function, Internalized

definition

```

succ_fm :: "[i,i]=>i" where
  "succ_fm(x,y) == cons_fm(x,x,y)"

```

lemma succ_type [TC]:

```

  "[| x  $\in$  nat; y  $\in$  nat |] ==> succ_fm(x,y)  $\in$  formula"
  <proof>

```

lemma sats_succ_fm [simp]:

```

  "[| x  $\in$  nat; y  $\in$  nat; env  $\in$  list(A) |]
    ==> sats(A, succ_fm(x,y), env)  $\longleftrightarrow$ 
      successor(\#\#A, nth(x,env), nth(y,env))"
  <proof>

```

lemma successor_iff_sats:

```

  "[| nth(i,env) = x; nth(j,env) = y;
    i  $\in$  nat; j  $\in$  nat; env  $\in$  list(A) |]
    ==> successor(\#\#A, x, y)  $\longleftrightarrow$  sats(A, succ_fm(i,j), env)"
  <proof>

```

theorem successor_reflection:

```

  "REFLECTS[ $\lambda x. \text{successor}(L, f(x), g(x)),$ 
     $\lambda i x. \text{successor}(\#\#L\text{set}(i), f(x), g(x))$ ]"
  <proof>

```

10.4.8 The Number 1, Internalized

definition

```

number1_fm :: "i=>i" where
  "number1_fm(a) == Exists(And(empty_fm(0), succ_fm(0,succ(a))))"

```

lemma number1_type [TC]:

```

  "x  $\in$  nat ==> number1_fm(x)  $\in$  formula"
  <proof>

```

lemma sats_number1_fm [simp]:

```

  "[| x  $\in$  nat; env  $\in$  list(A) |]
    ==> sats(A, number1_fm(x), env)  $\longleftrightarrow$  number1(\#\#A, nth(x,env))"
  <proof>

```

lemma number1_iff_sats:

```

  "[| nth(i,env) = x; nth(j,env) = y;
    i  $\in$  nat; env  $\in$  list(A) |]

```

```

==> number1(##A, x) <=> sats(A, number1_fm(i), env)"
<proof>

```

```

theorem number1_reflection:
  "REFLECTS[λx. number1(L,f(x)),
    λi x. number1(##Lset(i),f(x))]"
<proof>

```

10.4.9 Big Union, Internalized

definition

```

big_union_fm :: "[i,i]=>i" where
  "big_union_fm(A,z) ==
    Forall(Iff(Member(0,succ(z)),
      Exists(And(Member(0,succ(succ(A))), Member(1,0))))))"

```

```

lemma big_union_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> big_union_fm(x,y) ∈ formula"
<proof>

```

```

lemma sats_big_union_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
  ==> sats(A, big_union_fm(x,y), env) <=>
    big_union(##A, nth(x,env), nth(y,env))"
<proof>

```

```

lemma big_union_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]
  ==> big_union(##A, x, y) <=> sats(A, big_union_fm(i,j), env)"
<proof>

```

```

theorem big_union_reflection:
  "REFLECTS[λx. big_union(L,f(x),g(x)),
    λi x. big_union(##Lset(i),f(x),g(x))]"
<proof>

```

10.4.10 Variants of Satisfaction Definitions for Ordinals, etc.

The *sats* theorems below are standard versions of the ones proved in theory *Formula*. They relate elements of type *formula* to relativized concepts such as *subset* or *ordinal* rather than to real concepts such as *Ord*. Now that we have instantiated the locale *M_trivial*, we no longer require the earlier versions.

```

lemma sats_subset_fm':
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
  ==> sats(A, subset_fm(x,y), env) <=> subset(##A, nth(x,env), nth(y,env))"
<proof>

```

```

theorem subset_reflection:
  "REFLECTS[ $\lambda x. \text{subset}(L, f(x), g(x)),$ 
     $\lambda i x. \text{subset}(\#\#L\text{set}(i), f(x), g(x))]$ "
  <proof>

lemma sats_transset_fm':
  "[ $|x \in \text{nat}; \text{env} \in \text{list}(A)|]$ 
     $\implies \text{sats}(A, \text{transset\_fm}(x), \text{env}) \longleftrightarrow \text{transitive\_set}(\#\#A, \text{nth}(x, \text{env}))$ "
  <proof>

theorem transitive_set_reflection:
  "REFLECTS[ $\lambda x. \text{transitive\_set}(L, f(x)),$ 
     $\lambda i x. \text{transitive\_set}(\#\#L\text{set}(i), f(x))]$ "
  <proof>

lemma sats_ordinal_fm':
  "[ $|x \in \text{nat}; \text{env} \in \text{list}(A)|]$ 
     $\implies \text{sats}(A, \text{ordinal\_fm}(x), \text{env}) \longleftrightarrow \text{ordinal}(\#\#A, \text{nth}(x, \text{env}))$ "
  <proof>

lemma ordinal_iff_sats:
  "[ $| \text{nth}(i, \text{env}) = x; i \in \text{nat}; \text{env} \in \text{list}(A)|]$ 
     $\implies \text{ordinal}(\#\#A, x) \longleftrightarrow \text{sats}(A, \text{ordinal\_fm}(i), \text{env})$ "
  <proof>

theorem ordinal_reflection:
  "REFLECTS[ $\lambda x. \text{ordinal}(L, f(x)), \lambda i x. \text{ordinal}(\#\#L\text{set}(i), f(x))]$ "
  <proof>

```

10.4.11 Membership Relation, Internalized

definition

```

Memrel_fm :: "[i,i]=>i" where
  "Memrel_fm(A,r) ==
    Forall(Iff(Member(0,succ(r)),
      Exists(And(Member(0,succ(succ(A))),
        Exists(And(Member(0,succ(succ(succ(A)))),
          And(Member(1,0),
            pair_fm(1,0,2))))))))))"

```

```

lemma Memrel_type [TC]:
  "[ $| x \in \text{nat}; y \in \text{nat} |]$   $\implies \text{Memrel\_fm}(x,y) \in \text{formula}$ "
  <proof>

```

```

lemma sats_Memrel_fm [simp]:
  "[ $| x \in \text{nat}; y \in \text{nat}; \text{env} \in \text{list}(A)|]$ 
     $\implies \text{sats}(A, \text{Memrel\_fm}(x,y), \text{env}) \longleftrightarrow$ 
      membership( $\#\#A, \text{nth}(x, \text{env}), \text{nth}(y, \text{env}))$ "

```

<proof>

lemma *Memrel_iff_sats*:

```
"[| nth(i,env) = x; nth(j,env) = y;  
  i ∈ nat; j ∈ nat; env ∈ list(A) |]  
==> membership(##A, x, y) <=> sats(A, Memrel_fm(i,j), env)"
```

<proof>

theorem *membership_reflection*:

```
"REFLECTS[λx. membership(L,f(x),g(x)),  
  λi x. membership(##Lset(i),f(x),g(x))]"
```

<proof>

10.4.12 Predecessor Set, Internalized

definition

```
pred_set_fm :: "[i,i,i,i]=>i" where  
  "pred_set_fm(A,x,r,B) ==  
    Forall(Iff(Member(0,succ(B)),  
      Exists(And(Member(0,succ(succ(r))),  
        And(Member(1,succ(succ(A))),  
          pair_fm(1,succ(succ(x)),0))))))"
```

lemma *pred_set_type [TC]*:

```
"[| A ∈ nat; x ∈ nat; r ∈ nat; B ∈ nat |]  
==> pred_set_fm(A,x,r,B) ∈ formula"
```

<proof>

lemma *sats_pred_set_fm [simp]*:

```
"[| U ∈ nat; x ∈ nat; r ∈ nat; B ∈ nat; env ∈ list(A) |]  
==> sats(A, pred_set_fm(U,x,r,B), env) <=>  
  pred_set(##A, nth(U,env), nth(x,env), nth(r,env), nth(B,env))"
```

<proof>

lemma *pred_set_iff_sats*:

```
"[| nth(i,env) = U; nth(j,env) = x; nth(k,env) = r; nth(l,env) =  
B;  
  i ∈ nat; j ∈ nat; k ∈ nat; l ∈ nat; env ∈ list(A) |]  
==> pred_set(##A,U,x,r,B) <=> sats(A, pred_set_fm(i,j,k,l), env)"
```

<proof>

theorem *pred_set_reflection*:

```
"REFLECTS[λx. pred_set(L,f(x),g(x),h(x),b(x)),  
  λi x. pred_set(##Lset(i),f(x),g(x),h(x),b(x))]"
```

<proof>

10.4.13 Domain of a Relation, Internalized

definition

```

domain_fm :: "[i,i]=>i" where
  "domain_fm(r,z) ==
    Forall(Iff(Member(0,succ(z)),
      Exists(And(Member(0,succ(succ(r))),
        Exists(pair_fm(2,0,1))))))"

lemma domain_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> domain_fm(x,y) ∈ formula"
  <proof>

lemma sats_domain_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
  ==> sats(A, domain_fm(x,y), env) <=>
    is_domain(##A, nth(x,env), nth(y,env))"
  <proof>

lemma domain_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]
  ==> is_domain(##A, x, y) <=> sats(A, domain_fm(i,j), env)"
  <proof>

theorem domain_reflection:
  "REFLECTS[λx. is_domain(L,f(x),g(x)),
    λi x. is_domain(##Lset(i),f(x),g(x))]"
  <proof>

```

10.4.14 Range of a Relation, Internalized

definition

```

range_fm :: "[i,i]=>i" where
  "range_fm(r,z) ==
    Forall(Iff(Member(0,succ(z)),
      Exists(And(Member(0,succ(succ(r))),
        Exists(pair_fm(0,2,1))))))"

lemma range_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> range_fm(x,y) ∈ formula"
  <proof>

```

```

lemma sats_range_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
  ==> sats(A, range_fm(x,y), env) <=>
    is_range(##A, nth(x,env), nth(y,env))"
  <proof>

```

```

lemma range_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]

```

```

    ==> is_range(##A, x, y) <=> sats(A, range_fm(i,j), env)"
<proof>

```

```

theorem range_reflection:
  "REFLECTS[λx. is_range(L,f(x),g(x)),
    λi x. is_range(##Lset(i),f(x),g(x))]"
<proof>

```

10.4.15 Field of a Relation, Internalized

definition

```

field_fm :: "[i,i]=>i" where
  "field_fm(r,z) ==
    Exists(And(domain_fm(succ(r),0),
      Exists(And(range_fm(succ(succ(r)),0),
        union_fm(1,0,succ(succ(z)))))))"

```

```

lemma field_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> field_fm(x,y) ∈ formula"
<proof>

```

```

lemma sats_field_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
    ==> sats(A, field_fm(x,y), env) <=>
      is_field(##A, nth(x,env), nth(y,env))"
<proof>

```

```

lemma field_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]
    ==> is_field(##A, x, y) <=> sats(A, field_fm(i,j), env)"
<proof>

```

```

theorem field_reflection:
  "REFLECTS[λx. is_field(L,f(x),g(x)),
    λi x. is_field(##Lset(i),f(x),g(x))]"
<proof>

```

10.4.16 Image under a Relation, Internalized

definition

```

image_fm :: "[i,i,i]=>i" where
  "image_fm(r,A,z) ==
    Forall(Iff(Member(0,succ(z)),
      Exists(And(Member(0,succ(succ(r))),
        Exists(And(Member(0,succ(succ(succ(A))))),
          pair_fm(0,2,1)))))))"

```

```

lemma image_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> image_fm(x,y,z) ∈ formula"

```

<proof>

```
lemma sats_image_fm [simp]:  
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]  
  ==> sats(A, image_fm(x,y,z), env) ⟷  
    image(##A, nth(x,env), nth(y,env), nth(z,env))"  
<proof>
```

```
lemma image_iff_sats:  
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;  
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]  
  ==> image(##A, x, y, z) ⟷ sats(A, image_fm(i,j,k), env)"  
<proof>
```

```
theorem image_reflection:  
  "REFLECTS[λx. image(L,f(x),g(x),h(x)),  
    λi x. image(##Lset(i),f(x),g(x),h(x))]"  
<proof>
```

10.4.17 Pre-Image under a Relation, Internalized

definition

```
pre_image_fm :: "[i,i,i]=>i" where  
  "pre_image_fm(r,A,z) ==  
    Forall(Iff(Member(0,succ(z)),  
      Exists(And(Member(0,succ(succ(r))),  
        Exists(And(Member(0,succ(succ(succ(A)))),  
          pair_fm(2,0,1)))))))"
```

```
lemma pre_image_type [TC]:  
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> pre_image_fm(x,y,z) ∈ formula"  
<proof>
```

```
lemma sats_pre_image_fm [simp]:  
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]  
  ==> sats(A, pre_image_fm(x,y,z), env) ⟷  
    pre_image(##A, nth(x,env), nth(y,env), nth(z,env))"  
<proof>
```

```
lemma pre_image_iff_sats:  
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;  
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]  
  ==> pre_image(##A, x, y, z) ⟷ sats(A, pre_image_fm(i,j,k), env)"  
<proof>
```

```
theorem pre_image_reflection:  
  "REFLECTS[λx. pre_image(L,f(x),g(x),h(x)),  
    λi x. pre_image(##Lset(i),f(x),g(x),h(x))]"  
<proof>
```

10.4.18 Function Application, Internalized

definition

```
fun_apply_fm :: "[i,i,i]=>i" where
  "fun_apply_fm(f,x,y) ==
    Exists(Exists(And(upair_fm(succ(succ(x)), succ(succ(x)), 1),
                        And(image_fm(succ(succ(f)), 1, 0),
                            big_union_fm(0,succ(succ(y)))))))"
```

lemma fun_apply_type [TC]:

```
"[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> fun_apply_fm(x,y,z) ∈ formula"
⟨proof⟩
```

lemma sats_fun_apply_fm [simp]:

```
"[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
==> sats(A, fun_apply_fm(x,y,z), env) ⟷
    fun_apply(##A, nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩
```

lemma fun_apply_iff_sats:

```
"[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
==> fun_apply(##A, x, y, z) ⟷ sats(A, fun_apply_fm(i,j,k), env)"
⟨proof⟩
```

theorem fun_apply_reflection:

```
"REFLECTS[λx. fun_apply(L,f(x),g(x),h(x)),
           λi x. fun_apply(##Lset(i),f(x),g(x),h(x))]"
⟨proof⟩
```

10.4.19 The Concept of Relation, Internalized

definition

```
relation_fm :: "[i=>i]" where
  "relation_fm(r) ==
    Forall(Implies(Member(0,succ(r)), Exists(Exists(pair_fm(1,0,2)))))"
```

lemma relation_type [TC]:

```
"[| x ∈ nat |] ==> relation_fm(x) ∈ formula"
⟨proof⟩
```

lemma sats_relation_fm [simp]:

```
"[| x ∈ nat; env ∈ list(A)|]
==> sats(A, relation_fm(x), env) ⟷ is_relation(##A, nth(x,env))"
⟨proof⟩
```

lemma relation_iff_sats:

```
"[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; env ∈ list(A)|]
==> is_relation(##A, x) ⟷ sats(A, relation_fm(i), env)"
```

<proof>

```
theorem is_relation_reflection:
  "REFLECTS[ $\lambda x. \text{is\_relation}(L, f(x)),$ 
     $\lambda i x. \text{is\_relation}(\#\text{Lset}(i), f(x))]$ "
<proof>
```

10.4.20 The Concept of Function, Internalized

definition

```
function_fm :: "i=>i" where
  "function_fm(r) ==
    Forall(Forall(Forall(Forall(Forall(
      Implies(pair_fm(4,3,1),
        Implies(pair_fm(4,2,0),
          Implies(Member(1,r#+5),
            Implies(Member(0,r#+5), Equal(3,2))))))))))"
```

```
lemma function_type [TC]:
  "[| x  $\in$  nat |] ==> function_fm(x)  $\in$  formula"
<proof>
```

```
lemma sats_function_fm [simp]:
  "[| x  $\in$  nat; env  $\in$  list(A) |]
    ==> sats(A, function_fm(x), env)  $\longleftrightarrow$  is_function( $\#\text{A}$ , nth(x,env))"
<proof>
```

```
lemma is_function_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i  $\in$  nat; env  $\in$  list(A) |]
    ==> is_function( $\#\text{A}$ , x)  $\longleftrightarrow$  sats(A, function_fm(i), env)"
<proof>
```

```
theorem is_function_reflection:
  "REFLECTS[ $\lambda x. \text{is\_function}(L, f(x)),$ 
     $\lambda i x. \text{is\_function}(\#\text{Lset}(i), f(x))]$ "
<proof>
```

10.4.21 Typed Functions, Internalized

definition

```
typed_function_fm :: "[i,i,i]=>i" where
  "typed_function_fm(A,B,r) ==
    And(function_fm(r),
      And(relation_fm(r),
        And(domain_fm(r,A),
          Forall(Implies(Member(0,succ(r)),
            Forall(Forall(Implies(pair_fm(1,0,2), Member(0,B#+3))))))))"
```

```
lemma typed_function_type [TC]:
```

```

    "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> typed_function_fm(x,y,z) ∈
formula"
⟨proof⟩

```

```

lemma sats_typed_function_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
  ==> sats(A, typed_function_fm(x,y,z), env) ⟷
    typed_function(##A, nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

```

```

lemma typed_function_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
  ==> typed_function(##A, x, y, z) ⟷ sats(A, typed_function_fm(i,j,k),
env)"
⟨proof⟩

```

```

lemmas function_reflections =
  empty_reflection number1_reflection
  upair_reflection pair_reflection union_reflection
  big_union_reflection cons_reflection successor_reflection
  fun_apply_reflection subset_reflection
  transitive_set_reflection membership_reflection
  pred_set_reflection domain_reflection range_reflection field_reflection
  image_reflection pre_image_reflection
  is_relation_reflection is_function_reflection

```

```

lemmas function_iff_sats =
  empty_iff_sats number1_iff_sats
  upair_iff_sats pair_iff_sats union_iff_sats
  big_union_iff_sats cons_iff_sats successor_iff_sats
  fun_apply_iff_sats Memrel_iff_sats
  pred_set_iff_sats domain_iff_sats range_iff_sats field_iff_sats
  image_iff_sats pre_image_iff_sats
  relation_iff_sats is_function_iff_sats

```

```

theorem typed_function_reflection:
  "REFLECTS[λx. typed_function(L,f(x),g(x),h(x)),
    λi x. typed_function(##Lset(i),f(x),g(x),h(x))]"
⟨proof⟩

```

10.4.22 Composition of Relations, Internalized

definition

```

composition_fm :: "[i,i,i]=>i" where
  "composition_fm(r,s,t) ==
    Forall(Iff(Member(0,succ(t)),
      Exists(Exists(Exists(Exists(Exists(

```

```

And(pair_fm(4,2,5),
And(pair_fm(4,3,1),
And(pair_fm(3,2,0),
And(Member(1,s#+6), Member(0,r#+6))))))))))"

lemma composition_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> composition_fm(x,y,z) ∈ formula"
  <proof>

lemma sats_composition_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
  ==> sats(A, composition_fm(x,y,z), env) <=>
    composition(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

lemma composition_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
  ==> composition(##A, x, y, z) <=> sats(A, composition_fm(i,j,k),
env)"
  <proof>

theorem composition_reflection:
  "REFLECTS[λx. composition(L,f(x),g(x),h(x)),
    λi x. composition(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

10.4.23 Injections, Internalized

definition

```

injection_fm :: "[i,i,i]=>i" where
  "injection_fm(A,B,f) ==
    And(typed_function_fm(A,B,f),
      Forall(Forall(Forall(Forall(
        Implies(pair_fm(4,2,1),
          Implies(pair_fm(3,2,0),
            Implies(Member(1,f#+5),
              Implies(Member(0,f#+5), Equal(4,3))))))))))"

```

```

lemma injection_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> injection_fm(x,y,z) ∈ formula"
  <proof>

```

```

lemma sats_injection_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
  ==> sats(A, injection_fm(x,y,z), env) <=>
    injection(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

```

```

lemma injection_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> injection(##A, x, y, z) ⟷ sats(A, injection_fm(i,j,k), env)"
⟨proof⟩

```

```

theorem injection_reflection:
  "REFLECTS[λx. injection(L,f(x),g(x),h(x)),
    λi x. injection(##Lset(i),f(x),g(x),h(x))]"
⟨proof⟩

```

10.4.24 Surjections, Internalized

```

definition
  surjection_fm :: "[i,i,i]=>i" where
  "surjection_fm(A,B,f) ==
    And(typed_function_fm(A,B,f),
      Forall(Implies(Member(0,succ(B)),
        Exists(And(Member(0,succ(succ(A))),
          fun_apply_fm(succ(succ(f)),0,1))))))"

```

```

lemma surjection_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> surjection_fm(x,y,z) ∈ formula"
⟨proof⟩

```

```

lemma sats_surjection_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, surjection_fm(x,y,z), env) ⟷
    surjection(##A, nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

```

```

lemma surjection_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> surjection(##A, x, y, z) ⟷ sats(A, surjection_fm(i,j,k), env)"
⟨proof⟩

```

```

theorem surjection_reflection:
  "REFLECTS[λx. surjection(L,f(x),g(x),h(x)),
    λi x. surjection(##Lset(i),f(x),g(x),h(x))]"
⟨proof⟩

```

10.4.25 Bijections, Internalized

```

definition
  bijection_fm :: "[i,i,i]=>i" where
  "bijection_fm(A,B,f) == And(injection_fm(A,B,f), surjection_fm(A,B,f))"

```

```

lemma bijection_type [TC]:

```

"[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> bijection_fm(x,y,z) ∈ formula"
 <proof>

lemma sats_bijection_fm [simp]:
 "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
 ==> sats(A, bijection_fm(x,y,z), env) ↔
 bijection(##A, nth(x,env), nth(y,env), nth(z,env))"
 <proof>

lemma bijection_iff_sats:
 "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
 i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
 ==> bijection(##A, x, y, z) ↔ sats(A, bijection_fm(i,j,k), env)"
 <proof>

theorem bijection_reflection:
 "REFLECTS[λx. bijection(L,f(x),g(x),h(x)),
 λi x. bijection(##Lset(i),f(x),g(x),h(x))]"
 <proof>

10.4.26 Restriction of a Relation, Internalized

definition
 restriction_fm :: "[i,i,i]=>i" where
 "restriction_fm(r,A,z) ==
 Forall(Iff(Member(0,succ(z)),
 And(Member(0,succ(r)),
 Exists(And(Member(0,succ(succ(A))),
 Exists(pair_fm(1,0,2))))))"

lemma restriction_type [TC]:
 "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> restriction_fm(x,y,z) ∈ formula"
 <proof>

lemma sats_restriction_fm [simp]:
 "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
 ==> sats(A, restriction_fm(x,y,z), env) ↔
 restriction(##A, nth(x,env), nth(y,env), nth(z,env))"
 <proof>

lemma restriction_iff_sats:
 "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
 i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
 ==> restriction(##A, x, y, z) ↔ sats(A, restriction_fm(i,j,k),
 env)"
 <proof>

theorem restriction_reflection:
 "REFLECTS[λx. restriction(L,f(x),g(x),h(x)),

$\lambda i x. \text{restriction}(\#\text{Lset}(i), f(x), g(x), h(x))]$ "

<proof>

10.4.27 Order-Isomorphisms, Internalized

definition

```
order_isomorphism_fm :: "[i,i,i,i,i]=>i" where
"order_isomorphism_fm(A,r,B,s,f) ==
And(bijection_fm(A,B,f),
Forall(Implies(Member(0,succ(A)),
Forall(Implies(Member(0,succ(succ(A))),
Forall(Forall(Forall(Forall(
Implies(pair_fm(5,4,3),
Implies(fun_apply_fm(f#+6,5,2),
Implies(fun_apply_fm(f#+6,4,1),
Implies(pair_fm(2,1,0),
Iff(Member(3,r#+6), Member(0,s#+6))))))))))))))"
```

lemma order_isomorphism_type [TC]:

"[| A ∈ nat; r ∈ nat; B ∈ nat; s ∈ nat; f ∈ nat |]
==> order_isomorphism_fm(A,r,B,s,f) ∈ formula"

<proof>

lemma sats_order_isomorphism_fm [simp]:

"[| U ∈ nat; r ∈ nat; B ∈ nat; s ∈ nat; f ∈ nat; env ∈ list(A) |]
==> sats(A, order_isomorphism_fm(U,r,B,s,f), env) ↔
order_isomorphism(##A, nth(U,env), nth(r,env), nth(B,env),
nth(s,env), nth(f,env))"

<proof>

lemma order_isomorphism_iff_sats:

"[| nth(i,env) = U; nth(j,env) = r; nth(k,env) = B; nth(j',env) = s;
nth(k',env) = f;
i ∈ nat; j ∈ nat; k ∈ nat; j' ∈ nat; k' ∈ nat; env ∈ list(A) |]
==> order_isomorphism(##A,U,r,B,s,f) ↔
sats(A, order_isomorphism_fm(i,j,k,j',k'), env)"

<proof>

theorem order_isomorphism_reflection:

"REFLECTS[$\lambda x. \text{order_isomorphism}(L, f(x), g(x), h(x), g'(x), h'(x))$,
 $\lambda i x. \text{order_isomorphism}(\#\text{Lset}(i), f(x), g(x), h(x), g'(x), h'(x))]$ "

<proof>

10.4.28 Limit Ordinals, Internalized

A limit ordinal is a non-empty, successor-closed ordinal

definition

```
limit_ordinal_fm :: "i=>i" where
"limit_ordinal_fm(x) ==
```

```

And(ordinal_fm(x),
  And(Neg(empty_fm(x)),
    Forall(Implies(Member(0,succ(x)),
      Exists(And(Member(0,succ(succ(x))),
        succ_fm(1,0)))))))"

lemma limit_ordinal_type [TC]:
  "x ∈ nat ==> limit_ordinal_fm(x) ∈ formula"
⟨proof⟩

lemma sats_limit_ordinal_fm [simp]:
  "[| x ∈ nat; env ∈ list(A) |]
  ==> sats(A, limit_ordinal_fm(x), env) ⟷ limit_ordinal(##A, nth(x,env))"
⟨proof⟩

lemma limit_ordinal_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; env ∈ list(A) |]
  ==> limit_ordinal(##A, x) ⟷ sats(A, limit_ordinal_fm(i), env)"
⟨proof⟩

theorem limit_ordinal_reflection:
  "REFLECTS[λx. limit_ordinal(L,f(x)),
    λi x. limit_ordinal(##Lset(i),f(x))]"
⟨proof⟩

```

10.4.29 Finite Ordinals: The Predicate “Is A Natural Number”

definition

```

finite_ordinal_fm :: "i=>i" where
  "finite_ordinal_fm(x) ==
    And(ordinal_fm(x),
      And(Neg(limit_ordinal_fm(x)),
        Forall(Implies(Member(0,succ(x)),
          Neg(limit_ordinal_fm(0))))))"

lemma finite_ordinal_type [TC]:
  "x ∈ nat ==> finite_ordinal_fm(x) ∈ formula"
⟨proof⟩

lemma sats_finite_ordinal_fm [simp]:
  "[| x ∈ nat; env ∈ list(A) |]
  ==> sats(A, finite_ordinal_fm(x), env) ⟷ finite_ordinal(##A, nth(x,env))"
⟨proof⟩

lemma finite_ordinal_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; env ∈ list(A) |]
  ==> finite_ordinal(##A, x) ⟷ sats(A, finite_ordinal_fm(i), env)"

```

<proof>

```
theorem finite_ordinal_reflection:
  "REFLECTS[ $\lambda x. \text{finite\_ordinal}(L, f(x))$ ,
     $\lambda i x. \text{finite\_ordinal}(\#\#L\text{set}(i), f(x))$ ]"
```

<proof>

10.4.30 Omega: The Set of Natural Numbers

definition

```
omega_fm :: "i=>i" where
  "omega_fm(x) ==
    And(limit_ordinal_fm(x),
      Forall(Implies(Member(0,succ(x)),
        Neg(limit_ordinal_fm(0)))))"
```

lemma omega_type [TC]:

```
"x  $\in$  nat ==> omega_fm(x)  $\in$  formula"
```

<proof>

lemma sats_omega_fm [simp]:

```
"[| x  $\in$  nat; env  $\in$  list(A)|]
==> sats(A, omega_fm(x), env)  $\longleftrightarrow$  omega( $\#\#A$ , nth(x,env))"
```

<proof>

lemma omega_iff_sats:

```
"[| nth(i,env) = x; nth(j,env) = y;
  i  $\in$  nat; env  $\in$  list(A)|]
==> omega( $\#\#A$ , x)  $\longleftrightarrow$  sats(A, omega_fm(i), env)"
```

<proof>

theorem omega_reflection:

```
"REFLECTS[ $\lambda x. \text{omega}(L, f(x))$ ,
   $\lambda i x. \text{omega}(\#\#L\text{set}(i), f(x))$ ]"
```

<proof>

lemmas fun_plus_reflections =

```
typed_function_reflection composition_reflection
injection_reflection surjection_reflection
bijection_reflection restriction_reflection
order_isomorphism_reflection finite_ordinal_reflection
ordinal_reflection limit_ordinal_reflection omega_reflection
```

lemmas fun_plus_iff_sats =

```
typed_function_iff_sats composition_iff_sats
injection_iff_sats surjection_iff_sats
bijection_iff_sats restriction_iff_sats
order_isomorphism_iff_sats finite_ordinal_iff_sats
```

```

ordinal_iff_sats limit_ordinal_iff_sats omega_iff_sats

end

```

11 Early Instances of Separation and Strong Replacement

```

theory Separation imports L_axioms WF_absolute begin

```

This theory proves all instances needed for locale M_{basic}

Helps us solve for de Bruijn indices!

```

lemma nth_ConsI: "[|nth(n,l) = x; n ∈ nat|] ==> nth(succ(n), Cons(a,l))
= x"
<proof>

```

```

lemmas nth_rules = nth_0 nth_ConsI nat_0I nat_succI
lemmas sep_rules = nth_0 nth_ConsI FOL_iff_sats function_iff_sats
fun_plus_iff_sats

```

```

lemma Collect_conj_in_DPow:
  "[| {x∈A. P(x)} ∈ DPow(A); {x∈A. Q(x)} ∈ DPow(A) |]
  ==> {x∈A. P(x) & Q(x)} ∈ DPow(A)"
<proof>

```

```

lemma Collect_conj_in_DPow_Lset:
  "[|z ∈ Lset(j); {x ∈ Lset(j). P(x)} ∈ DPow(Lset(j))|]
  ==> {x ∈ Lset(j). x ∈ z & P(x)} ∈ DPow(Lset(j))"
<proof>

```

```

lemma separation_CollectI:
  "( $\bigwedge z. L(z) \implies L(\{x \in z . P(x)\})$ ) ==> separation(L,  $\lambda x. P(x)$ )"
<proof>

```

Reduces the original comprehension to the reflected one

```

lemma reflection_imp_L_separation:
  "[|  $\forall x \in Lset(j). P(x) \longleftrightarrow Q(x)$ ;
    {x ∈ Lset(j) . Q(x)} ∈ DPow(Lset(j));
    Ord(j); z ∈ Lset(j) |] ==> L({x ∈ z . P(x)})"
<proof>

```

Encapsulates the standard proof script for proving instances of Separation.

```

lemma gen_separation:
  assumes reflection: "REFLECTS [P,Q]"
  and Lu: "L(u)"
  and collI: "!!j. u ∈ Lset(j)
    ==> Collect(Lset(j), Q(j)) ∈ DPow(Lset(j))"
  shows "separation(L,P)"

```

<proof>

As above, but typically u is a finite enumeration such as $\{a, b\}$; thus the new subgoal gets the assumption $\{a, b\} \subseteq Lset(i)$, which is logically equivalent to $a \in Lset(i)$ and $b \in Lset(i)$.

```
lemma gen_separation_multi:
  assumes reflection: "REFLECTS [P,Q]"
    and Lu:          "L(u)"
    and collI: "!!j. u  $\subseteq$  Lset(j)
                 $\implies$  Collect(Lset(j), Q(j))  $\in$  DPow(Lset(j))"
  shows "separation(L,P)"
<proof>
```

11.1 Separation for Intersection

```
lemma Inter_Reflects:
  "REFLECTS [ $\lambda x. \forall y[L]. y \in A \longrightarrow x \in y$ ,
              $\lambda i x. \forall y \in Lset(i). y \in A \longrightarrow x \in y$ ]"
<proof>
```

```
lemma Inter_separation:
  "L(A)  $\implies$  separation(L,  $\lambda x. \forall y[L]. y \in A \longrightarrow x \in y$ )"
<proof>
```

11.2 Separation for Set Difference

```
lemma Diff_Reflects:
  "REFLECTS [ $\lambda x. x \notin B$ ,  $\lambda i x. x \notin B$ ]"
<proof>
```

```
lemma Diff_separation:
  "L(B)  $\implies$  separation(L,  $\lambda x. x \notin B$ )"
<proof>
```

11.3 Separation for Cartesian Product

```
lemma cartprod_Reflects:
  "REFLECTS [ $\lambda z. \exists x[L]. x \in A \ \& \ (\exists y[L]. y \in B \ \& \ pair(L,x,y,z))$ ,
              $\lambda i z. \exists x \in Lset(i). x \in A \ \& \ (\exists y \in Lset(i). y \in B \ \& \ pair(\#Lset(i),x,y,z))$ ]"
<proof>
```

```
lemma cartprod_separation:
  "[| L(A); L(B) |]
    $\implies$  separation(L,  $\lambda z. \exists x[L]. x \in A \ \& \ (\exists y[L]. y \in B \ \& \ pair(L,x,y,z))$ )"
<proof>
```

11.4 Separation for Image

```
lemma image_Reflects:
```

"REFLECTS[$\lambda y. \exists p[L]. p \in r \ \& \ (\exists x[L]. x \in A \ \& \ \text{pair}(L, x, y, p))$],
 $\lambda i y. \exists p \in \text{Lset}(i). p \in r \ \& \ (\exists x \in \text{Lset}(i). x \in A \ \& \ \text{pair}(\#\text{Lset}(i), x, y, p))$]"
 <proof>

lemma image_separation:
 "[| L(A); L(r) |]
 ==> separation(L, $\lambda y. \exists p[L]. p \in r \ \& \ (\exists x[L]. x \in A \ \& \ \text{pair}(L, x, y, p))$)"
 <proof>

11.5 Separation for Converse

lemma converse_Reflects:
 "REFLECTS[$\lambda z. \exists p[L]. p \in r \ \& \ (\exists x[L]. \exists y[L]. \text{pair}(L, x, y, p) \ \& \ \text{pair}(L, y, x, z))$],
 $\lambda i z. \exists p \in \text{Lset}(i). p \in r \ \& \ (\exists x \in \text{Lset}(i). \exists y \in \text{Lset}(i). \text{pair}(\#\text{Lset}(i), x, y, p) \ \& \ \text{pair}(\#\text{Lset}(i), y, x, z))$]"
 <proof>

lemma converse_separation:
 "L(r) ==> separation(L,
 $\lambda z. \exists p[L]. p \in r \ \& \ (\exists x[L]. \exists y[L]. \text{pair}(L, x, y, p) \ \& \ \text{pair}(L, y, x, z))$)"
 <proof>

11.6 Separation for Restriction

lemma restrict_Reflects:
 "REFLECTS[$\lambda z. \exists x[L]. x \in A \ \& \ (\exists y[L]. \text{pair}(L, x, y, z))$],
 $\lambda i z. \exists x \in \text{Lset}(i). x \in A \ \& \ (\exists y \in \text{Lset}(i). \text{pair}(\#\text{Lset}(i), x, y, z))$]"
 <proof>

lemma restrict_separation:
 "L(A) ==> separation(L, $\lambda z. \exists x[L]. x \in A \ \& \ (\exists y[L]. \text{pair}(L, x, y, z))$)"
 <proof>

11.7 Separation for Composition

lemma comp_Reflects:
 "REFLECTS[$\lambda xz. \exists x[L]. \exists y[L]. \exists z[L]. \exists xy[L]. \exists yz[L].$
 $\text{pair}(L, x, z, xz) \ \& \ \text{pair}(L, x, y, xy) \ \& \ \text{pair}(L, y, z, yz) \ \&$
 $xy \in s \ \& \ yz \in r,$
 $\lambda i xz. \exists x \in \text{Lset}(i). \exists y \in \text{Lset}(i). \exists z \in \text{Lset}(i). \exists xy \in \text{Lset}(i). \exists yz \in \text{Lset}(i).$
 $\text{pair}(\#\text{Lset}(i), x, z, xz) \ \& \ \text{pair}(\#\text{Lset}(i), x, y, xy) \ \&$
 $\text{pair}(\#\text{Lset}(i), y, z, yz) \ \& \ xy \in s \ \& \ yz \in r$]"
 <proof>

lemma comp_separation:
 "[| L(r); L(s) |]
 ==> separation(L, $\lambda xz. \exists x[L]. \exists y[L]. \exists z[L]. \exists xy[L]. \exists yz[L].$
 $\text{pair}(L, x, z, xz) \ \& \ \text{pair}(L, x, y, xy) \ \& \ \text{pair}(L, y, z, yz) \ \&$
 $xy \in s \ \& \ yz \in r$)"
 <proof>

11.8 Separation for Predecessors in an Order

```

lemma pred_Reflects:
  "REFLECTS[ $\lambda y. \exists p[L]. p \in r \ \& \ \text{pair}(L, y, x, p),$ 
     $\lambda i \ y. \exists p \in \text{Lset}(i). p \in r \ \& \ \text{pair}(\#\text{Lset}(i), y, x, p)]$ "
<proof>

lemma pred_separation:
  "[ $L(r); L(x) \mid ] \implies \text{separation}(L, \lambda y. \exists p[L]. p \in r \ \& \ \text{pair}(L, y, x, p))$ "
<proof>

```

11.9 Separation for the Membership Relation

```

lemma Memrel_Reflects:
  "REFLECTS[ $\lambda z. \exists x[L]. \exists y[L]. \text{pair}(L, x, y, z) \ \& \ x \in y,$ 
     $\lambda i \ z. \exists x \in \text{Lset}(i). \exists y \in \text{Lset}(i). \text{pair}(\#\text{Lset}(i), x, y, z)$ 
     $\ \& \ x \in y]$ "
<proof>

lemma Memrel_separation:
  "separation(L,  $\lambda z. \exists x[L]. \exists y[L]. \text{pair}(L, x, y, z) \ \& \ x \in y$ )"
<proof>

```

11.10 Replacement for FunSpace

```

lemma funspace_succ_Reflects:
  "REFLECTS[ $\lambda z. \exists p[L]. p \in A \ \& \ (\exists f[L]. \exists b[L]. \exists nb[L]. \exists cnbf[L].$ 
     $\text{pair}(L, f, b, p) \ \& \ \text{pair}(L, n, b, nb) \ \& \ \text{is\_cons}(L, nb, f, cnbf) \ \&$ 
     $\text{upair}(L, cnbf, cnbf, z)),$ 
     $\lambda i \ z. \exists p \in \text{Lset}(i). p \in A \ \& \ (\exists f \in \text{Lset}(i). \exists b \in \text{Lset}(i).$ 
     $\exists nb \in \text{Lset}(i). \exists cnbf \in \text{Lset}(i).$ 
     $\text{pair}(\#\text{Lset}(i), f, b, p) \ \& \ \text{pair}(\#\text{Lset}(i), n, b, nb) \ \&$ 
     $\text{is\_cons}(\#\text{Lset}(i), nb, f, cnbf) \ \& \ \text{upair}(\#\text{Lset}(i), cnbf, cnbf, z))]$ "
<proof>

lemma funspace_succ_replacement:
  "L(n) ==>
    strong_replacement(L,  $\lambda p \ z. \exists f[L]. \exists b[L]. \exists nb[L]. \exists cnbf[L].$ 
     $\text{pair}(L, f, b, p) \ \& \ \text{pair}(L, n, b, nb) \ \& \ \text{is\_cons}(L, nb, f, cnbf)$ 
    &
     $\text{upair}(L, cnbf, cnbf, z))$ "
<proof>

```

11.11 Separation for a Theorem about is_recfun

```

lemma is_recfun_reflects:
  "REFLECTS[ $\lambda x. \exists xa[L]. \exists xb[L].$ 
     $\text{pair}(L, x, a, xa) \ \& \ xa \in r \ \& \ \text{pair}(L, x, b, xb) \ \& \ xb \in r \ \&$ 
     $(\exists fx[L]. \exists gx[L]. \text{fun\_apply}(L, f, x, fx) \ \& \ \text{fun\_apply}(L, g, x, gx)$ 
    &

```

```

                                fx ≠ gx),
    λi x. ∃ xa ∈ Lset(i). ∃ xb ∈ Lset(i).
        pair(##Lset(i),x,a,xa) & xa ∈ r & pair(##Lset(i),x,b,xb) & xb
∈ r &
        (∃ fx ∈ Lset(i). ∃ gx ∈ Lset(i). fun_apply(##Lset(i),f,x,fx)
&
        fun_apply(##Lset(i),g,x,gx) & fx ≠ gx)]"
⟨proof⟩

lemma is_recfun_separation:
  — for well-founded recursion
  "[| L(r); L(f); L(g); L(a); L(b) |]
  ==> separation(L,
    λx. ∃ xa[L]. ∃ xb[L].
      pair(L,x,a,xa) & xa ∈ r & pair(L,x,b,xb) & xb ∈ r &
      (∃ fx[L]. ∃ gx[L]. fun_apply(L,f,x,fx) & fun_apply(L,g,x,gx)
&
      fx ≠ gx))"
⟨proof⟩

```

11.12 Instantiating the locale M_{basic}

Separation (and Strong Replacement) for basic set-theoretic constructions such as intersection, Cartesian Product and image.

```

lemma M_basic_axioms_L: "M_basic_axioms(L)"
  ⟨proof⟩

```

```

theorem M_basic_L: " M_basic(L)"
  ⟨proof⟩

```

```

interpretation L: M_basic L ⟨proof⟩

```

end

```

theory Internalize imports L_axioms Datatype_absolute begin

```

11.13 Internalized Forms of Data Structuring Operators

11.13.1 The Formula is_Inl , Internalized

definition

```

Inl_fm :: "[i,i]=>i" where
  "Inl_fm(a,z) == Exists(And(empty_fm(0), pair_fm(0,succ(a),succ(z))))"

```

```

lemma Inl_type [TC]:

```

```

  "[| x ∈ nat; z ∈ nat |] ==> Inl_fm(x,z) ∈ formula"
  ⟨proof⟩

```

```

lemma sats_Inl_fm [simp]:
  "[| x ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, Inl_fm(x,z), env) ⟷ is_Inl(##A, nth(x,env), nth(z,env))"
⟨proof⟩

```

```

lemma Inl_iff_sats:
  "[| nth(i,env) = x; nth(k,env) = z;
    i ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_Inl(##A, x, z) ⟷ sats(A, Inl_fm(i,k), env)"
⟨proof⟩

```

```

theorem Inl_reflection:
  "REFLECTS[λx. is_Inl(L,f(x),h(x)),
    λi x. is_Inl(##Lset(i),f(x),h(x))]"
⟨proof⟩

```

11.13.2 The Formula *is_Inr*, Internalized

definition

```

Inr_fm :: "[i,i]=>i" where
  "Inr_fm(a,z) == Exists(And(number1_fm(0), pair_fm(0,succ(a),succ(z))))"

```

```

lemma Inr_type [TC]:
  "[| x ∈ nat; z ∈ nat |] ==> Inr_fm(x,z) ∈ formula"
⟨proof⟩

```

```

lemma sats_Inr_fm [simp]:
  "[| x ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, Inr_fm(x,z), env) ⟷ is_Inr(##A, nth(x,env), nth(z,env))"
⟨proof⟩

```

```

lemma Inr_iff_sats:
  "[| nth(i,env) = x; nth(k,env) = z;
    i ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_Inr(##A, x, z) ⟷ sats(A, Inr_fm(i,k), env)"
⟨proof⟩

```

```

theorem Inr_reflection:
  "REFLECTS[λx. is_Inr(L,f(x),h(x)),
    λi x. is_Inr(##Lset(i),f(x),h(x))]"
⟨proof⟩

```

11.13.3 The Formula *is_Nil*, Internalized

definition

```

Nil_fm :: "i=>i" where
  "Nil_fm(x) == Exists(And(empty_fm(0), Inl_fm(0,succ(x))))"

```

```

lemma Nil_type [TC]: "x ∈ nat ==> Nil_fm(x) ∈ formula"

```

<proof>

```
lemma sats_Nil_fm [simp]:  
  "[| x ∈ nat; env ∈ list(A) |]  
  ==> sats(A, Nil_fm(x), env) ⟷ is_Nil(##A, nth(x,env))"  
<proof>
```

```
lemma Nil_iff_sats:  
  "[| nth(i,env) = x; i ∈ nat; env ∈ list(A) |]  
  ==> is_Nil(##A, x) ⟷ sats(A, Nil_fm(i), env)"  
<proof>
```

```
theorem Nil_reflection:  
  "REFLECTS[λx. is_Nil(L,f(x)),  
    λi x. is_Nil(##Lset(i),f(x))]"  
<proof>
```

11.13.4 The Formula *is_Cons*, Internalized

definition

```
Cons_fm :: "[i,i,i]=>i" where  
  "Cons_fm(a,l,Z) ==  
    Exists(And(pair_fm(succ(a),succ(l),0), Inr_fm(0,succ(Z))))"
```

```
lemma Cons_type [TC]:  
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> Cons_fm(x,y,z) ∈ formula"  
<proof>
```

```
lemma sats_Cons_fm [simp]:  
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]  
  ==> sats(A, Cons_fm(x,y,z), env) ⟷  
    is_Cons(##A, nth(x,env), nth(y,env), nth(z,env))"  
<proof>
```

```
lemma Cons_iff_sats:  
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;  
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]  
  ==> is_Cons(##A, x, y, z) ⟷ sats(A, Cons_fm(i,j,k), env)"  
<proof>
```

```
theorem Cons_reflection:  
  "REFLECTS[λx. is_Cons(L,f(x),g(x),h(x)),  
    λi x. is_Cons(##Lset(i),f(x),g(x),h(x))]"  
<proof>
```

11.13.5 The Formula *is_quaselist*, Internalized

definition

```
quaselist_fm :: "i=>i" where  
  "quaselist_fm(x) ==
```

```

Or( Nil_fm(x), Exists(Exists(Cons_fm(1,0,succ(succ(x))))))"

lemma quasilist_type [TC]: "x ∈ nat ==> quasilist_fm(x) ∈ formula"
⟨proof⟩

lemma sats_quasilist_fm [simp]:
  "[| x ∈ nat; env ∈ list(A)|]
  ==> sats(A, quasilist_fm(x), env) ⟷ is_quasilist(##A, nth(x,env))"
⟨proof⟩

lemma quasilist_iff_sats:
  "[| nth(i,env) = x; i ∈ nat; env ∈ list(A)|]
  ==> is_quasilist(##A, x) ⟷ sats(A, quasilist_fm(i), env)"
⟨proof⟩

theorem quasilist_reflection:
  "REFLECTS[λx. is_quasilist(L,f(x)),
    λi x. is_quasilist(##Lset(i),f(x))]"
⟨proof⟩

11.14 Absoluteness for the Function nth

11.14.1 The Formula is_hd, Internalized

definition
  hd_fm :: "[i,i]=>i" where
    "hd_fm(xs,H) ==
      And(Implies(Nil_fm(xs), empty_fm(H)),
        And(Forall(Forall(Or(Neg(Cons_fm(1,0,xs#+2)), Equal(H#+2,1)))),
          Or(quasilist_fm(xs), empty_fm(H))))"

lemma hd_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> hd_fm(x,y) ∈ formula"
⟨proof⟩

lemma sats_hd_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A)|]
  ==> sats(A, hd_fm(x,y), env) ⟷ is_hd(##A, nth(x,env), nth(y,env))"
⟨proof⟩

lemma hd_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A)|]
  ==> is_hd(##A, x, y) ⟷ sats(A, hd_fm(i,j), env)"
⟨proof⟩

theorem hd_reflection:
  "REFLECTS[λx. is_hd(L,f(x),g(x)),
    λi x. is_hd(##Lset(i),f(x),g(x))]"
⟨proof⟩

```

11.14.2 The Formula *is_tl*, Internalized

definition

```
tl_fm :: "[i,i]>=>i" where
  "tl_fm(xs,T) ==
    And(Implies(Nil_fm(xs), Equal(T,xs)),
      And(Forall(Forall(Or(Neg(Cons_fm(1,0,xs#+2)), Equal(T#+2,0)))),
        Or(quasilist_fm(xs), empty_fm(T))))"
```

lemma *tl_type* [TC]:

```
"[| x ∈ nat; y ∈ nat |] ==> tl_fm(x,y) ∈ formula"
⟨proof⟩
```

lemma *sats_tl_fm* [simp]:

```
"[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
==> sats(A, tl_fm(x,y), env) ⟷ is_tl(##A, nth(x,env), nth(y,env))"
⟨proof⟩
```

lemma *tl_iff_sats*:

```
"[| nth(i,env) = x; nth(j,env) = y;
  i ∈ nat; j ∈ nat; env ∈ list(A) |]
==> is_tl(##A, x, y) ⟷ sats(A, tl_fm(i,j), env)"
⟨proof⟩
```

theorem *tl_reflection*:

```
"REFLECTS[λx. is_tl(L,f(x),g(x)),
  λi x. is_tl(##Lset(i),f(x),g(x))]"
⟨proof⟩
```

11.14.3 The Operator *is_bool_of_o*

The formula *p* has no free variables.

definition

```
bool_of_o_fm :: "[i, i]>=>i" where
  "bool_of_o_fm(p,z) ==
    Or(And(p,number1_fm(z)),
      And(Neg(p),empty_fm(z)))"
```

lemma *is_bool_of_o_type* [TC]:

```
"[| p ∈ formula; z ∈ nat |] ==> bool_of_o_fm(p,z) ∈ formula"
⟨proof⟩
```

lemma *sats_bool_of_o_fm*:

```
assumes p_iff_sats: "P ⟷ sats(A, p, env)"
shows
  "[| z ∈ nat; env ∈ list(A) |]
  ==> sats(A, bool_of_o_fm(p,z), env) ⟷
    is_bool_of_o(##A, P, nth(z,env))"
⟨proof⟩
```

```

lemma is_bool_of_o_iff_sats:
  "[| P  $\longleftrightarrow$  sats(A, p, env); nth(k,env) = z; k  $\in$  nat; env  $\in$  list(A) |]
  ==> is_bool_of_o(##A, P, z)  $\longleftrightarrow$  sats(A, bool_of_o_fm(p,k), env)"
  <proof>

```

```

theorem bool_of_o_reflection:
  "REFLECTS [P(L),  $\lambda i$ . P(##Lset(i))] ==>
  REFLECTS [ $\lambda x$ . is_bool_of_o(L, P(L,x), f(x)),
   $\lambda i$  x. is_bool_of_o(##Lset(i), P(##Lset(i),x), f(x))]"
  <proof>

```

11.15 More Internalizations

11.15.1 The Operator *is_lambda*

The two arguments of *p* are always 1, 0. Remember that *p* will be enclosed by three quantifiers.

definition

```

lambda_fm :: "[i, i, i] => i" where
  "lambda_fm(p,A,z) ==
  Forall(Iff(Member(0,succ(z)),
    Exists(Exists(And(Member(1,A#+3),
      And(pair_fm(1,0,2), p))))))"

```

We call *p* with arguments *x*, *y* by equating them with the corresponding quantified variables with de Bruijn indices 1, 0.

```

lemma is_lambda_type [TC]:
  "[| p  $\in$  formula; x  $\in$  nat; y  $\in$  nat |]
  ==> lambda_fm(p,x,y)  $\in$  formula"
  <proof>

```

```

lemma sats_lambda_fm:
  assumes is_b_iff_sats:
    "!!a0 a1 a2.
    [|a0 $\in$ A; a1 $\in$ A; a2 $\in$ A|]
    ==> is_b(a1, a0)  $\longleftrightarrow$  sats(A, p, Cons(a0,Cons(a1,Cons(a2,env))))"
  shows
    "[|x  $\in$  nat; y  $\in$  nat; env  $\in$  list(A)|]
    ==> sats(A, lambda_fm(p,x,y), env)  $\longleftrightarrow$ 
    is_lambda(##A, nth(x,env), is_b, nth(y,env))"
  <proof>

```

```

theorem is_lambda_reflection:
  assumes is_b_reflection:
    "!!f g h. REFLECTS [ $\lambda x$ . is_b(L, f(x), g(x), h(x)),
     $\lambda i$  x. is_b(##Lset(i), f(x), g(x), h(x))]"
  shows "REFLECTS [ $\lambda x$ . is_lambda(L, A(x), is_b(L,x), f(x)),
     $\lambda i$  x. is_lambda(##Lset(i), A(x), is_b(##Lset(i),x), f(x))]"

```

<proof>

11.15.2 The Operator *is_Member*, Internalized

definition

```
Member_fm :: "[i,i,i]=>i" where
  "Member_fm(x,y,Z) ==
    Exists(Exists(And(pair_fm(x#+2,y#+2,1),
      And(Inl_fm(1,0), Inl_fm(0,Z#+2))))))"
```

lemma *is_Member_type* [TC]:

```
"[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> Member_fm(x,y,z) ∈ formula"
```

<proof>

lemma *sats_Member_fm* [simp]:

```
"[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
==> sats(A, Member_fm(x,y,z), env) <=>
  is_Member(##A, nth(x,env), nth(y,env), nth(z,env))"
```

<proof>

lemma *Member_iff_sats*:

```
"[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
  i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
==> is_Member(##A, x, y, z) <=> sats(A, Member_fm(i,j,k), env)"
```

<proof>

theorem *Member_reflection*:

```
"REFLECTS[λx. is_Member(L,f(x),g(x),h(x)),
  λi x. is_Member(##Lset(i),f(x),g(x),h(x))]"
```

<proof>

11.15.3 The Operator *is_Equal*, Internalized

definition

```
Equal_fm :: "[i,i,i]=>i" where
  "Equal_fm(x,y,Z) ==
    Exists(Exists(And(pair_fm(x#+2,y#+2,1),
      And(Inr_fm(1,0), Inl_fm(0,Z#+2))))))"
```

lemma *is_Equal_type* [TC]:

```
"[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> Equal_fm(x,y,z) ∈ formula"
```

<proof>

lemma *sats_Equal_fm* [simp]:

```
"[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
==> sats(A, Equal_fm(x,y,z), env) <=>
  is_Equal(##A, nth(x,env), nth(y,env), nth(z,env))"
```

<proof>

lemma *Equal_iff_sats*:

```

    "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
      i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
    ==> is_Equal(##A, x, y, z) <=> sats(A, Equal_fm(i,j,k), env)"
  <proof>

```

theorem *Equal_reflection*:

```

    "REFLECTS[λx. is_Equal(L,f(x),g(x),h(x)),
      λi x. is_Equal(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

11.15.4 The Operator *is_Nand*, Internalized

definition

```

  Nand_fm :: "[i,i,i]=>i" where
    "Nand_fm(x,y,Z) ==
      Exists(Exists(And(pair_fm(x#+2,y#+2,1),
        And(Inl_fm(1,0), Inr_fm(0,Z#+2))))))"

```

lemma *is_Nand_type* [TC]:

```

    "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> Nand_fm(x,y,z) ∈ formula"
  <proof>

```

lemma *sats_Nand_fm* [simp]:

```

    "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
    ==> sats(A, Nand_fm(x,y,z), env) <=>
      is_Nand(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

```

lemma *Nand_iff_sats*:

```

    "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
      i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
    ==> is_Nand(##A, x, y, z) <=> sats(A, Nand_fm(i,j,k), env)"
  <proof>

```

theorem *Nand_reflection*:

```

    "REFLECTS[λx. is_Nand(L,f(x),g(x),h(x)),
      λi x. is_Nand(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

11.15.5 The Operator *is_Forall*, Internalized

definition

```

  Forall_fm :: "[i,i]=>i" where
    "Forall_fm(x,Z) ==
      Exists(And(Inr_fm(succ(x),0), Inr_fm(0,succ(Z))))"

```

lemma *is_Forall_type* [TC]:

```

    "[| x ∈ nat; y ∈ nat |] ==> Forall_fm(x,y) ∈ formula"
  <proof>

```

```

lemma sats_Forall_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
  ==> sats(A, Forall_fm(x,y), env) ⟷
    is_Forall(##A, nth(x,env), nth(y,env))"
  <proof>

lemma Forall_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]
  ==> is_Forall(##A, x, y) ⟷ sats(A, Forall_fm(i,j), env)"
  <proof>

theorem Forall_reflection:
  "REFLECTS[λx. is_Forall(L,f(x),g(x)),
    λi x. is_Forall(##Lset(i),f(x),g(x))]"
  <proof>

```

11.15.6 The Operator *is_and*, Internalized

definition

```

and_fm :: "[i,i,i]=>i" where
  "and_fm(a,b,z) ==
    Or(And(number1_fm(a), Equal(z,b)),
      And(Neg(number1_fm(a)), empty_fm(z)))"

```

```

lemma is_and_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> and_fm(x,y,z) ∈ formula"
  <proof>

```

```

lemma sats_and_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, and_fm(x,y,z), env) ⟷
    is_and(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

```

```

lemma is_and_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_and(##A, x, y, z) ⟷ sats(A, and_fm(i,j,k), env)"
  <proof>

```

```

theorem is_and_reflection:
  "REFLECTS[λx. is_and(L,f(x),g(x),h(x)),
    λi x. is_and(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

11.15.7 The Operator *is_or*, Internalized

definition

```

or_fm :: "[i,i,i]=>i" where

```

```

"or_fm(a,b,z) ==
  Or(And(number1_fm(a), number1_fm(z)),
    And(Neg(number1_fm(a)), Equal(z,b)))"

lemma is_or_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> or_fm(x,y,z) ∈ formula"
⟨proof⟩

lemma sats_or_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, or_fm(x,y,z), env) ⟷
    is_or(##A, nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

lemma is_or_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_or(##A, x, y, z) ⟷ sats(A, or_fm(i,j,k), env)"
⟨proof⟩

theorem is_or_reflection:
  "REFLECTS[λx. is_or(L,f(x),g(x),h(x)),
    λi x. is_or(##Lset(i),f(x),g(x),h(x))]"
⟨proof⟩

```

11.15.8 The Operator *is_not*, Internalized

definition

```

not_fm :: "[i,i]=>i" where
  "not_fm(a,z) ==
    Or(And(number1_fm(a), empty_fm(z)),
      And(Neg(number1_fm(a)), number1_fm(z)))"

```

```

lemma is_not_type [TC]:
  "[| x ∈ nat; z ∈ nat |] ==> not_fm(x,z) ∈ formula"
⟨proof⟩

```

```

lemma sats_is_not_fm [simp]:
  "[| x ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, not_fm(x,z), env) ⟷ is_not(##A, nth(x,env), nth(z,env))"
⟨proof⟩

```

```

lemma is_not_iff_sats:
  "[| nth(i,env) = x; nth(k,env) = z;
    i ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_not(##A, x, z) ⟷ sats(A, not_fm(i,k), env)"
⟨proof⟩

```

theorem *is_not_reflection*:

```

"REFLECTS[ $\lambda x. \text{is\_not}(L, f(x), g(x)),$ 
 $\lambda i x. \text{is\_not}(\#\#L\text{set}(i), f(x), g(x))]$ "
<proof>

```

```

lemmas extra_reflections =
  Inl_reflection Inr_reflection Nil_reflection Cons_reflection
  quasilist_reflection hd_reflection tl_reflection bool_of_o_reflection
  is_lambda_reflection Member_reflection Equal_reflection Nand_reflection
  Forall_reflection is_and_reflection is_or_reflection is_not_reflection

```

11.16 Well-Founded Recursion!

11.16.1 The Operator $M_{\text{is_recfun}}$

Alternative definition, minimizing nesting of quantifiers around MH

```

lemma M_is_recfun_iff:
  "M_is_recfun(M, MH, r, a, f)  $\longleftrightarrow$ 
  ( $\forall z[M]. z \in f \longleftrightarrow$ 
  ( $\exists x[M]. \exists f\_r\_sx[M]. \exists y[M].$ 
  MH(x, f_r_sx, y) & pair(M, x, y, z) &
  ( $\exists xa[M]. \exists sx[M]. \exists r\_sx[M].$ 
  pair(M, x, a, xa) & upair(M, x, x, sx) &
  pre_image(M, r, sx, r_sx) & restriction(M, f, r_sx, f_r_sx) &
  xa  $\in$  r)))")
<proof>

```

The three arguments of p are always 2, 1, 0 and z

definition

```

is_recfun_fm :: "[i, i, i, i] => i" where
  "is_recfun_fm(p, r, a, f) ==
  Forall(Iff(Member(0, succ(f)),
  Exists(Exists(Exists(
  And(p,
  And(pair_fm(2, 0, 3),
  Exists(Exists(Exists(
  And(pair_fm(5, a#+7, 2),
  And(upair_fm(5, 5, 1),
  And(pre_image_fm(r#+7, 1, 0),
  And(restriction_fm(f#+7, 0, 4), Member(2, r#+7))))))))))))))"

```

```

lemma is_recfun_type [TC]:
  "[| p  $\in$  formula; x  $\in$  nat; y  $\in$  nat; z  $\in$  nat |]
  ==> is_recfun_fm(p, x, y, z)  $\in$  formula"
<proof>

```

```

lemma sats_is_recfun_fm:
  assumes MH_iff_sats:

```

```

    "!!a0 a1 a2 a3.
      [/a0∈A; a1∈A; a2∈A; a3∈A/]
      ==> MH(a2, a1, a0) <=> sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,env))))))"
  shows
    "[/x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)/]
    ==> sats(A, is_recfun_fm(p,x,y,z), env) <=>
      M_is_recfun(##A, MH, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

lemma is_recfun_iff_sats:
  assumes MH_iff_sats:
    "!!a0 a1 a2 a3.
      [/a0∈A; a1∈A; a2∈A; a3∈A/]
      ==> MH(a2, a1, a0) <=> sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,env))))))"
  shows
    "[/ nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
      i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)/]
    ==> M_is_recfun(##A, MH, x, y, z) <=> sats(A, is_recfun_fm(p,i,j,k),
env)"
  <proof>

```

The additional variable in the premise, namely f' , is essential. It lets MH depend upon x , which seems often necessary. The same thing occurs in $is_wfrec_reflection$.

```

theorem is_recfun_reflection:
  assumes MH_reflection:
    "!!f' f g h. REFLECTS[λx. MH(L, f'(x), f(x), g(x), h(x)),
      λi x. MH(##Lset(i), f'(x), f(x), g(x), h(x))]"
  shows "REFLECTS[λx. M_is_recfun(L, MH(L,x), f(x), g(x), h(x)),
    λi x. M_is_recfun(##Lset(i), MH(##Lset(i),x), f(x), g(x),
h(x))]"
  <proof>

```

11.16.2 The Operator is_wfrec

The three arguments of p are always 2, 1, 0; p is enclosed by 5 quantifiers.

definition

```

is_wfrec_fm :: "[i, i, i, i] => i" where
  "is_wfrec_fm(p,r,a,z) ==
    Exists(And(is_recfun_fm(p, succ(r), succ(a), 0),
      Exists(Exists(Exists(Exists(
        And(Equal(2,a#+5), And(Equal(1,4), And(Equal(0,z#+5), p))))))))"

```

We call p with arguments a, f, z by equating them with the corresponding quantified variables with de Bruijn indices 2, 1, 0.

There's an additional existential quantifier to ensure that the environments in both calls to MH have the same length.

```

lemma is_wfrec_type [TC]:
  "[| p ∈ formula; x ∈ nat; y ∈ nat; z ∈ nat |]
   ==> is_wfrec_fm(p,x,y,z) ∈ formula"
⟨proof⟩

lemma sats_is_wfrec_fm:
  assumes MH_iff_sats:
    "!!a0 a1 a2 a3 a4.
     [|a0∈A; a1∈A; a2∈A; a3∈A; a4∈A|]
     ==> MH(a2, a1, a0) ⟷ sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,Cons(a4,env))))))"
  shows
    "[|x ∈ nat; y < length(env); z < length(env); env ∈ list(A)|]
     ==> sats(A, is_wfrec_fm(p,x,y,z), env) ⟷
        is_wfrec(##A, MH, nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

lemma is_wfrec_iff_sats:
  assumes MH_iff_sats:
    "!!a0 a1 a2 a3 a4.
     [|a0∈A; a1∈A; a2∈A; a3∈A; a4∈A|]
     ==> MH(a2, a1, a0) ⟷ sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,Cons(a4,env))))))"
  shows
    "[|nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
     i ∈ nat; j < length(env); k < length(env); env ∈ list(A)|]
     ==> is_wfrec(##A, MH, x, y, z) ⟷ sats(A, is_wfrec_fm(p,i,j,k), env)"
⟨proof⟩

theorem is_wfrec_reflection:
  assumes MH_reflection:
    "!!f' f g h. REFLECTS[λx. MH(L, f'(x), f(x), g(x), h(x)),
                           λi x. MH(##Lset(i), f'(x), f(x), g(x), h(x))]"
  shows "REFLECTS[λx. is_wfrec(L, MH(L,x), f(x), g(x), h(x)),
                  λi x. is_wfrec(##Lset(i), MH(##Lset(i),x), f(x), g(x),
h(x))]"
⟨proof⟩

```

11.17 For Datatypes

11.17.1 Binary Products, Internalized

definition

cartprod_fm :: "[i,i,i]=>i" where

```

"cartprod_fm(A,B,z) ==
  Forall(Iff(Member(0,succ(z)),
               Exists(And(Member(0,succ(succ(A))),
                           Exists(And(Member(0,succ(succ(succ(B))))),
                                       pair_fm(1,0,2)))))))"

```

```

lemma cartprod_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> cartprod_fm(x,y,z) ∈ formula"
  <proof>

```

```

lemma sats_cartprod_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, cartprod_fm(x,y,z), env) ⟷
    cartprod(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

```

```

lemma cartprod_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> cartprod(##A, x, y, z) ⟷ sats(A, cartprod_fm(i,j,k), env)"
  <proof>

```

```

theorem cartprod_reflection:
  "REFLECTS[λx. cartprod(L,f(x),g(x),h(x)),
    λi x. cartprod(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

11.17.2 Binary Sums, Internalized

definition

```

sum_fm :: "[i,i,i]=>i" where
  "sum_fm(A,B,Z) ==
    Exists(Exists(Exists(Exists(
      And(number1_fm(2),
        And(cartprod_fm(2,A#+4,3),
          And(upair_fm(2,2,1),
            And(cartprod_fm(1,B#+4,0), union_fm(3,0,Z#+4))))))))))"

```

```

lemma sum_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> sum_fm(x,y,z) ∈ formula"
  <proof>

```

```

lemma sats_sum_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, sum_fm(x,y,z), env) ⟷
    is_sum(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

```

```

lemma sum_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_sum(##A, x, y, z) ⟷ sats(A, sum_fm(i,j,k), env)"
  <proof>

```

```

theorem sum_reflection:
  "REFLECTS[ $\lambda x. \text{is\_sum}(L, f(x), g(x), h(x)),$ 
     $\lambda i x. \text{is\_sum}(\#\#Lset(i), f(x), g(x), h(x))$ ]"
  <proof>

```

11.17.3 The Operator *quasinat*

definition

```

quasinat_fm :: "i=>i" where
  "quasinat_fm(z) == Or(empty_fm(z), Exists(succ_fm(0, succ(z))))"

```

lemma quasinat_type [TC]:

```

"x ∈ nat ==> quasinat_fm(x) ∈ formula"
  <proof>

```

lemma sats_quasinat_fm [simp]:

```

"[| x ∈ nat; env ∈ list(A) |]
  ==> sats(A, quasinat_fm(x), env) <=> is_quasinat(\#A, nth(x, env))"
  <proof>

```

lemma quasinat_iff_sats:

```

"[| nth(i, env) = x; nth(j, env) = y;
  i ∈ nat; env ∈ list(A) |]
  ==> is_quasinat(\#A, x) <=> sats(A, quasinat_fm(i), env)"
  <proof>

```

theorem quasinat_reflection:

```

"REFLECTS[ $\lambda x. \text{is\_quasinat}(L, f(x)),$ 
   $\lambda i x. \text{is\_quasinat}(\#\#Lset(i), f(x))$ ]"
  <proof>

```

11.17.4 The Operator *is_nat_case*

I could not get it to work with the more natural assumption that *is_b* takes two arguments. Instead it must be a formula where 1 and 0 stand for *m* and *b*, respectively.

The formula *is_b* has free variables 1 and 0.

definition

```

is_nat_case_fm :: "[i, i, i, i]=>i" where
  "is_nat_case_fm(a, is_b, k, z) ==
    And(Implies(empty_fm(k), Equal(z, a)),
      And(Forall(Implies(succ_fm(0, succ(k)),
        Forall(Implies(Equal(0, succ(succ(z))), is_b)))),
        Or(quasinat_fm(k), empty_fm(z))))"

```

lemma is_nat_case_type [TC]:

```

"[| is_b ∈ formula;
  x ∈ nat; y ∈ nat; z ∈ nat |]

```

```

    ==> is_nat_case_fm(x, is_b, y, z) ∈ formula"
  <proof>

lemma sats_is_nat_case_fm:
  assumes is_b_iff_sats:
    "!!a. a ∈ A ==> is_b(a, nth(z, env)) ⟷
      sats(A, p, Cons(nth(z, env), Cons(a, env)))"
  shows
    "[| x ∈ nat; y ∈ nat; z < length(env); env ∈ list(A) |]
    ==> sats(A, is_nat_case_fm(x, p, y, z), env) ⟷
      is_nat_case(##A, nth(x, env), is_b, nth(y, env), nth(z, env))"
  <proof>

lemma is_nat_case_iff_sats:
  "[| (!!a. a ∈ A ==> is_b(a, z) ⟷
      sats(A, p, Cons(z, Cons(a, env))));
    nth(i, env) = x; nth(j, env) = y; nth(k, env) = z;
    i ∈ nat; j ∈ nat; k < length(env); env ∈ list(A) |]
  ==> is_nat_case(##A, x, is_b, y, z) ⟷ sats(A, is_nat_case_fm(i, p, j, k),
  env)"
  <proof>

```

The second argument of *is_b* gives it direct access to *x*, which is essential for handling free variable references. Without this argument, we cannot prove reflection for *iterates_MH*.

```

theorem is_nat_case_reflection:
  assumes is_b_reflection:
    "!!h f g. REFLECTS[λx. is_b(L, h(x), f(x), g(x)),
      λi x. is_b(##Lset(i), h(x), f(x), g(x))]"
  shows "REFLECTS[λx. is_nat_case(L, f(x), is_b(L, x), g(x), h(x)),
    λi x. is_nat_case(##Lset(i), f(x), is_b(##Lset(i), x),
    g(x), h(x))]"
  <proof>

```

11.18 The Operator *iterates_MH*, Needed for Iteration

definition

```

  iterates_MH_fm :: "[i, i, i, i, i] => i" where
  "iterates_MH_fm(isF, v, n, g, z) ==
    is_nat_case_fm(v,
      Exists(And(fun_apply_fm(succ(succ(succ(g))), 2, 0),
        Forall(Implies(Equal(0, 2), isF)))),
    n, z)"

```

lemma *iterates_MH_type* [TC]:

```

  "[| p ∈ formula;
    v ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat |]
  ==> iterates_MH_fm(p, v, x, y, z) ∈ formula"
  <proof>

```

```

lemma sats_iterates_MH_fm:
  assumes is_F_iff_sats:
    "!!a b c d. [| a ∈ A; b ∈ A; c ∈ A; d ∈ A |]
      ==> is_F(a,b) <=>
        sats(A, p, Cons(b, Cons(a, Cons(c, Cons(d,env)))))"
  shows
    "[| v ∈ nat; x ∈ nat; y ∈ nat; z < length(env); env ∈ list(A) |]
      ==> sats(A, iterates_MH_fm(p,v,x,y,z), env) <=>
        iterates_MH(##A, is_F, nth(v,env), nth(x,env), nth(y,env),
nth(z,env))"
  <proof>

lemma iterates_MH_iff_sats:
  assumes is_F_iff_sats:
    "!!a b c d. [| a ∈ A; b ∈ A; c ∈ A; d ∈ A |]
      ==> is_F(a,b) <=>
        sats(A, p, Cons(b, Cons(a, Cons(c, Cons(d,env)))))"
  shows
    "[| nth(i',env) = v; nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;

        i' ∈ nat; i ∈ nat; j ∈ nat; k < length(env); env ∈ list(A) |]
      ==> iterates_MH(##A, is_F, v, x, y, z) <=>
        sats(A, iterates_MH_fm(p,i',i,j,k), env)"
  <proof>

```

The second argument of p gives it direct access to x , which is essential for handling free variable references. Without this argument, we cannot prove reflection for $list_N$.

```

theorem iterates_MH_reflection:
  assumes p_reflection:
    "!!f g h. REFLECTS[λx. p(L, h(x), f(x), g(x)),
      λi x. p(##Lset(i), h(x), f(x), g(x))]"
  shows "REFLECTS[λx. iterates_MH(L, p(L,x), e(x), f(x), g(x), h(x)),
    λi x. iterates_MH(##Lset(i), p(##Lset(i),x), e(x), f(x),
g(x), h(x))]"
  <proof>

```

11.18.1 The Operator $is_iterates$

The three arguments of p are always 2, 1, 0; p is enclosed by 9 (??) quantifiers.

definition

```

is_iterates_fm :: "[i, i, i, i] => i" where
  "is_iterates_fm(p,v,n,Z) ==
    Exists(Exists(
      And(succ_fm(n#+2,1),
        And(Memrel_fm(1,0),

```

```
is_wfrec_fm(iterates_MH_fm(p, v#+7, 2, 1, 0),
            0, n#+2, Z#+2))))))"
```

We call p with arguments a, f, z by equating them with the corresponding quantified variables with de Bruijn indices 2, 1, 0.

lemma *is_iterates_type* [TC]:

```
"[| p ∈ formula; x ∈ nat; y ∈ nat; z ∈ nat |]
==> is_iterates_fm(p,x,y,z) ∈ formula"
```

⟨proof⟩

lemma *sats_is_iterates_fm*:

assumes *is_F_iff_sats*:

```
"!!a b c d e f g h i j k.
```

```
[| a ∈ A; b ∈ A; c ∈ A; d ∈ A; e ∈ A; f ∈ A;
  g ∈ A; h ∈ A; i ∈ A; j ∈ A; k ∈ A|]
```

```
==> is_F(a,b) ⟷
```

```
sats(A, p, Cons(b, Cons(a, Cons(c, Cons(d, Cons(e, Cons(f,
```

```
Cons(g, Cons(h, Cons(i, Cons(j, Cons(k, env))))))))))"
```

shows

```
"[| x ∈ nat; y < length(env); z < length(env); env ∈ list(A)|]
```

```
==> sats(A, is_iterates_fm(p,x,y,z), env) ⟷
```

```
is_iterates(##A, is_F, nth(x,env), nth(y,env), nth(z,env))"
```

⟨proof⟩

lemma *is_iterates_iff_sats*:

assumes *is_F_iff_sats*:

```
"!!a b c d e f g h i j k.
```

```
[| a ∈ A; b ∈ A; c ∈ A; d ∈ A; e ∈ A; f ∈ A;
  g ∈ A; h ∈ A; i ∈ A; j ∈ A; k ∈ A|]
```

```
==> is_F(a,b) ⟷
```

```
sats(A, p, Cons(b, Cons(a, Cons(c, Cons(d, Cons(e, Cons(f,

```

```
Cons(g, Cons(h, Cons(i, Cons(j, Cons(k, env))))))))))"
```

shows

```
"[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
```

```
  i ∈ nat; j < length(env); k < length(env); env ∈ list(A)|]
```

```
==> is_iterates(##A, is_F, x, y, z) ⟷
```

```
sats(A, is_iterates_fm(p,i,j,k), env)"
```

⟨proof⟩

The second argument of p gives it direct access to x , which is essential for handling free variable references. Without this argument, we cannot prove reflection for *list_N*.

theorem *is_iterates_reflection*:

assumes *p_reflection*:

```
"!!f g h. REFLECTS[λx. p(L, h(x), f(x), g(x)),
```

```
λi x. p(##Lset(i), h(x), f(x), g(x))]"
```

shows "REFLECTS[$\lambda x. \text{is_iterates}(L, p(L,x), f(x), g(x), h(x)),$
 $\lambda i x. \text{is_iterates}(\#\#L\text{set}(i), p(\#\#L\text{set}(i),x), f(x), g(x),$
 $h(x))]$ "
 <proof>

11.18.2 The Formula is_eclose_n , Internalized

definition

$\text{eclose_n_fm} :: "[i,i,i] \Rightarrow i"$ where
 $\text{"eclose_n_fm}(A,n,Z) == \text{is_iterates_fm}(\text{big_union_fm}(1,0), A, n, Z)"$

lemma eclose_n_fm_type [TC]:

$\text{"[| } x \in \text{nat}; y \in \text{nat}; z \in \text{nat} \text{ |}] \Rightarrow \text{eclose_n_fm}(x,y,z) \in \text{formula}"}$
 <proof>

lemma sats_eclose_n_fm [simp]:

$\text{"[| } x \in \text{nat}; y < \text{length}(\text{env}); z < \text{length}(\text{env}); \text{env} \in \text{list}(A) \text{ |}]$
 $\Rightarrow \text{sats}(A, \text{eclose_n_fm}(x,y,z), \text{env}) \longleftrightarrow$
 $\text{is_eclose_n}(\#\#A, \text{nth}(x,\text{env}), \text{nth}(y,\text{env}), \text{nth}(z,\text{env}))"$
 <proof>

lemma eclose_n_iff_sats :

$\text{"[| } \text{nth}(i,\text{env}) = x; \text{nth}(j,\text{env}) = y; \text{nth}(k,\text{env}) = z;$
 $i \in \text{nat}; j < \text{length}(\text{env}); k < \text{length}(\text{env}); \text{env} \in \text{list}(A) \text{ |}]$
 $\Rightarrow \text{is_eclose_n}(\#\#A, x, y, z) \longleftrightarrow \text{sats}(A, \text{eclose_n_fm}(i,j,k), \text{env})"$
 <proof>

theorem $\text{eclose_n_reflection}$:

$\text{"REFLECTS[}\lambda x. \text{is_eclose_n}(L, f(x), g(x), h(x)),$
 $\lambda i x. \text{is_eclose_n}(\#\#L\text{set}(i), f(x), g(x), h(x))]$ "
 <proof>

11.18.3 Membership in $\text{eclose}(A)$

definition

$\text{mem_eclose_fm} :: "[i,i] \Rightarrow i"$ where
 $\text{"mem_eclose_fm}(x,y) ==$
 $\text{Exists}(\text{Exists}(\text{And}(\text{finite_ordinal_fm}(1),$
 $\text{And}(\text{eclose_n_fm}(x\#+2,1,0), \text{Member}(y\#+2,0))))"$

lemma mem_eclose_type [TC]:

$\text{"[| } x \in \text{nat}; y \in \text{nat} \text{ |}] \Rightarrow \text{mem_eclose_fm}(x,y) \in \text{formula}"}$
 <proof>

lemma $\text{sats_mem_eclose_fm}$ [simp]:

$\text{"[| } x \in \text{nat}; y \in \text{nat}; \text{env} \in \text{list}(A) \text{ |}]$
 $\Rightarrow \text{sats}(A, \text{mem_eclose_fm}(x,y), \text{env}) \longleftrightarrow \text{mem_eclose}(\#\#A, \text{nth}(x,\text{env}),$
 $\text{nth}(y,\text{env}))"$
 <proof>

```

lemma mem_eclose_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]
  ==> mem_eclose(##A, x, y) ⟷ sats(A, mem_eclose_fm(i,j), env)"
⟨proof⟩

```

```

theorem mem_eclose_reflection:
  "REFLECTS[λx. mem_eclose(L,f(x),g(x)),
    λi x. mem_eclose(##Lset(i),f(x),g(x))]"
⟨proof⟩

```

11.18.4 The Predicate “Is eclose(A)”

```

definition
  is_eclose_fm :: "[i,i] => i" where
    "is_eclose_fm(A,Z) ==
      Forall(Iff(Member(0,succ(Z)), mem_eclose_fm(succ(A),0)))"

```

```

lemma is_eclose_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> is_eclose_fm(x,y) ∈ formula"
⟨proof⟩

```

```

lemma sats_is_eclose_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
  ==> sats(A, is_eclose_fm(x,y), env) ⟷ is_eclose(##A, nth(x,env),
    nth(y,env))"
⟨proof⟩

```

```

lemma is_eclose_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]
  ==> is_eclose(##A, x, y) ⟷ sats(A, is_eclose_fm(i,j), env)"
⟨proof⟩

```

```

theorem is_eclose_reflection:
  "REFLECTS[λx. is_eclose(L,f(x),g(x)),
    λi x. is_eclose(##Lset(i),f(x),g(x))]"
⟨proof⟩

```

11.18.5 The List Functor, Internalized

```

definition
  list_functor_fm :: "[i,i,i] => i" where
    "list_functor_fm(A,X,Z) ==
      Exists(Exists(
        And(number1_fm(1),
          And(cartprod_fm(A#+2,X#+2,0), sum_fm(1,0,Z#+2))))))"

```

```

lemma list_functor_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> list_functor_fm(x,y,z) ∈ formula"
  <proof>

lemma sats_list_functor_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, list_functor_fm(x,y,z), env) <=>
    is_list_functor(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

lemma list_functor_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_list_functor(##A, x, y, z) <=> sats(A, list_functor_fm(i,j,k),
  env)"
  <proof>

theorem list_functor_reflection:
  "REFLECTS[λx. is_list_functor(L,f(x),g(x),h(x)),
    λi x. is_list_functor(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

11.18.6 The Formula *is_list_N*, Internalized

definition

```

list_N_fm :: "[i,i,i]=>i" where
  "list_N_fm(A,n,Z) ==
    Exists(
      And(empty_fm(0),
        is_iterates_fm(list_functor_fm(A#+9#+3,1,0), 0, n#+1, Z#+1)))"

```

```

lemma list_N_fm_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> list_N_fm(x,y,z) ∈ formula"
  <proof>

```

```

lemma sats_list_N_fm [simp]:
  "[| x ∈ nat; y < length(env); z < length(env); env ∈ list(A) |]
  ==> sats(A, list_N_fm(x,y,z), env) <=>
    is_list_N(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

```

```

lemma list_N_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j < length(env); k < length(env); env ∈ list(A) |]
  ==> is_list_N(##A, x, y, z) <=> sats(A, list_N_fm(i,j,k), env)"
  <proof>

```

```

theorem list_N_reflection:
  "REFLECTS[λx. is_list_N(L, f(x), g(x), h(x)),

```

$\lambda i x. is_list_N(\#\#Lset(i), f(x), g(x), h(x))]$ "

<proof>

11.18.7 The Predicate “Is A List”

definition

```
mem_list_fm :: "[i,i]=>i" where
  "mem_list_fm(x,y) ==
    Exists(Exists(
      And(finite_ordinal_fm(1),
        And(list_N_fm(x#+2,1,0), Member(y#+2,0)))))"
```

lemma *mem_list_type* [TC]:

$"[| x \in nat; y \in nat |] ==> mem_list_fm(x,y) \in formula"$

<proof>

lemma *sats_mem_list_fm* [simp]:

$"[| x \in nat; y \in nat; env \in list(A) |] ==> sats(A, mem_list_fm(x,y), env) \longleftrightarrow mem_list(\#\#A, nth(x,env), nth(y,env))"$

<proof>

lemma *mem_list_iff_sats*:

$"[| nth(i,env) = x; nth(j,env) = y; i \in nat; j \in nat; env \in list(A) |] ==> mem_list(\#\#A, x, y) \longleftrightarrow sats(A, mem_list_fm(i,j), env)"$

<proof>

theorem *mem_list_reflection*:

$"REFLECTS[\lambda x. mem_list(L,f(x),g(x)), \lambda i x. mem_list(\#\#Lset(i),f(x),g(x))]"$

<proof>

11.18.8 The Predicate “Is list(A)”

definition

```
is_list_fm :: "[i,i]=>i" where
  "is_list_fm(A,Z) ==
    Forall(Iff(Member(0,succ(Z)), mem_list_fm(succ(A),0)))"
```

lemma *is_list_type* [TC]:

$"[| x \in nat; y \in nat |] ==> is_list_fm(x,y) \in formula"$

<proof>

lemma *sats_is_list_fm* [simp]:

$"[| x \in nat; y \in nat; env \in list(A) |] ==> sats(A, is_list_fm(x,y), env) \longleftrightarrow is_list(\#\#A, nth(x,env), nth(y,env))"$

<proof>

lemma *is_list_iff_sats*:

$"[| nth(i,env) = x; nth(j,env) = y;$

```

      i ∈ nat; j ∈ nat; env ∈ list(A) |]
    ==> is_list(##A, x, y) <=> sats(A, is_list_fm(i,j), env)"
<proof>

```

```

theorem is_list_reflection:
  "REFLECTS[λx. is_list(L,f(x),g(x)),
    λi x. is_list(##Lset(i),f(x),g(x))]"
<proof>

```

11.18.9 The Formula Functor, Internalized

definition *formula_functor_fm* :: "[i,i]=>i" where

```

"formula_functor_fm(X,Z) ==
  Exists(Exists(Exists(Exists(Exists(
    And(omega_fm(4),
    And(cartprod_fm(4,4,3),
    And(sum_fm(3,3,2),
    And(cartprod_fm(X#+5,X#+5,1),
    And(sum_fm(1,X#+5,0), sum_fm(2,0,Z#+5))))))))))"

```

```

lemma formula_functor_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> formula_functor_fm(x,y) ∈ formula"
<proof>

```

```

lemma sats_formula_functor_fm [simp]:
  "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
  ==> sats(A, formula_functor_fm(x,y), env) <=>
    is_formula_functor(##A, nth(x,env), nth(y,env))"
<proof>

```

```

lemma formula_functor_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j ∈ nat; env ∈ list(A) |]
  ==> is_formula_functor(##A, x, y) <=> sats(A, formula_functor_fm(i,j),
env)"
<proof>

```

```

theorem formula_functor_reflection:
  "REFLECTS[λx. is_formula_functor(L,f(x),g(x)),
    λi x. is_formula_functor(##Lset(i),f(x),g(x))]"
<proof>

```

11.18.10 The Formula *is_formula_N*, Internalized

definition

```

formula_N_fm :: "[i,i]=>i" where
"formula_N_fm(n,Z) ==
  Exists(
    And(empty_fm(0),

```

```

is_iterates_fm(formula_functor_fm(1,0), 0, n#+1, Z#+1)))"

lemma formula_N_fm_type [TC]:
  "[| x ∈ nat; y ∈ nat |] ==> formula_N_fm(x,y) ∈ formula"
  <proof>

lemma sats_formula_N_fm [simp]:
  "[| x < length(env); y < length(env); env ∈ list(A)|]
  ==> sats(A, formula_N_fm(x,y), env) <=>
    is_formula_N(##A, nth(x,env), nth(y,env))"
  <proof>

lemma formula_N_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y;
    i < length(env); j < length(env); env ∈ list(A)|]
  ==> is_formula_N(##A, x, y) <=> sats(A, formula_N_fm(i,j), env)"
  <proof>

theorem formula_N_reflection:
  "REFLECTS[λx. is_formula_N(L, f(x), g(x)),
    λi x. is_formula_N(##Lset(i), f(x), g(x))]"
  <proof>

```

11.18.11 The Predicate “Is A Formula”

definition

```

mem_formula_fm :: "i=>i" where
  "mem_formula_fm(x) ==
    Exists(Exists(
      And(finite_ordinal_fm(1),
        And(formula_N_fm(1,0), Member(x#+2,0)))))"

lemma mem_formula_type [TC]:
  "x ∈ nat ==> mem_formula_fm(x) ∈ formula"
  <proof>

lemma sats_mem_formula_fm [simp]:
  "[| x ∈ nat; env ∈ list(A)|]
  ==> sats(A, mem_formula_fm(x), env) <=> mem_formula(##A, nth(x,env))"
  <proof>

lemma mem_formula_iff_sats:
  "[| nth(i,env) = x; i ∈ nat; env ∈ list(A)|]
  ==> mem_formula(##A, x) <=> sats(A, mem_formula_fm(i), env)"
  <proof>

theorem mem_formula_reflection:
  "REFLECTS[λx. mem_formula(L,f(x)),
    λi x. mem_formula(##Lset(i),f(x))]"

```

<proof>

11.18.12 The Predicate “Is formula”

definition

```
is_formula_fm :: "i=>i" where
  "is_formula_fm(Z) == Forall(Iff(Member(0,succ(Z)), mem_formula_fm(0)))"
```

lemma *is_formula_type* [TC]:

```
"x ∈ nat ==> is_formula_fm(x) ∈ formula"
```

<proof>

lemma *sats_is_formula_fm* [simp]:

```
"[| x ∈ nat; env ∈ list(A)|]
==> sats(A, is_formula_fm(x), env) <=> is_formula(##A, nth(x,env))"
```

<proof>

lemma *is_formula_iff_sats*:

```
"[| nth(i,env) = x; i ∈ nat; env ∈ list(A)|]
==> is_formula(##A, x) <=> sats(A, is_formula_fm(i), env)"
```

<proof>

theorem *is_formula_reflection*:

```
"REFLECTS[λx. is_formula(L,f(x)),
λi x. is_formula(##Lset(i),f(x))]"
```

<proof>

11.18.13 The Operator *is_transrec*

The three arguments of *p* are always 2, 1, 0. It is buried within eight quantifiers! We call *p* with arguments *a*, *f*, *z* by equating them with the corresponding quantified variables with de Bruijn indices 2, 1, 0.

definition

```
is_transrec_fm :: "[i, i, i]=>i" where
  "is_transrec_fm(p,a,z) ==
    Exists(Exists(Exists(
      And(upair_fm(a#+3,a#+3,2),
        And(is_eclose_fm(2,1),
          And(Memrel_fm(1,0), is_wfrec_fm(p,0,a#+3,z#+3)))))))"
```

lemma *is_transrec_type* [TC]:

```
"[| p ∈ formula; x ∈ nat; z ∈ nat |]
==> is_transrec_fm(p,x,z) ∈ formula"
```

<proof>

lemma *sats_is_transrec_fm*:

```
assumes MH_iff_sats:
  "!!a0 a1 a2 a3 a4 a5 a6 a7.
```

```

    [/a0∈A; a1∈A; a2∈A; a3∈A; a4∈A; a5∈A; a6∈A; a7∈A/]
    ==> MH(a2, a1, a0) <=>
        sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,
            Cons(a4,Cons(a5,Cons(a6,Cons(a7,env))))))))))"
  shows
    "[/x < length(env); z < length(env); env ∈ list(A)/]
    ==> sats(A, is_transrec_fm(p,x,z), env) <=>
        is_transrec(##A, MH, nth(x,env), nth(z,env))"
  <proof>

lemma is_transrec_iff_sats:
  assumes MH_iff_sats:
    "!!a0 a1 a2 a3 a4 a5 a6 a7.
      [/a0∈A; a1∈A; a2∈A; a3∈A; a4∈A; a5∈A; a6∈A; a7∈A/]
      ==> MH(a2, a1, a0) <=>
        sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,
            Cons(a4,Cons(a5,Cons(a6,Cons(a7,env))))))))))"
  shows
    "[/nth(i,env) = x; nth(k,env) = z;
      i < length(env); k < length(env); env ∈ list(A)/]
    ==> is_transrec(##A, MH, x, z) <=> sats(A, is_transrec_fm(p,i,k), env)"
  <proof>

theorem is_transrec_reflection:
  assumes MH_reflection:
    "!!f' f g h. REFLECTS[λx. MH(L, f'(x), f(x), g(x), h(x)),
      λi x. MH(##Lset(i), f'(x), f(x), g(x), h(x))]"
  shows "REFLECTS[λx. is_transrec(L, MH(L,x), f(x), h(x)),
    λi x. is_transrec(##Lset(i), MH(##Lset(i),x), f(x), h(x))]"
  <proof>

end

```

12 Separation for Facts About Recursion

theory *Rec_Separation* imports *Separation Internalize* begin

This theory proves all instances needed for locales M_tranc1 and $M_datatypes$

```

lemma eq_succ_imp_lt: "[/i = succ(j); Ord(i)/] ==> j<i"
  <proof>

```

12.1 The Locale M_tranc1

12.1.1 Separation for Reflexive/Transitive Closure

First, The Defining Formula

definition

```

rtran_closure_mem_fm :: "[i,i,i]>=>i" where
"rtran_closure_mem_fm(A,r,p) ==
  Exists(Exists(Exists(
    And(omega_fm(2),
    And(Member(1,2),
    And(succ_fm(1,0),
    Exists(And(typed_function_fm(1, A#+4, 0),
    And(Exists(Exists(Exists(
      And(pair_fm(2,1,p#+7),
      And(empty_fm(0),
      And(fun_apply_fm(3,0,2), fun_apply_fm(3,5,1)))))),
    Forall(Implies(Member(0,3),
    Exists(Exists(Exists(Exists(
      And(fun_apply_fm(5,4,3),
      And(succ_fm(4,2),
      And(fun_apply_fm(5,2,1),
      And(pair_fm(3,1,0), Member(0,r#+9)))))))))))))))))"

```

lemma rtran_closure_mem_type [TC]:

```

"[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> rtran_closure_mem_fm(x,y,z) ∈
formula"
<proof>

```

lemma sats_rtran_closure_mem_fm [simp]:

```

"[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
==> sats(A, rtran_closure_mem_fm(x,y,z), env) <=>
  rtran_closure_mem(##A, nth(x,env), nth(y,env), nth(z,env))"
<proof>

```

lemma rtran_closure_mem_iff_sats:

```

"[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
  i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
==> rtran_closure_mem(##A, x, y, z) <=> sats(A, rtran_closure_mem_fm(i,j,k),
env)"
<proof>

```

lemma rtran_closure_mem_reflection:

```

"REFLECTS[λx. rtran_closure_mem(L,f(x),g(x),h(x)),
  λi x. rtran_closure_mem(##Lset(i),f(x),g(x),h(x))]"
<proof>

```

Separation for r^* .

lemma rtranc1_separation:

```

"[| L(r); L(A) |] ==> separation (L, rtran_closure_mem(L,A,r))"
<proof>

```

12.1.2 Reflexive/Transitive Closure, Internalized

definition

```
rtran_closure_fm :: "[i,i]=>i" where
  "rtran_closure_fm(r,s) ==
    Forall(Implies(field_fm(succ(r),0),
      Forall(Iff(Member(0,succ(succ(s))),
        rtran_closure_mem_fm(1,succ(succ(r)),0))))))"
```

lemma rtran_closure_type [TC]:

```
"[| x ∈ nat; y ∈ nat |] ==> rtran_closure_fm(x,y) ∈ formula"
⟨proof⟩
```

lemma sats_rtran_closure_fm [simp]:

```
"[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
==> sats(A, rtran_closure_fm(x,y), env) ⟷
  rtran_closure(##A, nth(x,env), nth(y,env))"
⟨proof⟩
```

lemma rtran_closure_iff_sats:

```
"[| nth(i,env) = x; nth(j,env) = y;
  i ∈ nat; j ∈ nat; env ∈ list(A) |]
==> rtran_closure(##A, x, y) ⟷ sats(A, rtran_closure_fm(i,j),
env)"
⟨proof⟩
```

theorem rtran_closure_reflection:

```
"REFLECTS[λx. rtran_closure(L,f(x),g(x)),
  λi x. rtran_closure(##Lset(i),f(x),g(x))]"
⟨proof⟩
```

12.1.3 Transitive Closure of a Relation, Internalized

definition

```
tran_closure_fm :: "[i,i]=>i" where
  "tran_closure_fm(r,s) ==
    Exists(And(rtran_closure_fm(succ(r),0), composition_fm(succ(r),0,succ(s))))"
```

lemma tran_closure_type [TC]:

```
"[| x ∈ nat; y ∈ nat |] ==> tran_closure_fm(x,y) ∈ formula"
⟨proof⟩
```

lemma sats_tran_closure_fm [simp]:

```
"[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
==> sats(A, tran_closure_fm(x,y), env) ⟷
  tran_closure(##A, nth(x,env), nth(y,env))"
⟨proof⟩
```

lemma tran_closure_iff_sats:

```
"[| nth(i,env) = x; nth(j,env) = y;
```

$i \in \text{nat}; j \in \text{nat}; \text{env} \in \text{list}(A)[]$
 $\Rightarrow \text{tran_closure}(\#A, x, y) \longleftrightarrow \text{sats}(A, \text{tran_closure_fm}(i, j), \text{env})"$
 <proof>

theorem `tran_closure_reflection`:
 "REFLECTS[$\lambda x. \text{tran_closure}(L, f(x), g(x)),$
 $\lambda i x. \text{tran_closure}(\#L\text{set}(i), f(x), g(x))]$ "
 <proof>

12.1.4 Separation for the Proof of `wellfounded_on_trancl`

lemma `wellfounded_trancl_reflects`:
 "REFLECTS[$\lambda x. \exists w[L]. \exists wx[L]. \exists rp[L].$
 $w \in Z \ \& \ \text{pair}(L, w, x, wx) \ \& \ \text{tran_closure}(L, r, rp) \ \& \ wx \in$
 $rp,$
 $\lambda i x. \exists w \in L\text{set}(i). \exists wx \in L\text{set}(i). \exists rp \in L\text{set}(i).$
 $w \in Z \ \& \ \text{pair}(\#L\text{set}(i), w, x, wx) \ \& \ \text{tran_closure}(\#L\text{set}(i), r, rp) \ \&$
 $wx \in rp]$ "
 <proof>

lemma `wellfounded_trancl_separation`:
 "[$| L(r); L(Z) \ |$] $\Rightarrow$
 separation $(L, \lambda x.$
 $\exists w[L]. \exists wx[L]. \exists rp[L].$
 $w \in Z \ \& \ \text{pair}(L, w, x, wx) \ \& \ \text{tran_closure}(L, r, rp) \ \& \ wx \in rp)$ "
 <proof>

12.1.5 Instantiating the locale `M_trancl`

lemma `M_trancl_axioms_L`: "`M_trancl_axioms(L)`"
 <proof>

theorem `M_trancl_L`: "`M_trancl(L)`"
 <proof>

interpretation `L`: `M_trancl L` <proof>

12.2 `L` is Closed Under the Operator `list`

12.2.1 Instances of Replacement for Lists

lemma `list_replacement1_Reflects`:
 "REFLECTS
 [$\lambda x. \exists u[L]. u \in B \ \& \ (\exists y[L]. \text{pair}(L, u, y, x) \ \&$
 $\text{is_wfrec}(L, \text{iterates_MH}(L, \text{is_list_functor}(L, A), 0), \text{memsn}, u,$
 $y)),$
 $\lambda i x. \exists u \in L\text{set}(i). u \in B \ \& \ (\exists y \in L\text{set}(i). \text{pair}(\#L\text{set}(i), u, y,$
 $x) \ \&$
 $\text{is_wfrec}(\#L\text{set}(i),$
 $\text{iterates_MH}(\#L\text{set}(i),$

```

is_list_functor(##Lset(i), A), 0), memsn, u,
y))]"
⟨proof⟩

lemma list_replacement1:
  "L(A) ==> iterates_replacement(L, is_list_functor(L,A), 0)"
⟨proof⟩

lemma list_replacement2_Reflects:
  "REFLECTS
    [λx. ∃u[L]. u ∈ B & u ∈ nat &
      is_iterates(L, is_list_functor(L, A), 0, u, x),
     λi x. ∃u ∈ Lset(i). u ∈ B & u ∈ nat &
      is_iterates(##Lset(i), is_list_functor(##Lset(i), A), 0,
u, x)]"
⟨proof⟩

lemma list_replacement2:
  "L(A) ==> strong_replacement(L,
    λn y. n ∈ nat & is_iterates(L, is_list_functor(L,A), 0, n, y))"
⟨proof⟩

```

12.3 L is Closed Under the Operator *formula*

12.3.1 Instances of Replacement for Formulas

```

lemma formula_replacement1_Reflects:
  "REFLECTS
    [λx. ∃u[L]. u ∈ B & (∃y[L]. pair(L,u,y,x) &
      is_wfrec(L, iterates_MH(L, is_formula_functor(L), 0), memsn,
u, y)),
     λi x. ∃u ∈ Lset(i). u ∈ B & (∃y ∈ Lset(i). pair(##Lset(i), u, y,
x) &
      is_wfrec(##Lset(i),
        iterates_MH(##Lset(i),
          is_formula_functor(##Lset(i)), 0), memsn, u,
y))]]"
⟨proof⟩

lemma formula_replacement1:
  "iterates_replacement(L, is_formula_functor(L), 0)"
⟨proof⟩

lemma formula_replacement2_Reflects:
  "REFLECTS
    [λx. ∃u[L]. u ∈ B & u ∈ nat &
      is_iterates(L, is_formula_functor(L), 0, u, x),
     λi x. ∃u ∈ Lset(i). u ∈ B & u ∈ nat &

```

```

                                is_iterates(##Lset(i), is_formula_functor(##Lset(i)), 0,
u, x)]"
⟨proof⟩

```

```

lemma formula_replacement2:
  "strong_replacement(L,
    λn y. n ∈ nat & is_iterates(L, is_formula_functor(L), 0, n, y))"
⟨proof⟩

```

NB The proofs for type *formula* are virtually identical to those for *list(A)*.
It was a cut-and-paste job!

12.3.2 The Formula *is_nth*, Internalized

definition

```

nth_fm :: "[i,i,i] => i" where
  "nth_fm(n,l,Z) ==
    Exists(And(is_iterates_fm(tl_fm(1,0), succ(1), succ(n), 0),
      hd_fm(0,succ(Z))))"

```

```

lemma nth_fm_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> nth_fm(x,y,z) ∈ formula"
⟨proof⟩

```

```

lemma sats_nth_fm [simp]:
  "[| x < length(env); y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, nth_fm(x,y,z), env) ⟷
    is_nth(##A, nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

```

```

lemma nth_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i < length(env); j ∈ nat; k ∈ nat; env ∈ list(A) |]
  ==> is_nth(##A, x, y, z) ⟷ sats(A, nth_fm(i,j,k), env)"
⟨proof⟩

```

```

theorem nth_reflection:
  "REFLECTS[λx. is_nth(L, f(x), g(x), h(x)),
    λi x. is_nth(##Lset(i), f(x), g(x), h(x))]"
⟨proof⟩

```

12.3.3 An Instance of Replacement for *nth*

```

lemma nth_replacement_Reflects:
  "REFLECTS
    [λx. ∃u[L]. u ∈ B & (∃y[L]. pair(L,u,y,x) &
      is_wfrec(L, iterates_MH(L, is_tl(L), z), memsn, u, y)),
    λi x. ∃u ∈ Lset(i). u ∈ B & (∃y ∈ Lset(i). pair(##Lset(i), u, y,
x) &

```

```

      is_wfrec(##Lset(i),
               iterates_MH(##Lset(i),
                           is_tl(##Lset(i)), z), memsn, u, y))] "
⟨proof⟩

```

```

lemma nth_replacement:
  "L(w) ==> iterates_replacement(L, is_tl(L), w)"
⟨proof⟩

```

12.3.4 Instantiating the locale $M_datatypes$

```

lemma M_datatypes_axioms_L: "M_datatypes_axioms(L)"
⟨proof⟩

```

```

theorem M_datatypes_L: "M_datatypes(L)"
⟨proof⟩

```

```

interpretation L: M_datatypes L ⟨proof⟩

```

12.4 L is Closed Under the Operator $eclose$

12.4.1 Instances of Replacement for $eclose$

```

lemma eclose_replacement1_Reflects:
  "REFLECTS
   [λx. ∃u[L]. u ∈ B & (∃y[L]. pair(L,u,y,x) &
    is_wfrec(L, iterates_MH(L, big_union(L), A), memsn, u, y)),
    λi x. ∃u ∈ Lset(i). u ∈ B & (∃y ∈ Lset(i). pair(##Lset(i), u, y,
x) &
    is_wfrec(##Lset(i),
             iterates_MH(##Lset(i), big_union(##Lset(i)), A),
             memsn, u, y))]"
⟨proof⟩

```

```

lemma eclose_replacement1:
  "L(A) ==> iterates_replacement(L, big_union(L), A)"
⟨proof⟩

```

```

lemma eclose_replacement2_Reflects:
  "REFLECTS
   [λx. ∃u[L]. u ∈ B & u ∈ nat &
    is_iterates(L, big_union(L), A, u, x),
    λi x. ∃u ∈ Lset(i). u ∈ B & u ∈ nat &
    is_iterates(##Lset(i), big_union(##Lset(i)), A, u, x)]"
⟨proof⟩

```

```

lemma eclose_replacement2:
  "L(A) ==> strong_replacement(L,
    λn y. n ∈ nat & is_iterates(L, big_union(L), A, n, y))"

```

<proof>

12.4.2 Instantiating the locale M_{eclose}

lemma $M_{\text{eclose_axioms_L}}$: " $M_{\text{eclose_axioms}}(L)$ "
<proof>

theorem $M_{\text{eclose_L}}$: " $M_{\text{eclose}}(L)$ "
<proof>

interpretation L : $M_{\text{eclose}} L$ *<proof>*

end

13 Absoluteness for the Satisfies Relation on Formulas

theory $Satisfies_absolute$ imports $Datatype_absolute$ $Rec_Separation$ **begin**

13.1 More Internalization

13.1.1 The Formula is_depth , Internalized

definition

$depth_fm :: "[i,i] \Rightarrow i$ " **where**
" $depth_fm(p,n) ==$
 $Exists(Exists(Exists($
 $And(formula_N_fm(n\#+3,1),$
 $And(Neg(Member(p\#+3,1)),$
 $And(succ_fm(n\#+3,2),$
 $And(formula_N_fm(2,0), Member(p\#+3,0))))))$ "

lemma $depth_fm_type$ [TC]:
" $[| x \in nat; y \in nat |] \Rightarrow depth_fm(x,y) \in formula$ "
<proof>

lemma $sats_depth_fm$ [simp]:
" $[| x \in nat; y < length(env); env \in list(A) |]$
 $\Rightarrow sats(A, depth_fm(x,y), env) \longleftrightarrow$
 $is_depth(\#A, nth(x,env), nth(y,env))$ "
<proof>

lemma $depth_iff_sats$:
" $[| nth(i,env) = x; nth(j,env) = y;$
 $i \in nat; j < length(env); env \in list(A) |]$
 $\Rightarrow is_depth(\#A, x, y) \longleftrightarrow sats(A, depth_fm(i,j), env)$ "
<proof>

```

theorem depth_reflection:
  "REFLECTS[ $\lambda x. is\_depth(L, f(x), g(x)),$ 
     $\lambda i x. is\_depth(\#Lset(i), f(x), g(x))]$ "
<proof>

```

13.1.2 The Operator *is_formula_case*

The arguments of *is_a* are always 2, 1, 0, and the formula will be enclosed by three quantifiers.

definition

```

formula_case_fm :: "[i, i, i, i, i, i] => i" where
  "formula_case_fm(is_a, is_b, is_c, is_d, v, z) ==
    And(Forall(Forall(Implies(finite_ordinal_fm(1),
      Implies(finite_ordinal_fm(0),
        Implies(Member_fm(1,0,v#+2),
          Forall(Implies(Equal(0,z#+3), is_a))))))),
    And(Forall(Forall(Implies(finite_ordinal_fm(1),
      Implies(finite_ordinal_fm(0),
        Implies(Equal_fm(1,0,v#+2),
          Forall(Implies(Equal(0,z#+3), is_b))))))),
    And(Forall(Forall(Implies(mem_formula_fm(1),
      Implies(mem_formula_fm(0),
        Implies(Nand_fm(1,0,v#+2),
          Forall(Implies(Equal(0,z#+3), is_c))))))),
    Forall(Implies(mem_formula_fm(0),
      Implies(Forall_fm(0,succ(v)),
        Forall(Implies(Equal(0,z#+2), is_d)))))))))"

```

lemma *is_formula_case_type* [TC]:

```

  "[| is_a  $\in$  formula; is_b  $\in$  formula; is_c  $\in$  formula; is_d  $\in$  formula;
    x  $\in$  nat; y  $\in$  nat |]
  ==> formula_case_fm(is_a, is_b, is_c, is_d, x, y)  $\in$  formula"
<proof>

```

lemma *sats_formula_case_fm*:

```

  assumes is_a_iff_sats:
    "!!a0 a1 a2.
      [|a0 $\in$ A; a1 $\in$ A; a2 $\in$ A|]
      ==> ISA(a2, a1, a0)  $\longleftrightarrow$  sats(A, is_a, Cons(a0,Cons(a1,Cons(a2,env))))"
  and is_b_iff_sats:
    "!!a0 a1 a2.
      [|a0 $\in$ A; a1 $\in$ A; a2 $\in$ A|]
      ==> ISB(a2, a1, a0)  $\longleftrightarrow$  sats(A, is_b, Cons(a0,Cons(a1,Cons(a2,env))))"
  and is_c_iff_sats:
    "!!a0 a1 a2.
      [|a0 $\in$ A; a1 $\in$ A; a2 $\in$ A|]

```

```

      ==> ISC(a2, a1, a0) <=> sats(A, is_c, Cons(a0,Cons(a1,Cons(a2,env))))"
and is_d_iff_sats:
  "!!a0 a1.
    [/a0∈A; a1∈A/]
    ==> ISD(a1, a0) <=> sats(A, is_d, Cons(a0,Cons(a1,env)))"
shows
  "[/x ∈ nat; y < length(env); env ∈ list(A)/]
  ==> sats(A, formula_case_fm(is_a,is_b,is_c,is_d,x,y), env) <=>
    is_formula_case(##A, ISA, ISB, ISC, ISD, nth(x,env), nth(y,env))"
⟨proof⟩

lemma formula_case_iff_sats:
  assumes is_a_iff_sats:
    "!!a0 a1 a2.
      [/a0∈A; a1∈A; a2∈A/]
      ==> ISA(a2, a1, a0) <=> sats(A, is_a, Cons(a0,Cons(a1,Cons(a2,env))))"
  and is_b_iff_sats:
    "!!a0 a1 a2.
      [/a0∈A; a1∈A; a2∈A/]
      ==> ISB(a2, a1, a0) <=> sats(A, is_b, Cons(a0,Cons(a1,Cons(a2,env))))"
  and is_c_iff_sats:
    "!!a0 a1 a2.
      [/a0∈A; a1∈A; a2∈A/]
      ==> ISC(a2, a1, a0) <=> sats(A, is_c, Cons(a0,Cons(a1,Cons(a2,env))))"
  and is_d_iff_sats:
    "!!a0 a1.
      [/a0∈A; a1∈A/]
      ==> ISD(a1, a0) <=> sats(A, is_d, Cons(a0,Cons(a1,env)))"
  shows
    "[/nth(i,env) = x; nth(j,env) = y;
    i ∈ nat; j < length(env); env ∈ list(A)/]
    ==> is_formula_case(##A, ISA, ISB, ISC, ISD, x, y) <=>
      sats(A, formula_case_fm(is_a,is_b,is_c,is_d,i,j), env)"
⟨proof⟩

```

The second argument of `is_a` gives it direct access to `x`, which is essential for handling free variable references. Treatment is based on that of `is_nat_case_reflection`.

```

theorem is_formula_case_reflection:
  assumes is_a_reflection:
    "!!h f g g'. REFLECTS[λx. is_a(L, h(x), f(x), g(x), g'(x)),
      λi x. is_a(##Lset(i), h(x), f(x), g(x), g'(x))]"
  and is_b_reflection:
    "!!h f g g'. REFLECTS[λx. is_b(L, h(x), f(x), g(x), g'(x)),
      λi x. is_b(##Lset(i), h(x), f(x), g(x), g'(x))]"
  and is_c_reflection:
    "!!h f g g'. REFLECTS[λx. is_c(L, h(x), f(x), g(x), g'(x)),
      λi x. is_c(##Lset(i), h(x), f(x), g(x), g'(x))]"
  and is_d_reflection:

```

```

    "!!h f g g'. REFLECTS[λx. is_d(L, h(x), f(x), g(x)),
      λi x. is_d(##Lset(i), h(x), f(x), g(x))]"
  shows "REFLECTS[λx. is_formula_case(L, is_a(L,x), is_b(L,x), is_c(L,x),
    is_d(L,x), g(x), h(x)),
      λi x. is_formula_case(##Lset(i), is_a(##Lset(i), x), is_b(##Lset(i),
    x), is_c(##Lset(i), x), is_d(##Lset(i), x), g(x), h(x))]"
  <proof>

```

13.2 Absoluteness for the Function *satisfies*

definition

```

is_depth_apply :: "[i=>o,i,i,i] => o" where
  — Merely a useful abbreviation for the sequel.
  "is_depth_apply(M,h,p,z) ==
    ∃ dp[M]. ∃ sdp[M]. ∃ hsdp[M].
      finite_ordinal(M,dp) & is_depth(M,p,dp) & successor(M,dp,sdp)
  &
    fun_apply(M,h,sdp,hsdp) & fun_apply(M,hsdp,p,z)"

```

lemma (in *M_datatypes*) *is_depth_apply_abs [simp]*:

```

  "[|M(h); p ∈ formula; M(z)|]
    ==> is_depth_apply(M,h,p,z) ⟷ z = h ` succ(depth(p)) ` p"
  <proof>

```

There is at present some redundancy between the relativizations in e.g. *satisfies_is_a* and those in e.g. *Member_replacement*.

These constants let us instantiate the parameters *a*, *b*, *c*, *d*, etc., of the locale *Formula_Rec*.

definition

```

satisfies_a :: "[i,i,i]=>i" where
  "satisfies_a(A) ==
    λx y. λenv ∈ list(A). bool_of_o (nth(x,env) ∈ nth(y,env))"

```

definition

```

satisfies_is_a :: "[i=>o,i,i,i,i]=>o" where
  "satisfies_is_a(M,A) ==
    λx y zz. ∀ lA[M]. is_list(M,A,lA) ⟶
      is_lambda(M, lA,
        λenv z. is_bool_of_o(M,
          ∃ nx[M]. ∃ ny[M].
            is_nth(M,x,env,nx) & is_nth(M,y,env,ny) & nx ∈
ny, z),
        zz)"

```

definition

```

satisfies_b :: "[i,i,i]=>i" where
  "satisfies_b(A) ==
    λx y. λenv ∈ list(A). bool_of_o (nth(x,env) = nth(y,env))"

```

definition

```

satisfies_is_b :: "[i=>o,i,i,i,i]=>o" where
  — We simplify the formula to have just nx rather than introducing ny with nx
  = ny
  "satisfies_is_b(M,A) ==
    λx y zz. ∀ lA[M]. is_list(M,A,lA) →
      is_lambda(M, lA,
        λenv z. is_bool_of_o(M,
          ∃ nx[M]. is_nth(M,x,env,nx) & is_nth(M,y,env,nx),
z),
      zz)"

```

definition

```

satisfies_c :: "[i,i,i,i,i]=>i" where
  "satisfies_c(A) == λp q rp rq. λenv ∈ list(A). not(rp ' env and rq
' env)"

```

definition

```

satisfies_is_c :: "[i=>o,i,i,i,i,i]=>o" where
  "satisfies_is_c(M,A,h) ==
    λp q zz. ∀ lA[M]. is_list(M,A,lA) →
      is_lambda(M, lA, λenv z. ∃ hp[M]. ∃ hq[M].
        (∃ rp[M]. is_depth_apply(M,h,p,rp) & fun_apply(M,rp,env,hp))
&
        (∃ rq[M]. is_depth_apply(M,h,q,rq) & fun_apply(M,rq,env,hq))
&
        (∃ pq[M]. is_and(M,hp,hq,pq) & is_not(M,pq,z)),
      zz)"

```

definition

```

satisfies_d :: "[i,i,i]=>i" where
  "satisfies_d(A)
  == λp rp. λenv ∈ list(A). bool_of_o (∀ x∈A. rp ' (Cons(x,env)) =
1)"

```

definition

```

satisfies_is_d :: "[i=>o,i,i,i,i,i]=>o" where
  "satisfies_is_d(M,A,h) ==
    λp zz. ∀ lA[M]. is_list(M,A,lA) →
      is_lambda(M, lA,
        λenv z. ∃ rp[M]. is_depth_apply(M,h,p,rp) &
          is_bool_of_o(M,
            ∀ x[M]. ∀ xenv[M]. ∀ hp[M].
              x∈A → is_Cons(M,x,env,xenv) →
                fun_apply(M,rp,xenv,hp) → number1(M,hp),
z),
      zz)"

```

definition

```

satisfies_MH :: "[i=>o,i,i,i,i]=>o" where
  — The variable u is unused, but gives satisfies_MH the correct arity.
"satisfies_MH ==
  λM A u f z.
    ∀ fml[M]. is_formula(M,fml) →
      is_lambda (M, fml,
        is_formula_case (M, satisfies_is_a(M,A),
          satisfies_is_b(M,A),
            satisfies_is_c(M,A,f), satisfies_is_d(M,A,f)),
          z)"

```

definition

```

is_satisfies :: "[i=>o,i,i,i]=>o" where
"is_satisfies(M,A) == is_formula_rec (M, satisfies_MH(M,A))"

```

This lemma relates the fragments defined above to the original primitive recursion in *satisfies*. Induction is not required: the definitions are directly equal!

lemma satisfies_eq:

```

"satisfies(A,p) =
  formula_rec (satisfies_a(A), satisfies_b(A),
    satisfies_c(A), satisfies_d(A), p)"

```

<proof>

Further constraints on the class *M* in order to prove absoluteness for the constants defined above. The ultimate goal is the absoluteness of the function *satisfies*.

locale *M_satisfies* = *M_eclose* +

assumes

Member_replacement:

"[|M(A); x ∈ nat; y ∈ nat|]

==> *strong_replacement*

(M, λenv z. ∃ bo[M]. ∃ nx[M]. ∃ ny[M].

env ∈ list(A) & is_nth(M,x,env,nx) & is_nth(M,y,env,ny)

&

is_bool_of_o(M, nx ∈ ny, bo) &

pair(M, env, bo, z))"

and

Equal_replacement:

"[|M(A); x ∈ nat; y ∈ nat|]

==> *strong_replacement*

(M, λenv z. ∃ bo[M]. ∃ nx[M]. ∃ ny[M].

env ∈ list(A) & is_nth(M,x,env,nx) & is_nth(M,y,env,ny)

&

is_bool_of_o(M, nx = ny, bo) &

pair(M, env, bo, z))"

and

Nand_replacement:

```

"[/M(A); M(rp); M(rq)]
==> strong_replacement
  (M, λenv z. ∃rpe[M]. ∃rqe[M]. ∃andpq[M]. ∃notpq[M].
    fun_apply(M,rp,env,rpe) & fun_apply(M,rq,env,rqe) &
    is_and(M,rpe,rqe,andpq) & is_not(M,andpq,notpq) &
    env ∈ list(A) & pair(M, env, notpq, z)))"

and
forall_replacement:
"[/M(A); M(rp)]
==> strong_replacement
  (M, λenv z. ∃bo[M].
    env ∈ list(A) &
    is_bool_of_o (M,
      ∀a[M]. ∀co[M]. ∀rpco[M].
        a ∈ A → is_Cons(M,a,env,co) →
        fun_apply(M,rp,co,rpco) → number1(M,
rpco),
      bo) &
    pair(M,env,bo,z)))"

and
formula_rec_replacement:
  — For the transrec
  " [/n ∈ nat; M(A)] ==> transrec_replacement(M, satisfies_MH(M,A), n)"

and
formula_rec_lambda_replacement:
  — For the λ-abstraction in the transrec body
  " [/M(g); M(A)] ==>
    strong_replacement (M,
      λx y. mem_formula(M,x) &
        (∃c[M]. is_formula_case(M, satisfies_is_a(M,A),
          satisfies_is_b(M,A),
          satisfies_is_c(M,A,g),
          satisfies_is_d(M,A,g), x, c) &
          pair(M, x, c, y)))"

lemma (in M_satisfies) Member_replacement':
  " [/M(A); x ∈ nat; y ∈ nat]
  ==> strong_replacement
    (M, λenv z. env ∈ list(A) &
      z = ⟨env, bool_of_o(nth(x, env) ∈ nth(y, env))⟩)"
⟨proof⟩

lemma (in M_satisfies) Equal_replacement':
  " [/M(A); x ∈ nat; y ∈ nat]
  ==> strong_replacement
    (M, λenv z. env ∈ list(A) &
      z = ⟨env, bool_of_o(nth(x, env) = nth(y, env))⟩)"
⟨proof⟩

```

```

lemma (in M_satisfies) Nand_replacement':
  "[|M(A); M(rp); M(rq)|]
  ==> strong_replacement
    (M, λenv z. env ∈ list(A) & z = ⟨env, not(rp'env and rq'env)⟩)"
⟨proof⟩

lemma (in M_satisfies) Forall_replacement':
  "[|M(A); M(rp)|]
  ==> strong_replacement
    (M, λenv z.
      env ∈ list(A) &
      z = ⟨env, bool_of_o (∀a∈A. rp ' Cons(a,env) = 1)⟩)"
⟨proof⟩

lemma (in M_satisfies) a_closed:
  "[|M(A); x∈nat; y∈nat|] ==> M(satisfies_a(A,x,y))"
⟨proof⟩

lemma (in M_satisfies) a_rel:
  "M(A) ==> Relation2(M, nat, nat, satisfies_is_a(M,A), satisfies_a(A))"
⟨proof⟩

lemma (in M_satisfies) b_closed:
  "[|M(A); x∈nat; y∈nat|] ==> M(satisfies_b(A,x,y))"
⟨proof⟩

lemma (in M_satisfies) b_rel:
  "M(A) ==> Relation2(M, nat, nat, satisfies_is_b(M,A), satisfies_b(A))"
⟨proof⟩

lemma (in M_satisfies) c_closed:
  "[|M(A); x ∈ formula; y ∈ formula; M(rx); M(ry)|]
  ==> M(satisfies_c(A,x,y,rx,ry))"
⟨proof⟩

lemma (in M_satisfies) c_rel:
  "[|M(A); M(f)|] ==>
    Relation2 (M, formula, formula,
      satisfies_is_c(M,A,f),
      λu v. satisfies_c(A, u, v, f ' succ(depth(u)) ' u,
        f ' succ(depth(v)) ' v))"
⟨proof⟩

lemma (in M_satisfies) d_closed:
  "[|M(A); x ∈ formula; M(rx)|] ==> M(satisfies_d(A,x,rx))"
⟨proof⟩

lemma (in M_satisfies) d_rel:

```

```

"[/M(A); M(f)] =>
  Relation1(M, formula, satisfies_is_d(M,A,f),
    λu. satisfies_d(A, u, f ' succ(depth(u)) ' u))"
⟨proof⟩

```

```

lemma (in M_satisfies) fr_replace:
  " [/n ∈ nat; M(A)] => transrec_replacement(M,satisfies_MH(M,A),n)"
⟨proof⟩

```

```

lemma (in M_satisfies) formula_case_satisfies_closed:
  " [/M(g); M(A); x ∈ formula] =>
    M(formula_case (satisfies_a(A), satisfies_b(A),
      λu v. satisfies_c(A, u, v,
        g ' succ(depth(u)) ' u, g ' succ(depth(v)) '
v),
      λu. satisfies_d (A, u, g ' succ(depth(u)) ' u),
      x))"
⟨proof⟩

```

```

lemma (in M_satisfies) fr_lam_replace:
  " [/M(g); M(A)] =>
    strong_replacement (M, λx y. x ∈ formula &
      y = ⟨x,
        formula_rec_case(satisfies_a(A),
          satisfies_b(A),
          satisfies_c(A),
          satisfies_d(A), g, x)⟩)"
⟨proof⟩

```

Instantiate locale *Formula_Rec* for the Function *satisfies*

```

lemma (in M_satisfies) Formula_Rec_axioms_M:
  "M(A) =>
    Formula_Rec_axioms(M, satisfies_a(A), satisfies_is_a(M,A),
      satisfies_b(A), satisfies_is_b(M,A),
      satisfies_c(A), satisfies_is_c(M,A),
      satisfies_d(A), satisfies_is_d(M,A))"
⟨proof⟩

```

```

theorem (in M_satisfies) Formula_Rec_M:
  "M(A) =>
    Formula_Rec(M, satisfies_a(A), satisfies_is_a(M,A),
      satisfies_b(A), satisfies_is_b(M,A),
      satisfies_c(A), satisfies_is_c(M,A),
      satisfies_d(A), satisfies_is_d(M,A))"
⟨proof⟩

```

```

lemmas (in M_satisfies)
  satisfies_closed' = Formula_Rec.formula_rec_closed [OF Formula_Rec_M]
and satisfies_abs'   = Formula_Rec.formula_rec_abs [OF Formula_Rec_M]

```

```

lemma (in M_satisfies) satisfies_closed:
  "[|M(A); p ∈ formula|] ==> M(satisfies(A,p))"
<proof>

```

```

lemma (in M_satisfies) satisfies_abs:
  "[|M(A); M(z); p ∈ formula|]
  ==> is_satisfies(M,A,p,z) <=> z = satisfies(A,p)"
<proof>

```

13.3 Internalizations Needed to Instantiate $M_satisfies$

13.3.1 The Operator is_depth_apply , Internalized

definition

```

depth_apply_fm :: "[i,i,i]=>i" where
  "depth_apply_fm(h,p,z) ==
    Exists(Exists(Exists(
      And(finite_ordinal_fm(2),
        And(depth_fm(p#+3,2),
          And(succ_fm(2,1),
            And(fun_apply_fm(h#+3,1,0), fun_apply_fm(0,p#+3,z#+3)))))))"

```

```

lemma depth_apply_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> depth_apply_fm(x,y,z) ∈ formula"
<proof>

```

```

lemma sats_depth_apply_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
  ==> sats(A, depth_apply_fm(x,y,z), env) <=>
    is_depth_apply(##A, nth(x,env), nth(y,env), nth(z,env))"
<proof>

```

```

lemma depth_apply_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
  ==> is_depth_apply(##A, x, y, z) <=> sats(A, depth_apply_fm(i,j,k),
env)"
<proof>

```

```

lemma depth_apply_reflection:
  "REFLECTS[λx. is_depth_apply(L,f(x),g(x),h(x)),
    λi x. is_depth_apply(##Lset(i),f(x),g(x),h(x))]"
<proof>

```

13.3.2 The Operator *satisfies_is_a*, Internalized

definition

```
satisfies_is_a_fm :: "[i,i,i,i]=>i" where
"satisfies_is_a_fm(A,x,y,z) ==
  Forall(
    Implies(is_list_fm(succ(A),0),
      lambda_fm(
        bool_of_o_fm(Exists(
          Exists(And(nth_fm(x#+6,3,1),
            And(nth_fm(y#+6,3,0),
              Member(1,0))))), 0),
        0, succ(z))))"
```

lemma *satisfies_is_a_type* [TC]:

```
"[| A ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat |]
==> satisfies_is_a_fm(A,x,y,z) ∈ formula"
```

<proof>

lemma *sats_satisfies_is_a_fm* [simp]:

```
"[| u ∈ nat; x < length(env); y < length(env); z ∈ nat; env ∈ list(A) |]
==> sats(A, satisfies_is_a_fm(u,x,y,z), env) <=>
  satisfies_is_a(##A, nth(u,env), nth(x,env), nth(y,env), nth(z,env))"
```

<proof>

lemma *satisfies_is_a_iff_sats*:

```
"[| nth(u,env) = nu; nth(x,env) = nx; nth(y,env) = ny; nth(z,env) =
nz;
  u ∈ nat; x < length(env); y < length(env); z ∈ nat; env ∈ list(A) |]
==> satisfies_is_a(##A,nu,nx,ny,nz) <=>
  sats(A, satisfies_is_a_fm(u,x,y,z), env)"
```

<proof>

theorem *satisfies_is_a_reflection*:

```
"REFLECTS[λx. satisfies_is_a(L,f(x),g(x),h(x),g'(x)),
  λi x. satisfies_is_a(##Lset(i),f(x),g(x),h(x),g'(x))]"
```

<proof>

13.3.3 The Operator *satisfies_is_b*, Internalized

definition

```
satisfies_is_b_fm :: "[i,i,i,i]=>i" where
"satisfies_is_b_fm(A,x,y,z) ==
  Forall(
    Implies(is_list_fm(succ(A),0),
      lambda_fm(
        bool_of_o_fm(Exists(And(nth_fm(x#+5,2,0), nth_fm(y#+5,2,0))),
          0),
        0, succ(z))))"
```

```

lemma satisfies_is_b_type [TC]:
  "[| A ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat |]
   ==> satisfies_is_b_fm(A,x,y,z) ∈ formula"
  <proof>

lemma sats_satisfies_is_b_fm [simp]:
  "[| u ∈ nat; x < length(env); y < length(env); z ∈ nat; env ∈ list(A) |]
   ==> sats(A, satisfies_is_b_fm(u,x,y,z), env) <=>
       satisfies_is_b(##A, nth(u,env), nth(x,env), nth(y,env), nth(z,env))"
  <proof>

lemma satisfies_is_b_iff_sats:
  "[| nth(u,env) = nu; nth(x,env) = nx; nth(y,env) = ny; nth(z,env) =
  nz;
    u ∈ nat; x < length(env); y < length(env); z ∈ nat; env ∈ list(A) |]
   ==> satisfies_is_b(##A,nu,nx,ny,nz) <=>
       sats(A, satisfies_is_b_fm(u,x,y,z), env)"
  <proof>

theorem satisfies_is_b_reflection:
  "REFLECTS[λx. satisfies_is_b(L,f(x),g(x),h(x),g'(x)),
    λi x. satisfies_is_b(##Lset(i),f(x),g(x),h(x),g'(x))]"
  <proof>

```

13.3.4 The Operator `satisfies_is_c`, Internalized

definition

```

satisfies_is_c_fm :: "[i,i,i,i,i]=>i" where
"satisfies_is_c_fm(A,h,p,q,zz) ==
  Forall(
    Implies(is_list_fm(succ(A),0),
      lambda_fm(
        Exists(Exists(
          And(Exists(And(depth_apply_fm(h#+7,p#+7,0), fun_apply_fm(0,4,2))),
            And(Exists(And(depth_apply_fm(h#+7,q#+7,0), fun_apply_fm(0,4,1))),
              Exists(And(and_fm(2,1,0), not_fm(0,3))))))),
        0, succ(zz))))"

```

```

lemma satisfies_is_c_type [TC]:
  "[| A ∈ nat; h ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat |]
   ==> satisfies_is_c_fm(A,h,x,y,z) ∈ formula"
  <proof>

```

```

lemma sats_satisfies_is_c_fm [simp]:
  "[| u ∈ nat; v ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
   ==> sats(A, satisfies_is_c_fm(u,v,x,y,z), env) <=>
       satisfies_is_c(##A, nth(u,env), nth(v,env), nth(x,env),
         nth(y,env), nth(z,env))"
  <proof>

```

```

lemma satisfies_is_c_iff_sats:
  "[| nth(u,env) = nu; nth(v,env) = nv; nth(x,env) = nx; nth(y,env) =
ny;
    nth(z,env) = nz;
    u ∈ nat; v ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> satisfies_is_c(##A,nu,nv,nx,ny,nz) ⟷
    sats(A, satisfies_is_c_fm(u,v,x,y,z), env)"
⟨proof⟩

theorem satisfies_is_c_reflection:
  "REFLECTS[λx. satisfies_is_c(L,f(x),g(x),h(x),g'(x),h'(x)),
    λi x. satisfies_is_c(##Lset(i),f(x),g(x),h(x),g'(x),h'(x))]"
⟨proof⟩

```

13.3.5 The Operator `satisfies_is_d`, Internalized

definition

```

satisfies_is_d_fm :: "[i,i,i,i]=>i" where
"satisfies_is_d_fm(A,h,p,zz) ==
  Forall(
    Implies(is_list_fm(succ(A),0),
      lambda_fm(
        Exists(
          And(depth_apply_fm(h#+5,p#+5,0),
            bool_of_o_fm(
              Forall(Forall(Forall(
                Implies(Member(2,A#+8),
                  Implies(Cons_fm(2,5,1),
                    Implies(fun_apply_fm(3,1,0), number1_fm(0)))))), 1))),
            0, succ(zz))))"

```

```

lemma satisfies_is_d_type [TC]:
  "[| A ∈ nat; h ∈ nat; x ∈ nat; z ∈ nat |]
  ==> satisfies_is_d_fm(A,h,x,z) ∈ formula"
⟨proof⟩

```

```

lemma sats_satisfies_is_d_fm [simp]:
  "[| u ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, satisfies_is_d_fm(u,x,y,z), env) ⟷
    satisfies_is_d(##A, nth(u,env), nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

```

```

lemma satisfies_is_d_iff_sats:
  "[| nth(u,env) = nu; nth(x,env) = nx; nth(y,env) = ny; nth(z,env) =
nz;
    u ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> satisfies_is_d(##A,nu,nx,ny,nz) ⟷

```

```

      sats(A, satisfies_is_d_fm(u,x,y,z), env)"
⟨proof⟩

```

```

theorem satisfies_is_d_reflection:
  "REFLECTS[λx. satisfies_is_d(L,f(x),g(x),h(x),g'(x)),
    λi x. satisfies_is_d(##Lset(i),f(x),g(x),h(x),g'(x))]"
⟨proof⟩

```

13.3.6 The Operator *satisfies_MH*, Internalized

definition

```

satisfies_MH_fm :: "[i,i,i,i]=>i" where
"satisfies_MH_fm(A,u,f,zz) ==
  Forall(
    Implies(is_formula_fm(0),
      lambda_fm(
        formula_case_fm(satisfies_is_a_fm(A#+7,2,1,0),
          satisfies_is_b_fm(A#+7,2,1,0),
          satisfies_is_c_fm(A#+7,f#+7,2,1,0),
          satisfies_is_d_fm(A#+6,f#+6,1,0),
          1, 0),
        0, succ(zz))))"

```

```

lemma satisfies_MH_type [TC]:
  "[| A ∈ nat; u ∈ nat; x ∈ nat; z ∈ nat |]
  ==> satisfies_MH_fm(A,u,x,z) ∈ formula"
⟨proof⟩

```

```

lemma sats_satisfies_MH_fm [simp]:
  "[| u ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, satisfies_MH_fm(u,x,y,z), env) ⟷
    satisfies_MH(##A, nth(u,env), nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

```

```

lemma satisfies_MH_iff_sats:
  "[| nth(u,env) = nu; nth(x,env) = nx; nth(y,env) = ny; nth(z,env) =
  nz;
    u ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> satisfies_MH(##A,nu,nx,ny,nz) ⟷
    sats(A, satisfies_MH_fm(u,x,y,z), env)"
⟨proof⟩

```

```

lemmas satisfies_reflections =
  is_lambda_reflection is_formula_reflection
  is_formula_case_reflection
  satisfies_is_a_reflection satisfies_is_b_reflection
  satisfies_is_c_reflection satisfies_is_d_reflection

```

```

theorem satisfies_MH_reflection:
  "REFLECTS[λx. satisfies_MH(L,f(x),g(x),h(x),g'(x)),
    λi x. satisfies_MH(##Lset(i),f(x),g(x),h(x),g'(x))]"
<proof>

```

13.4 Lemmas for Instantiating the Locale $M_{\text{satisfies}}$

13.4.1 The Member Case

```

lemma Member_Reflects:
  "REFLECTS[λu. ∃v[L]. v ∈ B ∧ (∃bo[L]. ∃nx[L]. ∃ny[L].
    v ∈ lstA ∧ is_nth(L,x,v,nx) ∧ is_nth(L,y,v,ny) ∧
    is_bool_of_o(L, nx ∈ ny, bo) ∧ pair(L,v,bo,u)),
    λi u. ∃v ∈ Lset(i). v ∈ B ∧ (∃bo ∈ Lset(i). ∃nx ∈ Lset(i). ∃ny
    ∈ Lset(i).
      v ∈ lstA ∧ is_nth(##Lset(i), x, v, nx) ∧
      is_nth(##Lset(i), y, v, ny) ∧
      is_bool_of_o(##Lset(i), nx ∈ ny, bo) ∧ pair(##Lset(i), v, bo,
u))]"
<proof>

```

```

lemma Member_replacement:
  "[|L(A); x ∈ nat; y ∈ nat|]
  ==> strong_replacement
    (L, λenv z. ∃bo[L]. ∃nx[L]. ∃ny[L].
      env ∈ list(A) & is_nth(L,x,env,nx) & is_nth(L,y,env,ny)
&
      is_bool_of_o(L, nx ∈ ny, bo) &
      pair(L, env, bo, z))"
<proof>

```

13.4.2 The Equal Case

```

lemma Equal_Reflects:
  "REFLECTS[λu. ∃v[L]. v ∈ B ∧ (∃bo[L]. ∃nx[L]. ∃ny[L].
    v ∈ lstA ∧ is_nth(L, x, v, nx) ∧ is_nth(L, y, v, ny) ∧
    is_bool_of_o(L, nx = ny, bo) ∧ pair(L, v, bo, u)),
    λi u. ∃v ∈ Lset(i). v ∈ B ∧ (∃bo ∈ Lset(i). ∃nx ∈ Lset(i). ∃ny
    ∈ Lset(i).
      v ∈ lstA ∧ is_nth(##Lset(i), x, v, nx) ∧
      is_nth(##Lset(i), y, v, ny) ∧
      is_bool_of_o(##Lset(i), nx = ny, bo) ∧ pair(##Lset(i), v, bo,
u))]"
<proof>

```

```

lemma Equal_replacement:
  "[|L(A); x ∈ nat; y ∈ nat|]
  ==> strong_replacement

```

```

(L, λenv z. ∃ bo[L]. ∃ nx[L]. ∃ ny[L].
  env ∈ list(A) & is_nth(L,x,env,nx) & is_nth(L,y,env,ny)
&
  is_bool_of_o(L, nx = ny, bo) &
  pair(L, env, bo, z))"
⟨proof⟩

```

13.4.3 The Nand Case

lemma Nand_Reflects:

```

"REFLECTS [λx. ∃ u[L]. u ∈ B ∧
  (∃ rpe[L]. ∃ rqe[L]. ∃ andpq[L]. ∃ notpq[L].
    fun_apply(L, rp, u, rpe) ∧ fun_apply(L, rq, u, rqe) ∧
    is_and(L, rpe, rqe, andpq) ∧ is_not(L, andpq, notpq)
  ∧
    u ∈ list(A) ∧ pair(L, u, notpq, x)),
λi x. ∃ u ∈ Lset(i). u ∈ B ∧
  (∃ rpe ∈ Lset(i). ∃ rqe ∈ Lset(i). ∃ andpq ∈ Lset(i). ∃ notpq ∈ Lset(i).
    fun_apply(##Lset(i), rp, u, rpe) ∧ fun_apply(##Lset(i), rq, u,
rqe) ∧
    is_and(##Lset(i), rpe, rqe, andpq) ∧ is_not(##Lset(i), andpq, notpq)
  ∧
    u ∈ list(A) ∧ pair(##Lset(i), u, notpq, x))]"
⟨proof⟩

```

lemma Nand_replacement:

```

"[|L(A); L(rp); L(rq)|]
==> strong_replacement
(L, λenv z. ∃ rpe[L]. ∃ rqe[L]. ∃ andpq[L]. ∃ notpq[L].
  fun_apply(L,rp,env,rpe) & fun_apply(L,rq,env,rqe) &
  is_and(L,rpe,rqe,andpq) & is_not(L,andpq,notpq) &
  env ∈ list(A) & pair(L, env, notpq, z))"
⟨proof⟩

```

13.4.4 The Forall Case

lemma Forall_Reflects:

```

"REFLECTS [λx. ∃ u[L]. u ∈ B ∧ (∃ bo[L]. u ∈ list(A) ∧
  is_bool_of_o (L,
    ∀ a[L]. ∀ co[L]. ∀ rpco[L]. a ∈ A →
      is_Cons(L,a,u,co) → fun_apply(L,rp,co,rpco) →
        number1(L,rpco),
      bo) ∧ pair(L,u,bo,x)),
λi x. ∃ u ∈ Lset(i). u ∈ B ∧ (∃ bo ∈ Lset(i). u ∈ list(A) ∧
  is_bool_of_o (##Lset(i),
    ∀ a ∈ Lset(i). ∀ co ∈ Lset(i). ∀ rpco ∈ Lset(i). a ∈ A →
      is_Cons(##Lset(i),a,u,co) → fun_apply(##Lset(i),rp,co,rpco)
→
    number1(##Lset(i),rpco),
    bo) ∧ pair(##Lset(i),u,bo,x))]"

```

<proof>

```

lemma Forall_replacement:
  "[|L(A); L(rp)|]
  ==> strong_replacement
    (L, λenv z. ∃bo[L].
      env ∈ list(A) &
      is_bool_of_o (L,
        ∀a[L]. ∀co[L]. ∀rpco[L].
          a∈A → is_Cons(L,a,env,co) →
          fun_apply(L,rp,co,rpco) → number1(L,
rpco),
        bo) &
      pair(L,env,bo,z))"

```

<proof>

13.4.5 The transrec_replacement Case

```

lemma formula_rec_replacement_Reflects:
  "REFLECTS [λx. ∃u[L]. u ∈ B ∧ (∃y[L]. pair(L, u, y, x) ∧
    is_wfrec (L, satisfies_MH(L,A), mesa, u, y)),
    λi x. ∃u ∈ Lset(i). u ∈ B ∧ (∃y ∈ Lset(i). pair(##Lset(i), u, y,
x) ∧
    is_wfrec (##Lset(i), satisfies_MH(##Lset(i),A), mesa, u,
y))]"]"

```

```

lemma formula_rec_replacement:
  — For the transrec
  "[|n ∈ nat; L(A)|] ==> transrec_replacement(L, satisfies_MH(L,A), n)"

```

13.4.6 The Lambda Replacement Case

```

lemma formula_rec_lambda_replacement_Reflects:
  "REFLECTS [λx. ∃u[L]. u ∈ B &
    mem_formula(L,u) &
    (∃c[L].
      is_formula_case
        (L, satisfies_is_a(L,A), satisfies_is_b(L,A),
          satisfies_is_c(L,A,g), satisfies_is_d(L,A,g),
          u, c) &
      pair(L,u,c,x)),
    λi x. ∃u ∈ Lset(i). u ∈ B & mem_formula(##Lset(i),u) &
    (∃c ∈ Lset(i).
      is_formula_case
        (##Lset(i), satisfies_is_a(##Lset(i),A), satisfies_is_b(##Lset(i),A),
          satisfies_is_c(##Lset(i),A,g), satisfies_is_d(##Lset(i),A,g),
          u, c) &
      pair(##Lset(i),u,c,x))]"]"

```

<proof>

lemma *formula_rec_lambda_replacement*:

— For the *transrec*

"[|L(g); L(A)|] ==>

strong_replacement (L,

$\lambda x y. \text{mem_formula}(L, x) \ \&$

$(\exists c[L]. \text{is_formula_case}(L, \text{satisfies_is_a}(L, A),$

$\text{satisfies_is_b}(L, A),$

$\text{satisfies_is_c}(L, A, g),$

$\text{satisfies_is_d}(L, A, g), x, c) \ \&$

$\text{pair}(L, x, c, y)))"$

<proof>

13.5 Instantiating *M_satisfies*

lemma *M_satisfies_axioms_L*: "*M_satisfies_axioms*(L)"

<proof>

theorem *M_satisfies_L*: "*M_satisfies*(L)"

<proof>

Finally: the point of the whole theory!

lemmas *satisfies_closed* = *M_satisfies.satisfies_closed* [*OF M_satisfies_L*]
and satisfies_abs = *M_satisfies.satisfies_abs* [*OF M_satisfies_L*]

end

14 Absoluteness for the Definable Powerset Function

theory *DPow_absolute* imports *Satisfies_absolute* begin

14.1 Preliminary Internalizations

14.1.1 The Operator *is_formula_rec*

The three arguments of *p* are always 2, 1, 0. It is buried within 11 quantifiers!!

definition

formula_rec_fm :: "[i, i, i] => i" where
"formula_rec_fm(mh, p, z) ==
Exists(Exists(Exists(
And(finite_ordinal_fm(2),
And(depth_fm(p#+3, 2),
And(succ_fm(2, 1),
And(fun_apply_fm(0, p#+3, z#+3), is_transrec_fm(mh, 1, 0)))))))))"

```

lemma is_formula_rec_type [TC]:
  "[| p ∈ formula; x ∈ nat; z ∈ nat |]
   ==> formula_rec_fm(p,x,z) ∈ formula"
  <proof>

lemma sats_formula_rec_fm:
  assumes MH_iff_sats:
    "!!a0 a1 a2 a3 a4 a5 a6 a7 a8 a9 a10.
     [|a0∈A; a1∈A; a2∈A; a3∈A; a4∈A; a5∈A; a6∈A; a7∈A; a8∈A; a9∈A;
a10∈A|]
     ==> MH(a2, a1, a0) <=>
       sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,
         Cons(a4,Cons(a5,Cons(a6,Cons(a7,
           Cons(a8,Cons(a9,Cons(a10,env))))))))))"
  shows
    "[|x ∈ nat; z ∈ nat; env ∈ list(A)|]
     ==> sats(A, formula_rec_fm(p,x,z), env) <=>
       is_formula_rec(##A, MH, nth(x,env), nth(z,env))"
  <proof>

lemma formula_rec_iff_sats:
  assumes MH_iff_sats:
    "!!a0 a1 a2 a3 a4 a5 a6 a7 a8 a9 a10.
     [|a0∈A; a1∈A; a2∈A; a3∈A; a4∈A; a5∈A; a6∈A; a7∈A; a8∈A; a9∈A;
a10∈A|]
     ==> MH(a2, a1, a0) <=>
       sats(A, p, Cons(a0,Cons(a1,Cons(a2,Cons(a3,
         Cons(a4,Cons(a5,Cons(a6,Cons(a7,
           Cons(a8,Cons(a9,Cons(a10,env))))))))))"
  shows
    "[|nth(i,env) = x; nth(k,env) = z;
     i ∈ nat; k ∈ nat; env ∈ list(A)|]
     ==> is_formula_rec(##A, MH, x, z) <=> sats(A, formula_rec_fm(p,i,k),
env)"
  <proof>

theorem formula_rec_reflection:
  assumes MH_reflection:
    "!!f' f g h. REFLECTS[λx. MH(L, f'(x), f(x), g(x), h(x)),
      λi x. MH(##Lset(i), f'(x), f(x), g(x), h(x))]"
  shows "REFLECTS[λx. is_formula_rec(L, MH(L,x), f(x), h(x)),
    λi x. is_formula_rec(##Lset(i), MH(##Lset(i),x), f(x),
h(x))]"
  <proof>

```

14.1.2 The Operator *is_satisfies*

definition

satisfies_fm :: "[i,i,i]=>i" where

```

"satisfies_fm(x) == formula_rec_fm (satisfies_MH_fm(x#+5#+6, 2, 1,
0)))"

lemma is_satisfies_type [TC]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat |] ==> satisfies_fm(x,y,z) ∈ formula"
  <proof>

lemma sats_satisfies_fm [simp]:
  "[| x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A)|]
  ==> sats(A, satisfies_fm(x,y,z), env) <=>
    is_satisfies(##A, nth(x,env), nth(y,env), nth(z,env))"
  <proof>

lemma satisfies_iff_sats:
  "[| nth(i,env) = x; nth(j,env) = y; nth(k,env) = z;
    i ∈ nat; j ∈ nat; k ∈ nat; env ∈ list(A)|]
  ==> is_satisfies(##A, x, y, z) <=> sats(A, satisfies_fm(i,j,k),
env)"
  <proof>

theorem satisfies_reflection:
  "REFLECTS[λx. is_satisfies(L,f(x),g(x),h(x)),
    λi x. is_satisfies(##Lset(i),f(x),g(x),h(x))]"
  <proof>

```

14.2 Relativization of the Operator $DPow'$

```

lemma DPow'_eq:
  "DPow'(A) = {z . ep ∈ list(A) * formula,
    ∃ env ∈ list(A). ∃ p ∈ formula.
      ep = <env,p> & z = {x∈A. sats(A, p, Cons(x,env))}}"
  <proof>

```

Relativize the use of $\lambda A p \text{ env. sats}(A, p, \text{env})$ within $DPow'$ (the comprehension).

definition

```

is_DPow_sats :: "[i=>o,i,i,i,i] => o" where
  "is_DPow_sats(M,A,env,p,x) ==
    ∀ n1[M]. ∀ e[M]. ∀ sp[M].
      is_satisfies(M,A,p,sp) → is_Cons(M,x,env,e) →
      fun_apply(M, sp, e, n1) → number1(M, n1)"

```

```

lemma (in M_satisfies) DPow_sats_abs:
  "[| M(A); env ∈ list(A); p ∈ formula; M(x) |]
  ==> is_DPow_sats(M,A,env,p,x) <=> sats(A, p, Cons(x,env))"
  <proof>

```

```

lemma (in M_satisfies) Collect_DPow_sats_abs:
  "[| M(A); env ∈ list(A); p ∈ formula |]

```

```

==> Collect(A, is_DPow_sats(M,A,env,p)) =
      {x ∈ A. sats(A, p, Cons(x,env))}"
⟨proof⟩

```

14.2.1 The Operator *is_DPow_sats*, Internalized

definition

```

DPow_sats_fm :: "[i,i,i,i]=>i" where
  "DPow_sats_fm(A,env,p,x) ==
    Forall(Forall(Forall(
      Implies(satisfies_fm(A#+3,p#+3,0),
        Implies(Cons_fm(x#+3,env#+3,1),
          Implies(fun_apply_fm(0,1,2), number1_fm(2)))))))"

```

lemma *is_DPow_sats_type* [TC]:

```

  "[| A ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat |]
  ==> DPow_sats_fm(A,x,y,z) ∈ formula"
⟨proof⟩

```

lemma *sats_DPow_sats_fm* [simp]:

```

  "[| u ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> sats(A, DPow_sats_fm(u,x,y,z), env) ⟷
      is_DPow_sats(##A, nth(u,env), nth(x,env), nth(y,env), nth(z,env))"
⟨proof⟩

```

lemma *DPow_sats_iff_sats*:

```

  "[| nth(u,env) = nu; nth(x,env) = nx; nth(y,env) = ny; nth(z,env) =
  nz;
      u ∈ nat; x ∈ nat; y ∈ nat; z ∈ nat; env ∈ list(A) |]
  ==> is_DPow_sats(##A,nu,nx,ny,nz) ⟷
      sats(A, DPow_sats_fm(u,x,y,z), env)"
⟨proof⟩

```

theorem *DPow_sats_reflection*:

```

  "REFLECTS[λx. is_DPow_sats(L,f(x),g(x),h(x),g'(x)),
    λi x. is_DPow_sats(##Lset(i),f(x),g(x),h(x),g'(x))]"
⟨proof⟩

```

14.3 A Locale for Relativizing the Operator *DPow*'

locale *M_DPow* = *M_satisfies* +

assumes *sep*:

```

  "[| M(A); env ∈ list(A); p ∈ formula |]
  ==> separation(M, λx. is_DPow_sats(M,A,env,p,x))"

```

and *rep*:

```

  "M(A)
  ==> strong_replacement (M,
    λep z. ∃ env[M]. ∃ p[M]. mem_formula(M,p) & mem_list(M,A,env)

```

&

```

    pair(M,env,p,ep) &

```

```

is_Collect(M, A,  $\lambda x. is\_DPow\_sats(M,A,env,p,x), z))"$ 

lemma (in M_DPow) sep':
  "[| M(A); env  $\in$  list(A); p  $\in$  formula |]
   ==> separation(M,  $\lambda x. sats(A, p, Cons(x,env))$ )"
  <proof>

lemma (in M_DPow) rep':
  "M(A)
   ==> strong_replacement (M,
     $\lambda ep z. \exists env \in list(A). \exists p \in formula.
      ep = \langle env, p \rangle \ \& \ z = \{x \in A . sats(A, p, Cons(x, env))\}$ )"
  <proof>

lemma univalent_pair_eq:
  "univalent (M, A,  $\lambda xy z. \exists x \in B. \exists y \in C. xy = \langle x, y \rangle \wedge z = f(x, y)$ )"
  <proof>

lemma (in M_DPow) DPow'_closed: "M(A) ==> M(DPow'(A))"
  <proof>

Relativization of the Operator DPow'

definition
  is_DPow' :: "[i=>o,i,i] => o" where
    "is_DPow'(M,A,Z) ==
      $\forall X[M]. X \in Z \longleftrightarrow$ 
     subset(M,X,A) &
     ( $\exists env[M]. \exists p[M]. mem\_formula(M,p) \ \& \ mem\_list(M,A,env) \ \&
       is\_Collect(M, A, is\_DPow\_sats(M,A,env,p), X)$ )"

lemma (in M_DPow) DPow'_abs:
  "[| M(A); M(Z) |] ==> is_DPow'(M,A,Z)  $\longleftrightarrow Z = DPow'(A)$ "
  <proof>

```

14.4 Instantiating the Locale M_DPow

14.4.1 The Instance of Separation

```

lemma DPow_separation:
  "[| L(A); env  $\in$  list(A); p  $\in$  formula |]
   ==> separation(L,  $\lambda x. is\_DPow\_sats(L,A,env,p,x)$ )"
  <proof>

```

14.4.2 The Instance of Replacement

```

lemma DPow_replacement_Reflects:
  "REFLECTS [ $\lambda x. \exists u[L]. u \in B \ \&
    (\exists env[L]. \exists p[L].$ 

```

```

      mem_formula(L,p) & mem_list(L,A,env) & pair(L,env,p,u)
&
      is_Collect (L, A, is_DPow_sats(L,A,env,p), x)),
λi x. ∃u ∈ Lset(i). u ∈ B &
(∃env ∈ Lset(i). ∃p ∈ Lset(i).
  mem_formula(##Lset(i),p) & mem_list(##Lset(i),A,env) &
  pair(##Lset(i),env,p,u) &
  is_Collect (##Lset(i), A, is_DPow_sats(##Lset(i),A,env,p),
x))]"]
<proof>

```

```

lemma DPow_replacement:
  "L(A)
  ==> strong_replacement (L,
    λep z. ∃env[L]. ∃p[L]. mem_formula(L,p) & mem_list(L,A,env)
  &
    pair(L,env,p,ep) &
    is_Collect(L, A, λx. is_DPow_sats(L,A,env,p,x), z))"
<proof>

```

14.4.3 Actually Instantiating the Locale

```

lemma M_DPow_axioms_L: "M_DPow_axioms(L)"
<proof>

```

```

theorem M_DPow_L: "M_DPow(L)"
<proof>

```

```

lemmas DPow'_closed [intro, simp] = M_DPow.DPow'_closed [OF M_DPow_L]
and DPow'_abs [intro, simp] = M_DPow.DPow'_abs [OF M_DPow_L]

```

14.4.4 The Operator *is_Collect*

The formula *is_P* has one free variable, 0, and it is enclosed within a single quantifier.

definition

```

Collect_fm :: "[i, i, i]=>i" where
"Collect_fm(A,is_P,z) ==
  Forall(Iff(Member(0,succ(z)),
    And(Member(0,succ(A)), is_P)))"

```

```

lemma is_Collect_type [TC]:
  "[| is_P ∈ formula; x ∈ nat; y ∈ nat |]
  ==> Collect_fm(x,is_P,y) ∈ formula"
<proof>

```

```

lemma sats_Collect_fm:
  assumes is_P_iff_sats:

```

```

    "!!a. a ∈ A ==> is_P(a) <=> sats(A, p, Cons(a, env))"
  shows
    "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
    ==> sats(A, Collect_fm(x,p,y), env) <=>
        is_Collect(##A, nth(x,env), is_P, nth(y,env))"
  <proof>

lemma Collect_iff_sats:
  assumes is_P_iff_sats:
    "!!a. a ∈ A ==> is_P(a) <=> sats(A, p, Cons(a, env))"
  shows
    "[| nth(i,env) = x; nth(j,env) = y;
       i ∈ nat; j ∈ nat; env ∈ list(A) |]
    ==> is_Collect(##A, x, is_P, y) <=> sats(A, Collect_fm(i,p,j), env)"
  <proof>

The second argument of is_P gives it direct access to x, which is essential
for handling free variable references.

theorem Collect_reflection:
  assumes is_P_reflection:
    "!!h f g. REFLECTS[λx. is_P(L, f(x), g(x)),
                       λi x. is_P(##Lset(i), f(x), g(x))]"
  shows "REFLECTS[λx. is_Collect(L, f(x), is_P(L,x), g(x)),
                 λi x. is_Collect(##Lset(i), f(x), is_P(##Lset(i), x), g(x))]"
  <proof>

```

14.4.5 The Operator is_Replace

BEWARE! The formula `is_P` has free variables 0, 1 and not the usual 1, 0!
 It is enclosed within two quantifiers.

definition

```

Replace_fm :: "[i, i, i] => i" where
  "Replace_fm(A, is_P, z) ==
    Forall(Iff(Member(0, succ(z)),
                Exists(And(Member(0, A#+2), is_P))))"

```

lemma is_Replace_type [TC]:

```

  "[| is_P ∈ formula; x ∈ nat; y ∈ nat |]
  ==> Replace_fm(x, is_P, y) ∈ formula"
  <proof>

```

lemma sats_Replace_fm:

```

  assumes is_P_iff_sats:
    "!!a b. [| a ∈ A; b ∈ A |]
    ==> is_P(a, b) <=> sats(A, p, Cons(a, Cons(b, env)))"
  shows
    "[| x ∈ nat; y ∈ nat; env ∈ list(A) |]
    ==> sats(A, Replace_fm(x, p, y), env) <=>

```

```

      is_Replace(##A, nth(x,env), is_P, nth(y,env))"
⟨proof⟩

lemma Replace_iff_sats:
  assumes is_P_iff_sats:
    "!!a b. [|a ∈ A; b ∈ A|]
      ==> is_P(a,b) ⟷ sats(A, p, Cons(a,Cons(b,env)))"
  shows
    "[| nth(i,env) = x; nth(j,env) = y;
      i ∈ nat; j ∈ nat; env ∈ list(A)|]
      ==> is_Replace(##A, x, is_P, y) ⟷ sats(A, Replace_fm(i,p,j), env)"
⟨proof⟩

The second argument of is_P gives it direct access to x, which is essential
for handling free variable references.

theorem Replace_reflection:
  assumes is_P_reflection:
    "!!h f g. REFLECTS[λx. is_P(L, f(x), g(x), h(x)),
      λi x. is_P(##Lset(i), f(x), g(x), h(x))]"
  shows "REFLECTS[λx. is_Replace(L, f(x), is_P(L,x), g(x)),
    λi x. is_Replace(##Lset(i), f(x), is_P(##Lset(i), x), g(x))]"
⟨proof⟩

```

14.4.6 The Operator *is_DPow'*, Internalized

definition

```

DPow'_fm :: "[i,i]=>i" where
  "DPow'_fm(A,Z) ==
    Forall(
      Iff(Member(0,succ(Z)),
        And(subset_fm(0,succ(A)),
          Exists(Exists(
            And(mem_formula_fm(0),
              And(mem_list_fm(A#+3,1),
                Collect_fm(A#+3,
                  DPow_sats_fm(A#+4, 2, 1, 0), 2))))))))"

```

lemma *is_DPow'_type* [TC]:

```

  "[| x ∈ nat; y ∈ nat |] ==> DPow'_fm(x,y) ∈ formula"
⟨proof⟩

```

lemma *sats_DPow'_fm* [simp]:

```

  "[| x ∈ nat; y ∈ nat; env ∈ list(A)|]
    ==> sats(A, DPow'_fm(x,y), env) ⟷
      is_DPow'(##A, nth(x,env), nth(y,env))"
⟨proof⟩

```

lemma *DPow'_iff_sats*:

```

  "[| nth(i,env) = x; nth(j,env) = y;

```

```

      i ∈ nat; j ∈ nat; env ∈ list(A) |]
    ==> is_DPow' (##A, x, y) <=> sats(A, DPow'_fm(i,j), env)"
  <proof>

```

```

theorem DPow'_reflection:
  "REFLECTS[λx. is_DPow'(L,f(x),g(x)),
    λi x. is_DPow' (##Lset(i),f(x),g(x))]"
  <proof>

```

14.5 A Locale for Relativizing the Operator *Lset*

definition

```

  transrec_body :: "[i=>o,i,i,i,i] => o" where
    "transrec_body(M,g,x) ==
      λy z. ∃gy[M]. y ∈ x & fun_apply(M,g,y,gy) & is_DPow'(M,gy,z)"

```

```

lemma (in M_DPow) transrec_body_abs:
  "[|M(x); M(g)|] ==> transrec_body(M,g,x,y,z) <=> y ∈ x & z = DPow'(g'y)"
  <proof>

```

```

locale M_Lset = M_DPow +
  assumes strong_rep:
    "[|M(x); M(g)|] ==> strong_replacement(M, λy z. transrec_body(M,g,x,y,z))"
  and transrec_rep:
    "M(i) ==> transrec_replacement(M, λx f u.
      ∃ r[M]. is_Replace(M, x, transrec_body(M,f,x), r) &
        big_union(M, r, u), i)"

```

```

lemma (in M_Lset) strong_rep':
  "[|M(x); M(g)|] ==> strong_replacement(M, λy z. y ∈ x & z = DPow'(g'y))"
  <proof>

```

```

lemma (in M_Lset) DPow_apply_closed:
  "[|M(f); M(x); y∈x|] ==> M(DPow'(f'y))"
  <proof>

```

```

lemma (in M_Lset) RepFun_DPow_apply_closed:
  "[|M(f); M(x)|] ==> M({DPow'(f'y). y∈x})"
  <proof>

```

```

lemma (in M_Lset) RepFun_DPow_abs:
  "[|M(x); M(f); M(r)|] ==> is_Replace(M, x, λy z. transrec_body(M,f,x,y,z), r) <=>
    r = {DPow'(f'y). y∈x}"
  <proof>

```

```

lemma (in M_Lset) transrec_rep':
  "M(i) ==> transrec_replacement(M,  $\lambda x f u. u = (\bigcup_{y \in x}. DPow'(f \text{ ` } y))$ ,
  i)"
<proof>

```

Relativization of the Operator *Lset*

definition

```

is_Lset :: "[i=>o, i, i] => o" where
  — We can use the term language below because is_Lset will not have to be
  internalized: it isn't used in any instance of separation.
  "is_Lset(M,a,z) == is_transrec(M,  $\lambda x f u. u = (\bigcup_{y \in x}. DPow'(f \text{ ` } y))$ ,
  a, z)"

```

```

lemma (in M_Lset) Lset_abs:
  "[|Ord(i); M(i); M(z)|]
  ==> is_Lset(M,i,z)  $\longleftrightarrow$  z = Lset(i)"
<proof>

```

```

lemma (in M_Lset) Lset_closed:
  "[|Ord(i); M(i)|] ==> M(Lset(i))"
<proof>

```

14.6 Instantiating the Locale *M_Lset*

14.6.1 The First Instance of Replacement

```

lemma strong_rep_Reflects:
  "REFLECTS [ $\lambda u. \exists v[L]. v \in B \ \& \ (\exists gy[L].$ 
     $v \in x \ \& \ fun\_apply(L,g,v,gy) \ \& \ is\_DPow'(L,gy,u))$ ,
     $\lambda i u. \exists v \in Lset(i). v \in B \ \& \ (\exists gy \in Lset(i).$ 
     $v \in x \ \& \ fun\_apply(\#\#Lset(i),g,v,gy) \ \& \ is\_DPow'(\#\#Lset(i),gy,u))]$ "
<proof>

```

```

lemma strong_rep:
  "[|L(x); L(g)|] ==> strong_replacement(L,  $\lambda y z. transrec\_body(L,g,x,y,z)$ )"
<proof>

```

14.6.2 The Second Instance of Replacement

```

lemma transrec_rep_Reflects:
  "REFLECTS [ $\lambda x. \exists v[L]. v \in B \ \& \$ 
     $(\exists y[L]. pair(L,v,y,x) \ \& \$ 
     $is\_wfrec \ (L, \lambda x f u. \exists r[L].$ 
     $is\_Replace \ (L, x, \lambda y z.$ 
     $\exists gy[L]. y \in x \ \& \ fun\_apply(L,f,y,gy) \ \& \$ 
     $is\_DPow'(L,gy,z), r) \ \& \ big\_union(L,r,u), mr, v,$ 
     $y))$ ,
     $\lambda i x. \exists v \in Lset(i). v \in B \ \& \$ 
     $(\exists y \in Lset(i). pair(\#\#Lset(i),v,y,x) \ \& \$ 
     $is\_wfrec \ (\#\#Lset(i), \lambda x f u. \exists r \in Lset(i).$ 

```

```

      is_Replace (##Lset(i), x, λy z.
        ∃gy ∈ Lset(i). y ∈ x & fun_apply(##Lset(i),f,y,gy)
&
      is_DPow' (##Lset(i),gy,z), r) &
      big_union(##Lset(i),r,u), mr, v, y))]"
⟨proof⟩

```

```

lemma transrec_rep:
  "[|L(j)|]
  ==> transrec_replacement(L, λx f u.
    ∃r[L]. is_Replace(L, x, transrec_body(L,f,x), r) &
    big_union(L, r, u), j)"
⟨proof⟩

```

14.6.3 Actually Instantiating M_Lset

```

lemma M_Lset_axioms_L: "M_Lset_axioms(L)"
⟨proof⟩

```

```

theorem M_Lset_L: "M_Lset(L)"
⟨proof⟩

```

Finally: the point of the whole theory!

```

lemmas Lset_closed = M_Lset.Lset_closed [OF M_Lset_L]
and Lset_abs = M_Lset.Lset_abs [OF M_Lset_L]

```

14.7 The Notion of Constructible Set

```

definition
  constructible :: "[i=>o,i] => o" where
    "constructible(M,x) ==
      ∃ i[M]. ∃ Li[M]. ordinal(M,i) & is_Lset(M,i,Li) & x ∈ Li"

```

```

theorem V_equals_L_in_L:
  "L(x) ⟷ constructible(L,x)"
⟨proof⟩

```

end

15 The Axiom of Choice Holds in L!

```

theory AC_in_L imports Formula Separation begin

```

15.1 Extending a Wellordering over a List – Lexicographic Power

This could be moved into a library.

```

consts
  rlist    :: "[i,i]=>i"

inductive
  domains "rlist(A,r)"  $\subseteq$  "list(A) * list(A)"
  intros
    shorterI:
      "[| length(l') < length(l); l'  $\in$  list(A); l  $\in$  list(A) |]
      ==> <l', l>  $\in$  rlist(A,r)"

    sameI:
      "[| <l',l>  $\in$  rlist(A,r); a  $\in$  A |]
      ==> <Cons(a,l'), Cons(a,l)>  $\in$  rlist(A,r)"

    diffI:
      "[| length(l') = length(l); <a',a>  $\in$  r;
          l'  $\in$  list(A); l  $\in$  list(A); a'  $\in$  A; a  $\in$  A |]
      ==> <Cons(a',l'), Cons(a,l)>  $\in$  rlist(A,r)"
  type_intros list.intros

```

15.1.1 Type checking

```
lemmas rlist_type = rlist.dom_subset
```

```
lemmas field_rlist = rlist_type [THEN field_rel_subset]
```

15.1.2 Linearity

```

lemma rlist_Nil_Cons [intro]:
  "[| a  $\in$  A; l  $\in$  list(A) |] ==> <[], Cons(a,l)>  $\in$  rlist(A, r)"
<proof>

```

```

lemma linear_rlist:
  assumes r: "linear(A,r)" shows "linear(list(A),rlist(A,r))"
<proof>

```

15.1.3 Well-foundedness

Nothing preceeds Nil in this ordering.

```
inductive_cases rlist_NilE: " <l, []>  $\in$  rlist(A,r) "
```

```
inductive_cases rlist_ConsE: " <l', Cons(x,l)>  $\in$  rlist(A,r) "
```

```

lemma not_rlist_Nil [simp]: " <l, []>  $\notin$  rlist(A,r) "
<proof>

```

```

lemma rlist_imp_length_le: "<l',l>  $\in$  rlist(A,r) ==> length(l')  $\leq$  length(l)"
<proof>

```

```

lemma wf_on_rlist_n:
  "[| n ∈ nat; wf[A](r) |] ==> wf[{l ∈ list(A). length(l) = n}](rlist(A,r))"
  <proof>

lemma list_eq_UN_length: "list(A) = (⋃ n∈nat. {l ∈ list(A). length(l)
= n})"
  <proof>

lemma wf_on_rlist: "wf[A](r) ==> wf[list(A)](rlist(A,r))"
  <proof>

lemma wf_rlist: "wf(r) ==> wf(rlist(field(r),r))"
  <proof>

lemma well_ord_rlist:
  "well_ord(A,r) ==> well_ord(list(A), rlist(A,r))"
  <proof>

```

15.2 An Injection from Formulas into the Natural Numbers

There is a well-known bijection between $\text{nat} \times \text{nat}$ and nat given by the expression $f(m,n) = \text{triangle}(m+n) + m$, where $\text{triangle}(k)$ enumerates the triangular numbers and can be defined by $\text{triangle}(0)=0$, $\text{triangle}(\text{succ}(k)) = \text{succ}(k + \text{triangle}(k))$. Some small amount of effort is needed to show that f is a bijection. We already know that such a bijection exists by the theorem *well_ord_InfCard_square_eq*:

$$\llbracket \text{well_ord}(A, r); \text{InfCard}(|A|) \rrbracket \implies A \times A \approx A$$

However, this result merely states that there is a bijection between the two sets. It provides no means of naming a specific bijection. Therefore, we conduct the proofs under the assumption that a bijection exists. The simplest way to organize this is to use a locale.

Locale for any arbitrary injection between $\text{nat} \times \text{nat}$ and nat

```

locale Nat_Times_Nat =
  fixes fn
  assumes fn_inj: "fn ∈ inj(nat*nat, nat)"

consts   enum :: "[i,i] => i"
primrec
  "enum(f, Member(x,y)) = f ' <0, f ' <x,y>>"
  "enum(f, Equal(x,y)) = f ' <1, f ' <x,y>>"
  "enum(f, Nand(p,q)) = f ' <2, f ' <enum(f,p), enum(f,q)>>"
  "enum(f, Forall(p)) = f ' <succ(2), enum(f,p)>"

```

```

lemma (in Nat_Times_Nat) fn_type [TC,simp]:
  "[|x ∈ nat; y ∈ nat|] ==> fn'<x,y> ∈ nat"
  <proof>

lemma (in Nat_Times_Nat) fn_iff:
  "[|x ∈ nat; y ∈ nat; u ∈ nat; v ∈ nat|]
  ==> (fn'<x,y> = fn'<u,v>) <=> (x=u & y=v)"
  <proof>

lemma (in Nat_Times_Nat) enum_type [TC,simp]:
  "p ∈ formula ==> enum(fn,p) ∈ nat"
  <proof>

lemma (in Nat_Times_Nat) enum_inject [rule_format]:
  "p ∈ formula ==> ∀ q∈formula. enum(fn,p) = enum(fn,q) → p=q"
  <proof>

lemma (in Nat_Times_Nat) inj_formula_nat:
  "(λp ∈ formula. enum(fn,p)) ∈ inj(formula, nat)"
  <proof>

lemma (in Nat_Times_Nat) well_ord_formula:
  "well_ord(formula, measure(formula, enum(fn)))"
  <proof>

lemmas nat_times_nat_lepoll_nat =
  InfCard_nat [THEN InfCard_square_eqpoll, THEN eqpoll_imp_lepoll]

Not needed—but interesting?

theorem formula_lepoll_nat: "formula ≲ nat"
  <proof>

```

15.3 Defining the Wellordering on $DPow(A)$

The objective is to build a wellordering on $DPow(A)$ from a given one on A . We first introduce wellorderings for environments, which are lists built over A . We combine it with the enumeration of formulas. The order type of the resulting wellordering gives us a map from (environment, formula) pairs into the ordinals. For each member of $DPow(A)$, we take the minimum such ordinal.

definition

```

env_form_r :: "[i,i,i]=>i" where
  — wellordering on (environment, formula) pairs
  "env_form_r(f,r,A) ==
    rmult(list(A), rlist(A, r),
          formula, measure(formula, enum(f)))"

```

definition

```
env_form_map :: "[i,i,i,i]=>i" where
  — map from (environment, formula) pairs to ordinals
  "env_form_map(f,r,A,z)
    == ordermap(list(A) * formula, env_form_r(f,r,A)) ' z"
```

definition

```
DPow_ord :: "[i,i,i,i,i]=>o" where
  — predicate that holds if k is a valid index for X
  "DPow_ord(f,r,A,X,k) ==
    ∃ env ∈ list(A). ∃ p ∈ formula.
      arity(p) ≤ succ(length(env)) &
      X = {x∈A. sats(A, p, Cons(x,env))} &
      env_form_map(f,r,A,<env,p>) = k"
```

definition

```
DPow_least :: "[i,i,i,i]=>i" where
  — function yielding the smallest index for X
  "DPow_least(f,r,A,X) == μ k. DPow_ord(f,r,A,X,k)"
```

definition

```
DPow_r :: "[i,i,i]=>i" where
  — a wellordering on DPow(A)
  "DPow_r(f,r,A) == measure(DPow(A), DPow_least(f,r,A))"
```

lemma (in Nat_Times_Nat) well_ord_env_form_r:

```
"well_ord(A,r)
==> well_ord(list(A) * formula, env_form_r(fn,r,A))"
⟨proof⟩
```

lemma (in Nat_Times_Nat) Ord_env_form_map:

```
"[/well_ord(A,r); z ∈ list(A) * formula/]
==> Ord(env_form_map(fn,r,A,z))"
⟨proof⟩
```

lemma DPow_imp_ex_DPow_ord:

```
"X ∈ DPow(A) ==> ∃ k. DPow_ord(fn,r,A,X,k)"
⟨proof⟩
```

lemma (in Nat_Times_Nat) DPow_ord_imp_Ord:

```
"[/DPow_ord(fn,r,A,X,k); well_ord(A,r)/] ==> Ord(k)"
⟨proof⟩
```

lemma (in Nat_Times_Nat) DPow_imp_DPow_least:

```
"[/X ∈ DPow(A); well_ord(A,r)/]
==> DPow_ord(fn, r, A, X, DPow_least(fn,r,A,X))"
⟨proof⟩
```

```

lemma (in Nat_Times_Nat) env_form_map_inject:
  "[|env_form_map(fn,r,A,u) = env_form_map(fn,r,A,v); well_ord(A,r);
    u ∈ list(A) * formula; v ∈ list(A) * formula|]
  ==> u=v"
<proof>

lemma (in Nat_Times_Nat) DPow_ord_unique:
  "[|DPow_ord(fn,r,A,X,k); DPow_ord(fn,r,A,Y,k); well_ord(A,r)|]
  ==> X=Y"
<proof>

lemma (in Nat_Times_Nat) well_ord_DPow_r:
  "well_ord(A,r) ==> well_ord(DPow(A), DPow_r(fn,r,A))"
<proof>

lemma (in Nat_Times_Nat) DPow_r_type:
  "DPow_r(fn,r,A) ⊆ DPow(A) * DPow(A)"
<proof>

```

15.4 Limit Construction for Well-Orderings

Now we work towards the transfinite definition of wellorderings for $Lset(i)$. We assume as an inductive hypothesis that there is a family of wellorderings for smaller ordinals.

definition

$rlimit :: "[i,i=>i] => i$ where

— Expresses the wellordering at limit ordinals. The conditional lets us remove the premise $Limit(i)$ from some theorems.

```

"rlimit(i,r) ==
  if Limit(i) then
    {z: Lset(i) * Lset(i).
      ∃ x' x. z = <x',x> &
        (lrank(x') < lrank(x) /
          (lrank(x') = lrank(x) & <x',x> ∈ r(succ(lrank(x)))))}
  else 0"

```

definition

$Lset_new :: "i=>i$ where

— This constant denotes the set of elements introduced at level $succ(i)$

```

"Lset_new(i) == {x ∈ Lset(succ(i)). lrank(x) = i}"

```

lemma Limit_Lset_eq2:

```

"Limit(i) ==> Lset(i) = (⋃ j ∈ i. Lset_new(j))"

```

<proof>

lemma wf_on_Lset:

```

"wf[Lset(succ(j))](r(succ(j))) ==> wf[Lset_new(j)](rlimit(i,r))"

```

<proof>

```

lemma wf_on_rlimit:
  "( $\forall j < i. \text{wf}[\text{Lset}(j)](r(j))$ ) ==> wf[Lset(i)](rlimit(i,r))"
<proof>

lemma linear_rlimit:
  "[|Limit(i);  $\forall j < i. \text{linear}(\text{Lset}(j), r(j))$ |]
  ==> linear(Lset(i), rlimit(i,r))"
<proof>

lemma well_ord_rlimit:
  "[|Limit(i);  $\forall j < i. \text{well\_ord}(\text{Lset}(j), r(j))$ |]
  ==> well_ord(Lset(i), rlimit(i,r))"
<proof>

lemma rlimit_cong:
  "( $\forall j. j < i \implies r'(j) = r(j)$ ) ==> rlimit(i,r) = rlimit(i,r')"
<proof>

```

15.5 Transfinite Definition of the Wellordering on L

definition

```

L_r :: "[i, i] => i" where
  "L_r(f) == %i.
    transrec3(i, 0,  $\lambda x r. \text{DPow}_r(f, r, \text{Lset}(x)),$ 
       $\lambda x r. \text{rlimit}(x, \lambda y. r'y)$ )"

```

15.5.1 The Corresponding Recursion Equations

```

lemma [simp]: "L_r(f, 0) = 0"
<proof>

```

```

lemma [simp]: "L_r(f, succ(i)) = DPow_r(f, L_r(f,i), Lset(i))"
<proof>

```

The limit case is non-trivial because of the distinction between object-level and meta-level abstraction.

```

lemma [simp]: "Limit(i) ==> L_r(f,i) = rlimit(i, L_r(f))"
<proof>

```

```

lemma (in Nat_Times_Nat) L_r_type:
  "Ord(i) ==> L_r(fn,i)  $\subseteq$  Lset(i) * Lset(i)"
<proof>

```

```

lemma (in Nat_Times_Nat) well_ord_L_r:
  "Ord(i) ==> well_ord(Lset(i), L_r(fn,i))"
<proof>

```

```

lemma well_ord_L_r:
  "Ord(i) ==>  $\exists r. \text{well\_ord}(\text{Lset}(i), r)$ "

```

<proof>

Every constructible set is well-ordered! Therefore the Wellordering Theorem and the Axiom of Choice hold in L !!

theorem *L_implies_AC*: assumes x : " $L(x)$ " shows " $\exists r. \text{well_ord}(x,r)$ "
<proof>

interpretation *L*: *M_basic L* *<proof>*

theorem " $\forall x[L]. \exists r. \text{wellordered}(L,x,r)$ "
<proof>

In order to prove $\exists r[L]. \text{wellordered}(L, x, r)$, it's necessary to know that r is actually constructible. It follows from the assumption " $\forall$ equals L '", but this reasoning doesn't appear to work in Isabelle.

end

16 Absoluteness for Order Types, Rank Functions and Well-Founded Relations

theory *Rank* imports *WF_absolute* begin

16.1 Order Types: A Direct Construction by Replacement

locale *M_ordertype* = *M_basic* +
assumes *well_ord_iso_separation*:
 " $[M(A); M(f); M(r)]$
 $\implies \text{separation}(M, \lambda x. x \in A \longrightarrow (\exists y[M]. (\exists p[M]. \text{fun_apply}(M,f,x,y) \ \& \ \text{pair}(M,y,x,p) \ \& \ p \in r)))$ "
and *obase_separation*:
 — part of the order type formalization
 " $[M(A); M(r)]$
 $\implies \text{separation}(M, \lambda a. \exists x[M]. \exists g[M]. \exists mx[M]. \exists par[M]. \text{ordinal}(M,x) \ \& \ \text{membership}(M,x,mx) \ \& \ \text{pred_set}(M,A,a,r,par)$
 $\&$
 $\text{order_isomorphism}(M,par,r,x,mx,g))$ "
and *obase_equals_separation*:
 " $[M(A); M(r)]$
 $\implies \text{separation}(M, \lambda x. x \in A \longrightarrow \sim(\exists y[M]. \exists g[M]. \text{ordinal}(M,y) \ \& \ (\exists my[M]. \exists pxr[M]. \text{membership}(M,y,my) \ \& \ \text{pred_set}(M,A,x,r,pxr)$
 $\&$
 $\text{order_isomorphism}(M,pxr,r,y,my,g))))$ "
and *omap_replacement*:
 " $[M(A); M(r)]$
 $\implies \text{strong_replacement}(M,$
 $\lambda a \ z. \exists x[M]. \exists g[M]. \exists mx[M]. \exists par[M].$
 $\text{ordinal}(M,x) \ \& \ \text{pair}(M,a,x,z) \ \& \ \text{membership}(M,x,mx) \ \&$

$\text{pred_set}(M, A, a, r, \text{par}) \ \& \ \text{order_isomorphism}(M, \text{par}, r, x, \text{mx}, g))"$

Inductive argument for Kunen's Lemma I 6.1, etc. Simple proof from Hal-
mos, page 72

lemma (in $M_ordertype$) $\text{wellordered_iso_subset_lemma}$:
 $"[| \text{wellordered}(M, A, r); \ f \in \text{ord_iso}(A, r, A', r); \ A' \leq A; \ y \in A;$
 $\quad M(A); \ M(f); \ M(r) \ |] \implies \sim \langle f'y, y \rangle \in r"$
 $\langle \text{proof} \rangle$

Kunen's Lemma I 6.1, page 14: there's no order-isomorphism to an initial
segment of a well-ordering

lemma (in $M_ordertype$) $\text{wellordered_iso_predD}$:
 $"[| \text{wellordered}(M, A, r); \ f \in \text{ord_iso}(A, r, \text{Order.pred}(A, x, r), r);$
 $\quad M(A); \ M(f); \ M(r) \ |] \implies x \notin A"$
 $\langle \text{proof} \rangle$

lemma (in $M_ordertype$) $\text{wellordered_iso_pred_eq_lemma}$:
 $"[| f \in \langle \text{Order.pred}(A, y, r), r \rangle \cong \langle \text{Order.pred}(A, x, r), r \rangle;$
 $\quad \text{wellordered}(M, A, r); \ x \in A; \ y \in A; \ M(A); \ M(f); \ M(r) \ |] \implies \langle x, y \rangle \notin$
 $\quad r"$
 $\langle \text{proof} \rangle$

Simple consequence of Lemma 6.1

lemma (in $M_ordertype$) $\text{wellordered_iso_pred_eq}$:
 $"[| \text{wellordered}(M, A, r);$
 $\quad f \in \text{ord_iso}(\text{Order.pred}(A, a, r), r, \text{Order.pred}(A, c, r), r);$
 $\quad M(A); \ M(f); \ M(r); \ a \in A; \ c \in A \ |] \implies a = c"$
 $\langle \text{proof} \rangle$

Following Kunen's Theorem I 7.6, page 17. Note that this material is not
required elsewhere.

Can't use $\text{well_ord_iso_preserving}$ because it needs the strong premise
 $\text{well_ord}(A, r)$

lemma (in $M_ordertype$) $\text{ord_iso_pred_imp_lt}$:
 $"[| f \in \text{ord_iso}(\text{Order.pred}(A, x, r), r, i, \text{Memrel}(i));$
 $\quad g \in \text{ord_iso}(\text{Order.pred}(A, y, r), r, j, \text{Memrel}(j));$
 $\quad \text{wellordered}(M, A, r); \ x \in A; \ y \in A; \ M(A); \ M(r); \ M(f); \ M(g);$
 $\quad M(j);$
 $\quad \text{Ord}(i); \ \text{Ord}(j); \ \langle x, y \rangle \in r \ |]$
 $\implies i < j"$
 $\langle \text{proof} \rangle$

lemma ord_iso_converse1 :

```

      "[| f: ord_iso(A,r,B,s); <b, f'a>: s; a:A; b:B |]
      ==> <converse(f) ' b, a> ∈ r"
⟨proof⟩

```

definition

```

obase :: "[i=>o,i,i] => i" where
  — the domain of om, eventually shown to equal A
  "obase(M,A,r) == {a∈A. ∃ x[M]. ∃ g[M]. Ord(x) &
                    g ∈ ord_iso(Order.pred(A,a,r),r,x,Memrel(x))}"

```

definition

```

omap :: "[i=>o,i,i,i] => o" where
  — the function that maps wosets to order types
  "omap(M,A,r,f) ==
    ∀ z[M].
    z ∈ f ⟷ (∃ a∈A. ∃ x[M]. ∃ g[M]. z = <a,x> & Ord(x) &
              g ∈ ord_iso(Order.pred(A,a,r),r,x,Memrel(x)))"

```

definition

```

otype :: "[i=>o,i,i,i] => o" where — the order types themselves
  "otype(M,A,r,i) == ∃ f[M]. omap(M,A,r,f) & is_range(M,f,i)"

```

Can also be proved with the premise $M(z)$ instead of $M(f)$, but that version is less useful. This lemma is also more useful than the definition, *omap_def*.

lemma (in *M_ordertype*) *omap_iff*:

```

      "[| omap(M,A,r,f); M(A); M(f) |]
      ==> z ∈ f ⟷
        (∃ a∈A. ∃ x[M]. ∃ g[M]. z = <a,x> & Ord(x) &
          g ∈ ord_iso(Order.pred(A,a,r),r,x,Memrel(x)))"

```

⟨proof⟩

lemma (in *M_ordertype*) *omap_unique*:

```

      "[| omap(M,A,r,f); omap(M,A,r,f'); M(A); M(r); M(f); M(f') |] ==>
      f' = f"

```

⟨proof⟩

lemma (in *M_ordertype*) *omap_yields_Ord*:

```

      "[| omap(M,A,r,f); <a,x> ∈ f; M(a); M(x) |] ==> Ord(x)"

```

⟨proof⟩

lemma (in *M_ordertype*) *otype_iff*:

```

      "[| otype(M,A,r,i); M(A); M(r); M(i) |]
      ==> x ∈ i ⟷
        (M(x) & Ord(x) &
         (∃ a∈A. ∃ g[M]. g ∈ ord_iso(Order.pred(A,a,r),r,x,Memrel(x))))"

```

⟨proof⟩

lemma (in *M_ordertype*) *otype_eq_range*:

```

    "[| omap(M,A,r,f); otype(M,A,r,i); M(A); M(r); M(f); M(i) |]
      ==> i = range(f)"
  <proof>

lemma (in M_ordertype) Ord_otype:
  "[| otype(M,A,r,i); trans[A](r); M(A); M(r); M(i) |] ==> Ord(i)"
  <proof>

lemma (in M_ordertype) domain_omap:
  "[| omap(M,A,r,f); M(A); M(r); M(B); M(f) |]
    ==> domain(f) = obase(M,A,r)"
  <proof>

lemma (in M_ordertype) omap_subset:
  "[| omap(M,A,r,f); otype(M,A,r,i);
      M(A); M(r); M(f); M(B); M(i) |] ==> f ⊆ obase(M,A,r) * i"
  <proof>

lemma (in M_ordertype) omap_funtype:
  "[| omap(M,A,r,f); otype(M,A,r,i);
      M(A); M(r); M(f); M(i) |] ==> f ∈ obase(M,A,r) -> i"
  <proof>

lemma (in M_ordertype) wellordered_omap_bij:
  "[| wellordered(M,A,r); omap(M,A,r,f); otype(M,A,r,i);
      M(A); M(r); M(f); M(i) |] ==> f ∈ bij(obase(M,A,r),i)"
  <proof>

This is not the final result: we must show  $oB(A, r) = A$ 

lemma (in M_ordertype) omap_ord_iso:
  "[| wellordered(M,A,r); omap(M,A,r,f); otype(M,A,r,i);
      M(A); M(r); M(f); M(i) |] ==> f ∈ ord_iso(obase(M,A,r),r,i,Memrel(i))"
  <proof>

lemma (in M_ordertype) Ord_omap_image_pred:
  "[| wellordered(M,A,r); omap(M,A,r,f); otype(M,A,r,i);
      M(A); M(r); M(f); M(i); b ∈ A |] ==> Ord(f `` Order.pred(A,b,r))"
  <proof>

lemma (in M_ordertype) restrict_omap_ord_iso:
  "[| wellordered(M,A,r); omap(M,A,r,f); otype(M,A,r,i);
      D ⊆ obase(M,A,r); M(A); M(r); M(f); M(i) |]
    ==> restrict(f,D) ∈ (⟨D,r⟩ ≅ ⟨f `` D, Memrel(f `` D)⟩)"
  <proof>

lemma (in M_ordertype) obase_equals:
  "[| wellordered(M,A,r); omap(M,A,r,f); otype(M,A,r,i);

```

$M(A); M(r); M(f); M(i) \mid \Rightarrow \text{obase}(M, A, r) = A$
 $\langle \text{proof} \rangle$

Main result: om gives the order-isomorphism $\langle A, r \rangle \cong \langle i, \text{Memrel}(i) \rangle$

theorem (in $M_ordertype$) $omap_ord_iso_otype$:
 $"[| \text{wellordered}(M, A, r); omap(M, A, r, f); otype(M, A, r, i);$
 $M(A); M(r); M(f); M(i) \mid \Rightarrow f \in \text{ord_iso}(A, r, i, \text{Memrel}(i))"$
 $\langle \text{proof} \rangle$

lemma (in $M_ordertype$) $obase_exists$:
 $"[| M(A); M(r) \mid \Rightarrow M(\text{obase}(M, A, r))"$
 $\langle \text{proof} \rangle$

lemma (in $M_ordertype$) $omap_exists$:
 $"[| M(A); M(r) \mid \Rightarrow \exists z[M]. omap(M, A, r, z)"$
 $\langle \text{proof} \rangle$

lemma (in $M_ordertype$) $otype_exists$:
 $"[| \text{wellordered}(M, A, r); M(A); M(r) \mid \Rightarrow \exists i[M]. otype(M, A, r, i)"$
 $\langle \text{proof} \rangle$

lemma (in $M_ordertype$) $ordertype_exists$:
 $"[| \text{wellordered}(M, A, r); M(A); M(r) \mid$
 $\Rightarrow \exists f[M]. (\exists i[M]. \text{Ord}(i) \ \& \ f \in \text{ord_iso}(A, r, i, \text{Memrel}(i)))"$
 $\langle \text{proof} \rangle$

lemma (in $M_ordertype$) $relativized_imp_well_ord$:
 $"[| \text{wellordered}(M, A, r); M(A); M(r) \mid \Rightarrow \text{well_ord}(A, r)"$
 $\langle \text{proof} \rangle$

16.2 Kunen's theorem 5.4, page 127

(a) The notion of Wellordering is absolute

theorem (in $M_ordertype$) $\text{well_ord_abs} \text{ [simp]}$:
 $"[| M(A); M(r) \mid \Rightarrow \text{wellordered}(M, A, r) \longleftrightarrow \text{well_ord}(A, r)"$
 $\langle \text{proof} \rangle$

(b) Order types are absolute

theorem (in $M_ordertype$) $\text{ordertypes_are_absolute}$:
 $"[| \text{wellordered}(M, A, r); f \in \text{ord_iso}(A, r, i, \text{Memrel}(i));$
 $M(A); M(r); M(f); M(i); \text{Ord}(i) \mid \Rightarrow i = \text{ordertype}(A, r)"$
 $\langle \text{proof} \rangle$

16.3 Ordinal Arithmetic: Two Examples of Recursion

Note: the remainder of this theory is not needed elsewhere.

16.3.1 Ordinal Addition

definition

```
is_oadd_fun :: "[i=>o,i,i,i,i] => o" where
  "is_oadd_fun(M,i,j,x,f) ==
    (∀ sj msj. M(sj) → M(msj) →
      successor(M,j,sj) → membership(M,sj,msj) →
      M_is_recfun(M,
        %x g y. ∃ gx[M]. image(M,g,x,gx) & union(M,i,gx,y),
        msj, x, f))"
```

definition

```
is_oadd :: "[i=>o,i,i,i,i] => o" where
  "is_oadd(M,i,j,k) ==
    (~ ordinal(M,i) & ~ ordinal(M,j) & k=0) |
    (~ ordinal(M,i) & ordinal(M,j) & k=j) |
    (ordinal(M,i) & ~ ordinal(M,j) & k=i) |
    (ordinal(M,i) & ordinal(M,j) &
      (∃ f fj sj. M(f) & M(fj) & M(sj) &
        successor(M,j,sj) & is_oadd_fun(M,i,sj,sj,f) &
        fun_apply(M,f,j,fj) & fj = k))"
```

definition

```
omult_eqns :: "[i,i,i,i,i] => o" where
  "omult_eqns(i,x,g,z) ==
    Ord(x) &
    (x=0 → z=0) &
    (∀ j. x = succ(j) → z = g'j ++ i) &
    (Limit(x) → z = ⋃ (g'x))"
```

definition

```
is_omult_fun :: "[i=>o,i,i,i,i] => o" where
  "is_omult_fun(M,i,j,f) ==
    (∃ df. M(df) & is_function(M,f) &
      is_domain(M,f,df) & subset(M, j, df)) &
    (∀ x∈j. omult_eqns(i,x,f,f'x))"
```

definition

```
is_omult :: "[i=>o,i,i,i,i] => o" where
  "is_omult(M,i,j,k) ==
    ∃ f fj sj. M(f) & M(fj) & M(sj) &
      successor(M,j,sj) & is_omult_fun(M,i,sj,f) &
      fun_apply(M,f,j,fj) & fj = k"
```

```
locale M_ord_arith = M_ordertype +
  assumes oadd_strong_replacement:
    "[| M(i); M(j) |] ==>
      strong_replacement(M,
```

```

      λx z. ∃y[M]. pair(M,x,y,z) &
      (∃f[M]. ∃fx[M]. is_oadd_fun(M,i,j,x,f) &
      image(M,f,x,fx) & y = i ∪ fx))"

and omult_strong_replacement':
  "[| M(i); M(j) |] ==>
  strong_replacement(M,
    λx z. ∃y[M]. z = <x,y> &
    (∃g[M]. is_recfun(Memrel(succ(j)),x,%x g. THE z. omult_eqns(i,x,g,z),g)
&
      y = (THE z. omult_eqns(i, x, g, z))))"

is_oadd_fun: Relating the pure "language of set theory" to Isabelle/ZF

lemma (in M_ord_arith) is_oadd_fun_iff:
  "[| a ≤ j; M(i); M(j); M(a); M(f) |]
  ==> is_oadd_fun(M,i,j,a,f) <=>
  f ∈ a → range(f) & (∀x. M(x) → x < a → f'x = i ∪ f'x)"
  <proof>

lemma (in M_ord_arith) oadd_strong_replacement':
  "[| M(i); M(j) |] ==>
  strong_replacement(M,
    λx z. ∃y[M]. z = <x,y> &
    (∃g[M]. is_recfun(Memrel(succ(j)),x,%x g. i ∪ g'x,g)
&
      y = i ∪ g'x))"
  <proof>

lemma (in M_ord_arith) exists_oadd:
  "[| Ord(j); M(i); M(j) |]
  ==> ∃f[M]. is_recfun(Memrel(succ(j)), j, %x g. i ∪ g'x, f)"
  <proof>

lemma (in M_ord_arith) exists_oadd_fun:
  "[| Ord(j); M(i); M(j) |] ==> ∃f[M]. is_oadd_fun(M,i,succ(j),succ(j),f)"
  <proof>

lemma (in M_ord_arith) is_oadd_fun_apply:
  "[| x < j; M(i); M(j); M(f); is_oadd_fun(M,i,j,j,f) |]
  ==> f'x = i ∪ (⋃k<x. {f'k})"
  <proof>

lemma (in M_ord_arith) is_oadd_fun_iff_oadd [rule_format]:
  "[| is_oadd_fun(M,i,J,J,f); M(i); M(J); M(f); Ord(i); Ord(j) |]
  ==> j < J → f'j = i++j"
  <proof>

```

```

lemma (in M_ord_arith) Ord_oadd_abs:
  "[| M(i); M(j); M(k); Ord(i); Ord(j) |] ==> is_oadd(M,i,j,k) <=> k
= i++j"
<proof>

```

```

lemma (in M_ord_arith) oadd_abs:
  "[| M(i); M(j); M(k) |] ==> is_oadd(M,i,j,k) <=> k = i++j"
<proof>

```

```

lemma (in M_ord_arith) oadd_closed [intro,simp]:
  "[| M(i); M(j) |] ==> M(i++j)"
<proof>

```

16.3.2 Ordinal Multiplication

```

lemma omult_eqns_unique:
  "[| omult_eqns(i,x,g,z); omult_eqns(i,x,g,z') |] ==> z=z'"
<proof>

```

```

lemma omult_eqns_0: "omult_eqns(i,0,g,z) <=> z=0"
<proof>

```

```

lemma the_omult_eqns_0: "(THE z. omult_eqns(i,0,g,z)) = 0"
<proof>

```

```

lemma omult_eqns_succ: "omult_eqns(i,succ(j),g,z) <=> Ord(j) & z = g'j
++ i"
<proof>

```

```

lemma the_omult_eqns_succ:
  "Ord(j) ==> (THE z. omult_eqns(i,succ(j),g,z)) = g'j ++ i"
<proof>

```

```

lemma omult_eqns_Limit:
  "Limit(x) ==> omult_eqns(i,x,g,z) <=> z = ⋃ (g'`x)"
<proof>

```

```

lemma the_omult_eqns_Limit:
  "Limit(x) ==> (THE z. omult_eqns(i,x,g,z)) = ⋃ (g'`x)"
<proof>

```

```

lemma omult_eqns_Not: "~ Ord(x) ==> ~ omult_eqns(i,x,g,z)"
<proof>

```

```

lemma (in M_ord_arith) the_omult_eqns_closed:
  "[| M(i); M(x); M(g); function(g) |]
==> M(THE z. omult_eqns(i, x, g, z))"
<proof>

```

```

lemma (in M_ord_arith) exists_omult:
  "[| Ord(j); M(i); M(j) |]
   ==> ∃ f[M]. is_recfun(Memrel(succ(j)), j, %x g. THE z. omult_eqns(i,x,g,z),
f)"
⟨proof⟩

lemma (in M_ord_arith) exists_omult_fun:
  "[| Ord(j); M(i); M(j) |] ==> ∃ f[M]. is_omult_fun(M,i,succ(j),f)"
⟨proof⟩

lemma (in M_ord_arith) is_omult_fun_apply_0:
  "[| 0 < j; is_omult_fun(M,i,j,f) |] ==> f'0 = 0"
⟨proof⟩

lemma (in M_ord_arith) is_omult_fun_apply_succ:
  "[| succ(x) < j; is_omult_fun(M,i,j,f) |] ==> f'succ(x) = f'x ++ i"
⟨proof⟩

lemma (in M_ord_arith) is_omult_fun_apply_Limit:
  "[| x < j; Limit(x); M(j); M(f); is_omult_fun(M,i,j,f) |]
   ==> f' x = (⋃ y∈x. f'y)"
⟨proof⟩

lemma (in M_ord_arith) is_omult_fun_eq_omult:
  "[| is_omult_fun(M,i,J,f); M(J); M(f); Ord(i); Ord(j) |]
   ==> j < J ⟶ f'j = i**j"
⟨proof⟩

lemma (in M_ord_arith) omult_abs:
  "[| M(i); M(j); M(k); Ord(i); Ord(j) |] ==> is_omult(M,i,j,k) ⟷
k = i**j"
⟨proof⟩

```

16.4 Absoluteness of Well-Founded Relations

Relativized to M : Every well-founded relation is a subset of some inverse image of an ordinal. Key step is the construction (in M) of a rank function.

```

locale M_wfrank = M_tranc1 +
  assumes wfrank_separation:
    "M(r) ==>
     separation (M, λx.
       ∀ rplus[M]. tran_closure(M,r,rplus) ⟶
       ~ (∃ f[M]. M_is_recfun(M, %x f y. is_range(M,f,y), rplus, x, f)))"
  and wfrank_strong_replacement:
    "M(r) ==>
     strong_replacement(M, λx z.
       ∀ rplus[M]. tran_closure(M,r,rplus) ⟶
       (∃ y[M]. ∃ f[M]. pair(M,x,y,z) &

```

```

                                M_is_recfun(M, %x f y. is_range(M,f,y), rplus,
x, f) &
                                is_range(M,f,y)))"
and Ord_wfrank_separation:
  "M(r) ==>
    separation (M, λx.
      ∀ rplus[M]. tran_closure(M,r,rplus) →
      ~ (∀ f[M]. ∀ rangef[M].
        is_range(M,f,rangef) →
        M_is_recfun(M, λx f y. is_range(M,f,y), rplus, x, f) →
        ordinal(M,rangef)))"

```

Proving that the relativized instances of Separation or Replacement agree with the "real" ones.

```

lemma (in M_wfrank) wfrank_separation':
  "M(r) ==>
    separation
      (M, λx. ~ (∃ f[M]. is_recfun(r^+, x, %x f. range(f), f)))"
<proof>

```

```

lemma (in M_wfrank) wfrank_strong_replacement':
  "M(r) ==>
    strong_replacement(M, λx z. ∃ y[M]. ∃ f[M].
      pair(M,x,y,z) & is_recfun(r^+, x, %x f. range(f), f)
&
      y = range(f))"
<proof>

```

```

lemma (in M_wfrank) Ord_wfrank_separation':
  "M(r) ==>
    separation (M, λx.
      ~ (∀ f[M]. is_recfun(r^+, x, λx. range, f) → Ord(range(f))))"
<proof>

```

This function, defined using replacement, is a rank function for well-founded relations within the class M.

definition

```

wellfoundedrank :: "[i=>o,i,i] => i" where
  "wellfoundedrank(M,r,A) ==
    {p. x∈A, ∃ y[M]. ∃ f[M].
      p = <x,y> & is_recfun(r^+, x, %x f. range(f), f)
&
      y = range(f)}"

```

```

lemma (in M_wfrank) exists_wfrank:
  "[| wellfounded(M,r); M(a); M(r) |]
  ==> ∃ f[M]. is_recfun(r^+, a, %x f. range(f), f)"
<proof>

```

```

lemma (in M_wfrank) M_wellfoundedrank:
  "[| wellfounded(M,r); M(r); M(A) |] ==> M(wellfoundedrank(M,r,A))"
  <proof>

lemma (in M_wfrank) Ord_wfrank_range [rule_format]:
  "[| wellfounded(M,r); a∈A; M(r); M(A) |]
  ==> ∀ f[M]. is_recfun(r^+, a, %x f. range(f), f) → Ord(range(f))"
  <proof>

lemma (in M_wfrank) Ord_range_wellfoundedrank:
  "[| wellfounded(M,r); r ⊆ A*A; M(r); M(A) |]
  ==> Ord (range(wellfoundedrank(M,r,A)))"
  <proof>

lemma (in M_wfrank) function_wellfoundedrank:
  "[| wellfounded(M,r); M(r); M(A) |]
  ==> function(wellfoundedrank(M,r,A))"
  <proof>

lemma (in M_wfrank) domain_wellfoundedrank:
  "[| wellfounded(M,r); M(r); M(A) |]
  ==> domain(wellfoundedrank(M,r,A)) = A"
  <proof>

lemma (in M_wfrank) wellfoundedrank_type:
  "[| wellfounded(M,r); M(r); M(A) |]
  ==> wellfoundedrank(M,r,A) ∈ A -> range(wellfoundedrank(M,r,A))"
  <proof>

lemma (in M_wfrank) Ord_wellfoundedrank:
  "[| wellfounded(M,r); a ∈ A; r ⊆ A*A; M(r); M(A) |]
  ==> Ord(wellfoundedrank(M,r,A) ` a)"
  <proof>

lemma (in M_wfrank) wellfoundedrank_eq:
  "[| is_recfun(r^+, a, %x. range, f);
  wellfounded(M,r); a ∈ A; M(f); M(r); M(A) |]
  ==> wellfoundedrank(M,r,A) ` a = range(f)"
  <proof>

lemma (in M_wfrank) wellfoundedrank_lt:
  "[| <a,b> ∈ r;
  wellfounded(M,r); r ⊆ A*A; M(r); M(A) |]
  ==> wellfoundedrank(M,r,A) ` a < wellfoundedrank(M,r,A) ` b"
  <proof>

```

```

lemma (in M_wfrank) wellfounded_imp_subset_rvimage:
  "[|wellfounded(M,r); r ⊆ A*A; M(r); M(A)|]
  ==> ∃ i f. Ord(i) & r ⊆ rvimage(A, f, Memrel(i))"
<proof>

lemma (in M_wfrank) wellfounded_imp_wf:
  "[|wellfounded(M,r); relation(r); M(r)|] ==> wf(r)"
<proof>

lemma (in M_wfrank) wellfounded_on_imp_wf_on:
  "[|wellfounded_on(M,A,r); relation(r); M(r); M(A)|] ==> wf[A](r)"
<proof>

theorem (in M_wfrank) wf_abs:
  "[|relation(r); M(r)|] ==> wellfounded(M,r) ⟷ wf(r)"
<proof>

theorem (in M_wfrank) wf_on_abs:
  "[|relation(r); M(r); M(A)|] ==> wellfounded_on(M,A,r) ⟷ wf[A](r)"
<proof>

end

```

17 Separation for Facts About Order Types, Rank Functions and Well-Founded Relations

theory Rank_Separation imports Rank Rec_Separation begin

This theory proves all instances needed for locales $M_ordertype$ and M_wfrank .
But the material is not needed for proving the relative consistency of AC.

17.1 The Locale $M_ordertype$

17.1.1 Separation for Order-Isomorphisms

```

lemma well_ord_iso_Reflects:
  "REFLECTS[λx. x∈A ⟶
    (∃ y[L]. ∃ p[L]. fun_apply(L,f,x,y) & pair(L,y,x,p) & p
  ∈ r),
    λi x. x∈A ⟶ (∃ y ∈ Lset(i). ∃ p ∈ Lset(i).
    fun_apply(##Lset(i),f,x,y) & pair(##Lset(i),y,x,p) & p
  ∈ r)]"
<proof>

```

```

lemma well_ord_iso_separation:
  "[| L(A); L(f); L(r) |]
  ==> separation (L, λx. x∈A ⟶ (∃ y[L]. (∃ p[L].

```

$\text{fun_apply}(L, f, x, y) \ \& \ \text{pair}(L, y, x, p) \ \& \ p \in r)))"$

$\langle \text{proof} \rangle$

17.1.2 Separation for obase

lemma *obase_reflects*:

"REFLECTS[$\lambda a. \exists x[L]. \exists g[L]. \exists mx[L]. \exists par[L].$
 $\text{ordinal}(L, x) \ \& \ \text{membership}(L, x, mx) \ \& \ \text{pred_set}(L, A, a, r, par)$
 $\&$
 $\text{order_isomorphism}(L, par, r, x, mx, g),$
 $\lambda i \ a. \exists x \in \text{Lset}(i). \exists g \in \text{Lset}(i). \exists mx \in \text{Lset}(i). \exists par \in \text{Lset}(i).$
 $\text{ordinal}(\#\text{Lset}(i), x) \ \& \ \text{membership}(\#\text{Lset}(i), x, mx) \ \& \ \text{pred_set}(\#\text{Lset}(i), A, a, r, par)$
 $\&$
 $\text{order_isomorphism}(\#\text{Lset}(i), par, r, x, mx, g)]"$

$\langle \text{proof} \rangle$

lemma *obase_separation*:

— part of the order type formalization
" $[\mid L(A); L(r) \mid]$
 $\implies \text{separation}(L, \lambda a. \exists x[L]. \exists g[L]. \exists mx[L]. \exists par[L].$
 $\text{ordinal}(L, x) \ \& \ \text{membership}(L, x, mx) \ \& \ \text{pred_set}(L, A, a, r, par)$
 $\&$
 $\text{order_isomorphism}(L, par, r, x, mx, g))"$

$\langle \text{proof} \rangle$

17.1.3 Separation for a Theorem about obase

lemma *obase_equals_reflects*:

"REFLECTS[$\lambda x. x \in A \longrightarrow \sim(\exists y[L]. \exists g[L].$
 $\text{ordinal}(L, y) \ \& \ (\exists my[L]. \exists pxr[L].$
 $\text{membership}(L, y, my) \ \& \ \text{pred_set}(L, A, x, r, pxr) \ \&$
 $\text{order_isomorphism}(L, pxr, r, y, my, g)))$,
 $\lambda i \ x. x \in A \longrightarrow \sim(\exists y \in \text{Lset}(i). \exists g \in \text{Lset}(i).$
 $\text{ordinal}(\#\text{Lset}(i), y) \ \& \ (\exists my \in \text{Lset}(i). \exists pxr \in \text{Lset}(i).$
 $\text{membership}(\#\text{Lset}(i), y, my) \ \& \ \text{pred_set}(\#\text{Lset}(i), A, x, r, pxr)$
 $\&$
 $\text{order_isomorphism}(\#\text{Lset}(i), pxr, r, y, my, g)))]"$

$\langle \text{proof} \rangle$

lemma *obase_equals_separation*:

" $[\mid L(A); L(r) \mid]$
 $\implies \text{separation}(L, \lambda x. x \in A \longrightarrow \sim(\exists y[L]. \exists g[L].$
 $\text{ordinal}(L, y) \ \& \ (\exists my[L]. \exists pxr[L].$
 $\text{membership}(L, y, my) \ \& \ \text{pred_set}(L, A, x, r, pxr)$
 $\&$
 $\text{order_isomorphism}(L, pxr, r, y, my, g)))]"$

$\langle \text{proof} \rangle$

17.1.4 Replacement for omap

```

lemma omap_reflects:
  "REFLECTS[ $\lambda z. \exists a[L]. a \in B \ \& \ (\exists x[L]. \exists g[L]. \exists mx[L]. \exists par[L].$ 
    ordinal( $L, x$ ) & pair( $L, a, x, z$ ) & membership( $L, x, mx$ ) &
    pred_set( $L, A, a, r, par$ ) & order_isomorphism( $L, par, r, x, mx, g$ )),
   $\lambda i z. \exists a \in Lset(i). a \in B \ \& \ (\exists x \in Lset(i). \exists g \in Lset(i). \exists mx \in Lset(i).$ 
     $\exists par \in Lset(i).$ 
    ordinal( $\#\#Lset(i), x$ ) & pair( $\#\#Lset(i), a, x, z$ ) &
    membership( $\#\#Lset(i), x, mx$ ) & pred_set( $\#\#Lset(i), A, a, r, par$ ) &
    order_isomorphism( $\#\#Lset(i), par, r, x, mx, g$ ))]"
<proof>

lemma omap_replacement:
  "[| L(A); L(r) |]
  ==> strong_replacement(L,
     $\lambda a z. \exists x[L]. \exists g[L]. \exists mx[L]. \exists par[L].$ 
    ordinal( $L, x$ ) & pair( $L, a, x, z$ ) & membership( $L, x, mx$ ) &
    pred_set( $L, A, a, r, par$ ) & order_isomorphism( $L, par, r, x, mx, g$ ))]"
<proof>

```

17.2 Instantiating the locale $M_ordertype$

Separation (and Strong Replacement) for basic set-theoretic constructions such as intersection, Cartesian Product and image.

```

lemma M_ordertype_axioms_L: "M_ordertype_axioms(L)"
<proof>

```

```

theorem M_ordertype_L: "M_ordertype(L)"
<proof>

```

17.3 The Locale M_wfrank

17.3.1 Separation for wfrank

```

lemma wfrank_Reflects:
  "REFLECTS[ $\lambda x. \forall rplus[L]. \text{tran\_closure}(L, r, rplus) \longrightarrow$ 
     $\sim (\exists f[L]. M\_is\_recfun(L, \%x f y. \text{is\_range}(L, f, y), rplus,$ 
     $x, f)),$ 
   $\lambda i x. \forall rplus \in Lset(i). \text{tran\_closure}(\#\#Lset(i), r, rplus) \longrightarrow$ 
     $\sim (\exists f \in Lset(i).$ 
     $M\_is\_recfun(\#\#Lset(i), \%x f y. \text{is\_range}(\#\#Lset(i), f, y),$ 
     $rplus, x, f))]"$ 
<proof>

lemma wfrank_separation:
  "L(r) ==>
  separation (L,  $\lambda x. \forall rplus[L]. \text{tran\_closure}(L, r, rplus) \longrightarrow$ 
     $\sim (\exists f[L]. M\_is\_recfun(L, \%x f y. \text{is\_range}(L, f, y), rplus, x, f)))"$ 
<proof>

```

17.3.2 Replacement for wfrank

lemma wfrank_replacement_Reflects:

```
"REFLECTS[λz. ∃x[L]. x ∈ A &
  (∀rplus[L]. tran_closure(L,r,rplus) →
    (∃y[L]. ∃f[L]. pair(L,x,y,z) &
      M_is_recfun(L, %x f y. is_range(L,f,y), rplus,
x, f) &
        is_range(L,f,y))),
  λi z. ∃x ∈ Lset(i). x ∈ A &
    (∀rplus ∈ Lset(i). tran_closure(##Lset(i),r,rplus) →
      (∃y ∈ Lset(i). ∃f ∈ Lset(i). pair(##Lset(i),x,y,z) &
        M_is_recfun(##Lset(i), %x f y. is_range(##Lset(i),f,y), rplus,
x, f) &
          is_range(##Lset(i),f,y)))]]"
⟨proof⟩
```

lemma wfrank_strong_replacement:

```
"L(r) ==>
  strong_replacement(L, λx z.
    ∀rplus[L]. tran_closure(L,r,rplus) →
      (∃y[L]. ∃f[L]. pair(L,x,y,z) &
        M_is_recfun(L, %x f y. is_range(L,f,y), rplus,
x, f) &
          is_range(L,f,y)))"
⟨proof⟩
```

17.3.3 Separation for Proving Ord_wfrank_range

lemma Ord_wfrank_Reflects:

```
"REFLECTS[λx. ∀rplus[L]. tran_closure(L,r,rplus) →
  ~ (∀f[L]. ∀rangef[L].
    is_range(L,f,rangef) →
      M_is_recfun(L, λx f y. is_range(L,f,y), rplus, x, f) →
        ordinal(L,rangef)),
  λi x. ∀rplus ∈ Lset(i). tran_closure(##Lset(i),r,rplus) →
  ~ (∀f ∈ Lset(i). ∀rangef ∈ Lset(i).
    is_range(##Lset(i),f,rangef) →
      M_is_recfun(##Lset(i), λx f y. is_range(##Lset(i),f,y),
        rplus, x, f) →
        ordinal(##Lset(i),rangef))]"
⟨proof⟩
```

lemma Ord_wfrank_separation:

```
"L(r) ==>
  separation (L, λx.
    ∀rplus[L]. tran_closure(L,r,rplus) →
      ~ (∀f[L]. ∀rangef[L].
        is_range(L,f,rangef) →
          M_is_recfun(L, λx f y. is_range(L,f,y), rplus, x, f) →
```

`ordinal(L, range f)))"`

`<proof>`

17.3.4 Instantiating the locale M_{wfrank}

lemma $M_{\text{wfrank_axioms_L}}$: " $M_{\text{wfrank_axioms}}(L)$ "

`<proof>`

theorem $M_{\text{wfrank_L}}$: " $M_{\text{wfrank}}(L)$ "

`<proof>`

```

lemmas exists_wfrank = M_wfrank.exists_wfrank [OF M_wfrank_L]
  and M_wellfoundedrank = M_wfrank.M_wellfoundedrank [OF M_wfrank_L]
  and Ord_wfrank_range = M_wfrank.Ord_wfrank_range [OF M_wfrank_L]
  and Ord_range_wellfoundedrank = M_wfrank.Ord_range_wellfoundedrank [OF
M_wfrank_L]
  and function_wellfoundedrank = M_wfrank.function_wellfoundedrank [OF
M_wfrank_L]
  and domain_wellfoundedrank = M_wfrank.domain_wellfoundedrank [OF M_wfrank_L]
  and wellfoundedrank_type = M_wfrank.wellfoundedrank_type [OF M_wfrank_L]
  and Ord_wellfoundedrank = M_wfrank.Ord_wellfoundedrank [OF M_wfrank_L]
  and wellfoundedrank_eq = M_wfrank.wellfoundedrank_eq [OF M_wfrank_L]
  and wellfoundedrank_lt = M_wfrank.wellfoundedrank_lt [OF M_wfrank_L]
  and wellfounded_imp_subset_rvimage = M_wfrank.wellfounded_imp_subset_rvimage
[OF M_wfrank_L]
  and wellfounded_imp_wf = M_wfrank.wellfounded_imp_wf [OF M_wfrank_L]
  and wellfounded_on_imp_wf_on = M_wfrank.wellfounded_on_imp_wf_on [OF
M_wfrank_L]
  and wf_abs = M_wfrank.wf_abs [OF M_wfrank_L]
  and wf_on_abs = M_wfrank.wf_on_abs [OF M_wfrank_L]

end

```

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