

Fine Structure Seminar

Rutgers University

Stefan Mesken

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1 Fine Structure

Unless specified otherwise, M, N are acceptable \mathcal{J} -structures, $k, l, m, n < \omega$, $\alpha, \beta, \gamma, \dots \in \text{Ord}$.

1.8 Substitution and Good Functions

Talk 1, first draft

Problem 1.8.1. $\Sigma_1^{(n)}(M)$ -relations are not necessarily closed under substitution of $\Sigma_1^{(n)}(M)$ -functions.

Exercise 1.8.1. Find an example for a $\Sigma_1^{(n)}(M)$ -relation R and a (partial) $\Sigma_1^{(n)}(M)$ -function f such that $R \circ f$ is not a $\Sigma_1^{(n)}(M)$ relation.

Hint 1.8.1. Suppose that M is an acceptable \mathcal{J} -structure s.t. $\omega\rho_M^2 < \omega\rho_M^1$ and such that there is some $\Sigma_0^{(0)}$ -formula ϕ and some $p \in M$ with

$$A := \{\xi < \omega\rho_M^2 \mid M \models \exists x^1 \phi[\xi, x^{(1)}, p]\} \notin M.$$

(Such M exist. In fact, we can pick $M = J_\alpha$ for some countable α .)

Let f be the partial $\Sigma_1^{(0)}(M)$ -function defined by the formula

$$\psi(y^{(0)}, z^{(1)}) : \iff y^{(0)} = z^{(1)}.$$

Consider $\phi(x^{(0)}, f(y^{(0)}), p)$.

Our goal is to identify a sufficiently large collection of good $\Sigma_1^{(n)}$ -functions that can be substituted into $\Sigma_1^{(n)}$ -relations without increasing their complexity. The key step to the definition of good $\Sigma_1^{(n)}$ -functions is the following

Lemma 1.8.1. *Let $n < \omega$ and $R(\vec{x}^0, \dots, \vec{x}^n)$ be a $\Sigma_1^{(n)}(M)$ -relation. Let F^0, \dots, F^n be such that for all $i \leq n$ $F^i(\vec{x}^0, \dots, \vec{x}^{(n)})$ is a partial $\Sigma_1^{(i)}(M)$ -function to H_M^i . Then*

$$R(F^0(\vec{x}^0, \dots, \vec{x}^n), \dots, F^n(\vec{x}^0, \dots, \vec{x}^n))$$

is (uniformly) a $\Sigma_1^{(n)}(M)$ -relation.

Proof. By induction on n . The case $n = 0$ is a simplification of the induction step $n \mapsto n + 1$, hence we will only consider the latter:

Let $R(\vec{x}^0, \dots, \vec{x}^n)$ be a $\Sigma_1^{(n+1)}(M)$ relation and let F^0, \dots, F^{n+1} be as above. Write

$$R(\vec{x}^0, \dots, \vec{x}^{n+1}) \equiv \exists z^{n+1} B(v^{n+1}, \vec{x}^{n+1}) R^*(\vec{x}^0, \dots, \vec{x}^{n+1}, v^{n+1}, z^{n+1})$$

with

1. B being a block of bounded quantifiers and
2. R^* being a Boolean combinatin of $\Sigma_1^{(n)}(M)$ -relations.

By our induction hypothesis and the fact that every $\Sigma_1^{(n)}(M)$ -relation is the specialization of a $\Sigma_1^{(n)}(M)$ with arguments of type $\leq n$, we obtain that

$$R(F^0(\vec{y}), \dots, F^n(\vec{y}), \vec{x}^{n+1})$$

is $\Sigma_1^{(n+1)}(M)$. But now

$$R(F^0(\vec{y}), \dots, F^{n+1}(\vec{y})) \equiv \exists \vec{x}^{n+1}: x^{n+1} = F^{n+1}(\vec{y}) \wedge R(F^0(\vec{y}), \dots, F^n(\vec{y}), \vec{x}^{n+1})$$

is $\Sigma_1^{(n+1)}(M)$.

Note that this transformation only depends on the formulae defining R, F^0, \dots, F^{n+1} and not on M , which yields the uniformity we claimed. \square

Corollary 1.8.1. *Let $n < \omega$, $1 \leq l < \omega$ and $R(\vec{x}^0, \dots, \vec{x}^n)$ be a $\Sigma_l^{(n)}(M)$ -relation. Let F^0, \dots, F^n be such that for all $i \leq n$ $F^i(\vec{x}^0, \dots, \vec{x}^{(n)})$ is a partial $\Sigma_1^{(i)}(M)$ -function to H_M^i . Then*

$$R(F^0(\vec{x}^0, \dots, \vec{x}^n), \dots, F^n(\vec{x}^0, \dots, \vec{x}^n))$$

is (uniformly) a $\Sigma_l^{(n)}(M)$ -relation.

Corollary 1.8.2. *Let $R(x^{i_0}, \dots, x^{i_l})$ be a $\Sigma_l^{(n)}(M)$ -relation with $1 \leq l < \omega$ and $i_0, \dots, i_k \leq n < \omega$. Then there is a $\Sigma_l^{(n)}(M)$ -relation $R^*(x^0, \dots, x^0)$ with the same graph as R*

Proof. Let R^{**} be the result of replacing each x^{i_0} with x^0 in R . For $j \leq k$ let F^j be the partial $\Sigma_1^{i_j}(M)$ -function to $H_M^{i_j}$ defined by

$$\phi^j(x^0, y^{i_j}) \equiv x^0 = y^{i_j}.$$

Then $R^{**}(F^{i_0}(x^0), \dots, F^{i_k}(x^0))$ is a $\Sigma_l^{(n)}(M)$ -relation with the same graph as R . \square

Definition 1.8.1. *Let $n < \omega$. The good $\Sigma_1^{(n)}(M)$ -functions consists of the \subseteq -smallest class $\mathcal{G}_1^{(n)}$ such that*

1. *Every partial $\Sigma_1^{(i)}(M)$ -function $F(x^{i_0}, \dots, x^{i_k})$ to H_M^i with $i_0, \dots, i_k, i \leq n$ is in $\mathcal{G}_1^{(n)}$ and*
2. *$\mathcal{G}_1^{(n)}$ is closed under composition, i.e. if $F(x^{i_0}, \dots, x^{i_k})$ is in $\mathcal{G}_1^{(n)}$ and $G(\vec{z})$ is a function to $H_M^{i_j}$ for some $j \leq k$ in $\mathcal{G}_1^{(n)}$, then*

$$F(x^{i_0}, \dots, x^{i_{j-1}}, G(\vec{z}), x^{i_{j+1}}, \dots, x^{i_k})$$

is in $\mathcal{G}_1^{(n)}$.

Lemma 1.8.2. *Let $n < \omega, 1 \leq l < \omega, i_0, \dots, i_k \leq n$ and $R(x^{i_0}, \dots, x^{i_k})$ be a $\Sigma_l^{(n)}(M)$ -relation. If, for $j \leq k$, $F_j(\vec{z})$ is a good $\Sigma_1^{(n)}(M)$ -function to $H_M^{i_j}$, then*

$$R(F_0(\vec{z}), \dots, F_n(\vec{z}))$$

is $\Sigma_l^{(n)}(M)$.

Proof. Repeated application of Corollary 1.8.1. \square

We are now ready to prove one of the main pillars of basic Σ^* fine structure:

Theorem 1.8.1 ($\Sigma_1^{(n)}$ -Uniformization). *Let $n < \omega$ and $R(\vec{x}^0, \dots, \vec{x}^n, y^n)$ be a $\Sigma_1^{(n)}(M)$ -relation. Then there is a partial $\Sigma_1^{(n)}(M)$ -function F to H_M^n such that*

1. $\text{dom}(F) = \{\vec{x} \mid \exists y^n R(\vec{x}, y^n)\}$ and
2. $\forall \vec{x} (\exists y^n R(\vec{x}, y^n) \implies R(\vec{x}, F(\vec{x})))$

Moreover, F can be chosen to have a uniform definition in R 's definition.

Proof. Recall that

$$R_{\vec{x}} := \{(\vec{x}^n, y^n) \mid R(\vec{x}^0, \dots, \vec{x}^n, y^n)\}$$

is uniformly $\Sigma_1(M^{n,(\vec{x}^0, \dots, \vec{x}^{n-1})})$. Let $i < \omega$ be such that ϕ_i defines $R_{\vec{x}}$ and let

$$F(\vec{x}^0, \dots, \vec{x}^n) := h_{M^{n,(\vec{x}^0, \dots, \vec{x}^{n-1})}}(i, \vec{x}^n).$$

Since $h_{M^{n,(\vec{x}^0, \dots, \vec{x}^{n-1})}}$ is uniformly $\Sigma_1(M^{n,(\vec{x}^0, \dots, \vec{x}^{n-1})})$, we have that F is $\Sigma_1^{(n)}(M)$ and clearly F uniformizes R . \square

Remark 1.8.1. In these notes, we don't cover the definition of $Q^{(n)}$ -formulae. Consult Zeman's book.

Lemma 1.8.3. Let $n < \omega$. There is a uniform good $\Sigma_1^{(n)}(M)$ function

$$F: H_M^{n+1} \times H_M^0 \rightarrow H_M^0$$

such that for all $r \in R_M^{n+1}$

$$F_r: H_M^{n+1} \rightarrow M, x^{n+1} \mapsto F(x^{n+1}, r)$$

is surjective.

Proof. By induction on $n < \omega$.

$n = 0$: Let

$$F: H_M^1 \times H_M^0 \rightarrow H_M^0, (w, p) \mapsto h_M(w(0), (w(1), p(0))).$$

$n \mapsto n + 1$: Let

$$G: H_M^{n+1} \times H_M^0 \rightarrow H_M^0$$

be as above. Define

$$F: H_M^{n+1} \times H_M^0 \rightarrow H_M^0, (w, p) \mapsto G(h_{M^{n,p \upharpoonright n}}(w(0), (w(1), p(n))), p \upharpoonright n).$$

Here we let $w(k), p(k), p \upharpoonright k, k < \omega$ be the usual interpretation for functions if w, p are functions whose domain contains $k + 1$ and otherwise we define them to be \emptyset .

\square

Exercise 1.8.2. Verify that the functions defined above are as desired.

Hint: Recall that if $r \in R_M^{n+1}$ then $r \upharpoonright n \in R_M^n$ and $r(n) \in R_{M^{n,r \upharpoonright n}}$.

Definition 1.8.2. For $p \in \Gamma_M^n$ let

1. $h_M^{n,p} := h_{M^{n,p}}$ and
2. \tilde{h}_M^n be uniform good $\Sigma_1^{(n-1)}(M)$ -function given nesting Skolem functions of the i -th projecta as in Lemma 1.8.3, i.e.

$$\tilde{h}_M^1(w, p) := h_M(w(0), (w(1), p(0)))$$

and

$$\tilde{h}_M^{n+1}(w, p) := h_M^n(h_{M^{n,p \upharpoonright n}}(w(0), (w(1), p(n))), p \upharpoonright n).$$

Remark 1.8.2. If $r \in R_M^{n+1}$, then every $x \in M$ is of the form $\tilde{h}^{n+1}(z, r)$ for some $z \in H_M^{n+1}$. In fact, we can choose $z \in [\omega \rho_M^{n+1}]^{<\omega}$.

Corollary 1.8.3. Let $1 \leq n < \omega$ and $r \in R_M^n$. Then every $A \subseteq H_M^n$ which is $\Sigma_1^n(M)$ is $\Sigma_1(M^{n,r})$.

Proof. We already know that $\Sigma_1(M^{n,r}) \subseteq \Sigma_1^{(n)}(M)$.

Conversely let

$$A = \{x \in H_M^n \mid M \models \phi[x, q]\}$$

for some $\Sigma_1^{(n)}$ -formula ϕ and some $q \in M$. Fix $\vec{\xi} \in [\omega \rho_M^n]^{<\omega}$ such that $q = \tilde{h}_M^n(\vec{\xi}, r)$. Then

$$A(x^n) \iff M \models \phi[x^n, \tilde{h}_M^n(\vec{\xi}^n, r^0)].$$

Since $\tilde{h}^n(y^n, z^0)$ is a good $\Sigma_1^{(n-1)}(M)$ -function (and thus a good $\Sigma_1^{(n)}(M)$ -function), this witnesses that A is $\Sigma_1^{(n)}(M)$ in parameters $\vec{\xi}, r$ and hence $\Sigma_1(M^{n,r})$ (by the characterization of $\Sigma_l^{(n)}(M)$ subsets of H_M^n as $\Sigma_l(M^{n,r})$ relations in $\Sigma_1^{(n-1)}(M)$ predicates). \square

Corollary 1.8.4. Let $n < \omega$ and $r \in R_M^n$. Then $\rho_M^{n+1} = \rho_{M^{n,r}}$.

Proof. By definition $\rho_M^{n+1} \leq \rho_{M^{n,r}}$, hence it suffices to show the converse.

Let $q \in P_M^{n+1}$ and A be $\Sigma_1^{(n)}(M)$ in q such that $A \cap \omega \rho_M^{n+1} \not\subseteq M$. By Corollary 1.8.3, A is $\Sigma_1(M^{n,r})$, so that $\rho_{M^{n,r}} \leq \rho_M^{n+1}$. \square

Corollary 1.8.5. Let $r \in R_M^n$ and $m \leq n$. Then

- $\rho_M^n = \rho_{M^{m,r \upharpoonright m}}^{n-m}$ and
- $M^{n,r} = (M^{m,r \upharpoonright m})^{n-m,s}$, where $s: n-m \rightarrow M$ is given by $s(i) := r(m+i)$.

Proof. By induction on $n - m$ and the two preceding corollaries. \square

Exercise 1.8.3. Let $r, s \in R_M^n$. Then

$$\Sigma_1(M^{n,r}) = \Sigma_1(M^{n,s}).$$

Remark 1.8.3. In these notes, I don't cover functionally absolute definitions of good $\Sigma_1^{(n)}(M)$ -functions. Consult Zeman's book.

Lemma 1.8.4. If $R_M^n \neq \emptyset$, then $\Sigma_l(M) \subseteq \Sigma_l^{(n)}(M)$ for every $l \geq 1$.

Proof. We will prove the result for $l = 1$. The general case follows by a straightforward induction. Let $r \in R_M^n, \phi$ be a Σ_0 formula, $q \in M$ and

$$A = \{a \in M \mid M \models \exists x \phi[x, a, q]\}.$$

Fix $\vec{\xi} \in [\omega \rho_M^n]^{<\omega}$ such that $q = \tilde{h}^n(\vec{\xi}, r)$. Then

$$A = \{a \in M \mid M \models \exists x^{(n)} \phi[\tilde{h}^n(x^n, r^0), a^0, \tilde{h}^n(\vec{\xi}^n, r^0)]\}$$

is $\Sigma_1^{(n)}(M)$. \square

Corollary 1.8.6. If $R_M^n \neq \emptyset$, then $\Sigma_{<\omega}(M) = \Sigma_{<\omega}^{(n)}(M)$.

Proof. Lemma 1.8.4 yields $\Sigma_{<\omega}(M) \subseteq \Sigma_{<\omega}^{(n)}(M)$. For the converse just note that every $\Sigma_l^{(n)}$ -formulae can be expressed as a Σ_l -formula (in parameters) by replacing each occurrence of the variable x^i with $x \in H_M^i$ if $\omega \rho_M^i < o(M)$ or with x if $\omega \rho_M^i = o(M)$. \square

1.9 Standard Parameters

Talk 2, first draft

Lemma 1.9.1. $h_M''[o(M)]^{<\omega} = M$.

Proof. Let $X := h_M''[o(M)]^{<\omega}$. Since X is closed under pairing, we have $X \prec_1 M$. Let

$$N \cong^\pi X \prec_1 M$$

be the Mostowski collapse. Since being an acceptable \mathcal{J} -structure is a Q -property, we have that N is an acceptable \mathcal{J} -structure and clearly $\pi^{-1} \upharpoonright o(M) = \text{id}$. Since there is, for acceptable \mathcal{J} -structures K , a uniform lightface Σ_1 -definable surjection $f^K: [o(M)]^{<\omega} \twoheadrightarrow K$, it follows that $N = M$. \square

Lemma 1.9.2. *Let A be $\Sigma_1^{(n)}(M)$ in the parameter $p \in M$. Then there is some $p' \in [o(M)]^{<\omega}$ such that A is $\Sigma_1^{(n)}(M)$ in p' .*

Proof. Fix $\phi \in \Sigma_1^{(n)}(M)$ such that

$$A = \{a \in M \mid M \models \phi[a, p]\}.$$

Let $p' \in [o(M)]^{<\omega}$ be such that $p = h_M(p')$. Then

$$A = \{a \in M \mid M \models \exists x^{(0)}: \underbrace{h_M(p') = x^{(0)}}_{\Sigma_1^{(0)}} \wedge \phi[a, x^0]\}.$$

is $\Sigma_1^{(n)}(M)$ in p' . □

Convention 1.9.1. *Let $p \in P_M^{(n)}$. If, for every $i \in \text{dom}(i)$, $p(i)$ is a finite set of ordinals, we will identify p with $\bigcup \text{ran}(p) \in [\text{Ord}]^{<\omega}$. And we let $P_M^{(n)} \cap [o(M)]^{<\omega}$ be the collection of these good parameters.*

By the previous lemma we may restrict ourselves to good parameters which are finite sets of ordinals, i.e. to $P_M^{(n)} \cap [o(M)]^{<\omega}$ and we shall do so from now on.

Definition 1.9.1. *Let $a, b \in [\text{Ord}]^{<\omega}$.*

1. $a \Delta b := (a \setminus b) \cup (b \setminus a)$ and
2. $a <^* b : \iff \max(a \Delta b) \in b$.

Exercise 1.9.1. *Let $a, b \in [\text{Ord}]^{<\omega}$. The following are equivalent*

1. $a <^* b$,
2. $\exists \xi \in b \setminus a: b \setminus (\xi + 1) = a \setminus (\xi + 1)$,
3. $\vec{a} <_{\text{lex}} \vec{b}$,

where $\begin{Bmatrix} \vec{a} \\ \vec{b} \end{Bmatrix}$ is the strictly decreasing enumeration of $\begin{Bmatrix} a \\ b \end{Bmatrix}$.

Definition 1.9.2. *A definable, binary relation R is set-like if for all y*

$$(_R y) := \{x \mid (x, y) \in R\}$$

is a set.

Exercise 1.9.2. $<^*$ is a set-like strict, Σ_0 -definable well-order of $[\text{Ord}]^{<\omega}$.

(Hint: The only tricky bit is to show that $<^*$ is well-founded. So, suppose it isn't. Fix a set $A \subseteq [\text{Ord}]^{<^*}$ with no $<^*$ -minimal element. Recursively construct a strictly decreasing sequence $(\xi_n \mid n < \omega)$ via $\xi_0 := \min\{\max(a) \mid a \in A\}$ and $\xi_{n+1} := \min\{\max(a \cap \xi_n) \mid a \in A \wedge a \setminus \xi_n = \{\xi_0, \dots, \xi_n\}\}$. Verify that this construction never breaks down (i.e. $\xi_{n+1} \neq 0$.)

Definition 1.9.3. The $<^*$ -least $p \in P_M^{(n)} \cap [o(M)]^{<\omega}$, denoted by $p_{M,n}$, is called the n -th standard parameter of M .¹
The $<^*$ -least $p \in P_M^* \cap [o(M)]^{<\omega}$ is called the (ultimate) standard parameter of M .

Notation 1.9.1. 1. If $a \in [o(M)]^{<\omega}$ we set

- (a) $a^n := a \cap [\omega\rho_M^{n+1}, \omega\rho_M^n)$ and
- (b) $a \upharpoonright n = a \setminus \omega\rho_M^n$.

Exercise 1.9.3. Let $p \in [o(M)]^{<\omega}$. Then

- 1. $p \in P_M^n \implies p \upharpoonright (n-1) \in P_M^{n-1}$ and $p^{n-1} \in P_{M^{n-1}, p \upharpoonright n-1}$,
- 2. $p \upharpoonright (n-1) \in P_M^{n-1}$, $p^{n-1} \in P_{M^{n-1}, p \upharpoonright n-1}$ and $\omega\rho_M^n = \omega\rho_{M^{n-1}, p \upharpoonright n-1} \implies p \in P_M^n$.
- 3. $r \in R_M^n \iff \forall i < n: r^i \in R_{M^i, r \upharpoonright i}$.

Corollary 1.9.1. $p_{M,n} \setminus \omega\rho_M^n = \emptyset$.

Proof. $p_{M,n} \setminus \omega\rho_M^n \leq^* p_{M,n}$ and by Exercise 1.9.4 we have that $p_{M,n} \setminus \omega\rho_M^n \in P_M^n$. \square

Corollary 1.9.2. Let $r \in R_M^n$. Then r can be lengthened to some $p \in P_M^{n+1}$. If, in addition, $r \in [o(M)]^{<\omega}$, then r can be lengthened to some $p \in P_M^{n+1} \cap [o(M)]^{<\omega}$.

Proof. Let $p^- \in P_{M^n, r}$. Then, by Exercise 1.9.4, $p := r \frown p^- \in P_M^{n+1}$. If $r \in [o(M)]^{<\omega}$, pick $p^- \in P_{M^n, r} \cap [o(M)]^{<\omega}$ and let $p = r \cup p^-$. \square

Corollary 1.9.3. Let M be sound and $p \in P_M^n$. Then p can be lengthened to a $p^* \in P_M^*$. If, in addition, $p \in [o(M)]^{<\omega}$, then p can be lengthened to some $p^* \in P_M^* \cap [o(M)]^{<\omega}$.

¹Zeman calls $p_{M,n}$ the standard parameter above $\omega\rho_M^n$.

Proof. Let $k < \omega$ be such that $\omega\rho_M^\omega = \omega\rho_M^k$. Now apply Corollary 1.9.2 k times. \square

Corollary 1.9.4. *Let M be n -sound. Then $p_{M,n-1} = p_{M,n} \upharpoonright (n-1)$.*

Proof. By Corollary 1.9.2 there is some q such that $p_{M,n-1} \cup q \in P_M^n$. Note that we may pick $q \subseteq [\omega\rho_M^n, \omega\rho_M^{n-1})$. Now $p_{M,n-1} = p_{M,n-1} \setminus \omega\rho_M^{n-1}$ and $p_{M,n-1} \cup q \leq^* p_{M,n}$. If $p_{M,n-1} \cup q = p_{M,n}$, we are done. Otherwise fix $\xi \in p_{M,n} \setminus p_{M,n-1} \cup q$ such that

$$p_{M,n} \setminus (\xi + 1) = (p_{M,n-1} \cup q) \setminus (\xi + 1).$$

Since $p_{M,n} \upharpoonright (n-1) \in P_M^n$ and hence $p_{M,n} \upharpoonright (n-1) \leq^* p_{M,n-1}$, we must have that $\xi \geq \omega\rho^{n-1}$ and thus $p_{M,n-1} = p_{M,n} \upharpoonright (n-1)$ as desired. \square

We are now ready to prove the main result of this section

Theorem 1.9.1. *M is n -sound iff $p_{M,n} \in R_M^n$.*

Proof. If M is n -sound, then $p_{M,n} \in P_M^n = R_M^n$ and there is nothing to do. Conversely, suppose that n is minimal with $p_{M,n} \in R_M^n$ but M is not n -sound. We will derive a contradiction via the downward extension of embeddings lemma:

Let $q = \min_{<} (P_M^n \setminus R_M^n)$. Since $p_{M,n} = \min_{<} P_M^n$, we have $p_{M,n} <^* q$. Let $i < \omega$ be minimal such that $(p_{M,n} \cap [\omega\rho_M^{i+1}, \omega\rho_M^i) =) p_{M,n}^i <^* q^i$.

Claim 1.9.1. $i = n-1$.

Proof. Suppose $i < n-1$. Consider the map

$$\text{id}: M^{n,q} \rightarrow M^{n,q}.$$

By the downward extension of embeddings lemma there are unique π, \bar{M}, \bar{q} such that

1. $\pi: \bar{M} \rightarrow_{\Sigma_1^{(n)}} M$,
2. $\pi \upharpoonright H_M^n = \text{id}$,
3. $\pi(\bar{q}) = q$,
4. $\bar{q} \in R_{\bar{M}}^n$ and
5. $\bar{M}^{n,\bar{q}} = M^{n,q}$.

By induction hypothesis $p_{M,n} \upharpoonright (i+1) = p_{M,i+1} \in R_M^{i+1}$. We may thus fix a good $\Sigma_1^{(i)}(M)$ -function and some $z \in [\omega\rho_M^{i+1}]$ such that $q^i = f(z, p_{M,n} \upharpoonright i, p_{M,n}^i)$. Since $p_{M,n} \upharpoonright i = q \upharpoonright i$, this witnesses

$$M \models \exists z^{i+1} \exists r^i <^* q^i : z^{i+1}, r^i \in [\text{Ord}]^{<\omega} \wedge q^i = f(z^{i+1}, q \upharpoonright i, r^i).$$

This is a $\Sigma_1^{(i+1)}$ -statement and thus preserved downwards by π . Hence there is a finite set of ordinals $\bar{z} \subseteq \omega\rho_M^{i+1}$, $\bar{r} \subseteq \omega\rho_M^{i+1}$ such that $\bar{q}^i = \bar{f}(\bar{z}, \bar{q} \upharpoonright i, \bar{r})$, where \bar{f} is the interpretation of f 's $\Sigma_1^{(i)}$ definition over \bar{M} . Let $z = \pi(\bar{z})$, $r = \pi(\bar{r})$. Then $q^i = f(z, q \upharpoonright i, r)$. Now consider

$$q^* := q \upharpoonright i \cup r \cup z \cup (q \cap \omega\rho_M^{i+1}).$$

q and q^* can be translated into each other via a $\Sigma_1^{(i)}(M)$ function, so that $q^* \in P_M^n \upharpoonright R_M^n$. On the other hand, since $r < q^i$, $q^* <^* q$. This contradicts the fact that $q = \min_{<^*} P_M^n \setminus R_M^n$. \square

We may now run the same proof as for the claim, but for $i = n - 1$, to show that in fact $R_M^n = P_M^n$. \square

1.10 Two Applications to L

Theorem 1.10.1. *For every $\alpha \in \text{Ord}$ J_α is acceptable and sound.*

Before we can prove this, we need one more lemma about $\Sigma_1^{(n)}$ -definability:

Lemma 1.10.1. *Suppose $R_M^n \neq \emptyset$. If $A \in \Sigma_{n+1}(M) \cap \mathcal{P}(H_M^n)$, then A is $\Sigma_1^{(n)}(M)$.*

Proof. For $n = 0$ this is trivial. We'll provide the proof for $n = 1$ and leave the induction step as an exercise.

Let ϕ be a Σ_0 -formula, $\vec{p} \in M$ such that

$$A = \{a \mid M \models \exists x \phi[a, x, \vec{p}]\}.$$

Now let $r \in R_M^1$ and fix $\xi \in \omega\rho_M^1$ such that $\vec{p} = h_M(\xi, r)$. We have

$$\begin{aligned} A &= \{a \mid M \models \exists x^1 \phi[a^1, h_M(x^1, r^0), h_M(\xi^1, r^0)]\} \\ &= \{a \mid M^{1,r} \models \exists x \phi^*[a, x, \xi]\} \end{aligned}$$

where ϕ^* is the natural Σ_1 -formula corresponding to ϕ .² Since A is $\Sigma_1(M^{1,r})$, it is $\Sigma_1^{(1)}(M)$. \square

²Recall that ϕ is Σ_1 in the language $\{\in, A_M^{1,r}\}$

Exercise 1.10.1. *Provide the induction step.*

(Hint: Let $r \in R_M^{(n+1)}$. Then $r(0) \in R_M^1$ and $H_M^{n+1} = H_{M^1, r(0)}^n$. Furthermore recall that $M^{r(0)}$ has a very good parameter $r^* \in R_{M^1, r(0)}^n$ such that $r = r(0) \cap r^*$. Use the induction hypothesis on $M^{1, r(0)}$.)

Proof of Theorem 1.10.1. We proceed by induction on α :

First let $\alpha = 1$: $J_1 = (V_\omega; \in)$ is trivially acceptable and since V_ω is the image of ω under the Ackermann coding function (without parameter), it is also sound.

Suppose J_β is acceptable and sound for all $\beta < \alpha$. We will first show that J_α is acceptable. If α is a limit ordinal, there is nothing to do. So suppose that $\alpha = \beta + 1$. It suffices to show that

$$(\exists \tau < \beta \exists a \subseteq \tau a \in J_{\beta+1} \setminus J_\beta) \implies \exists f \in J_{\beta+1} f: \tau \twoheadrightarrow J_\beta.$$

Fix a, τ as above with τ minimal.

Claim 1.10.1. $\tau = \omega \rho_{J_\beta}^\omega$.

Proof. Let $n < \omega$ be such that $\omega \rho_{J_\beta}^\omega = \omega \rho_{J_\beta}^n$. Then there is some $\Sigma_1^{(n-1)}(M)$ -subset of $\omega \rho_{J_\beta}^\omega$ not in J_β . Since $\Sigma_{<\omega}(J_\beta) \subseteq J_{\beta+1}$, this new subset is in $J_{\beta+1}$ and hence witnesses that $\tau \leq \omega \rho_{J_\beta}^\omega$.

Conversely, let $a \subseteq \tau$ be $\Sigma_n(J_\beta)$. Since $\tau \leq \omega \rho_{J_\beta}^n$, we have that $a \subseteq H_{J_\beta}^n$. Since J_β is sound, we have $R_{J_\beta}^n \neq \emptyset$. And hence, by Lemma 1.10.1, we have that a is $\Sigma_1^{(n-1)}(J_\beta)$, witnessing that $\omega \rho_{J_\beta}^\omega \leq \tau$. \square

Now, since J_β is sound, there is a $\Sigma^*(J_\beta)$ function

$$f: \omega \rho_{J_\beta}^\omega \twoheadrightarrow J_\beta.$$

But $f \in \Sigma_{<\omega}(J_\beta) \subseteq J_{\beta+1}$. Thus $J_{\beta+1}$ is acceptable.

Let us now verify that J_α is sound:

By Theorem 1.9.1, it suffices to show that $p_{n, J_\alpha} \in R_{J_\alpha}^n$ for all $n < \omega$. Suppose this is false and let $n < \omega$ be minimal such that $p := p_{n, J_\alpha} \notin R_{J_\alpha}^n$. Let a be $\Sigma_1^{(n-1)}(M)$ in p such that $a \cap \omega \rho_{J_\alpha}^n \notin J_\alpha$. Once again, consider

$$\text{id}: (H_{J_\alpha}^n; \in, A_{J_\alpha}^{n,p}) \rightarrow (H_{J_\alpha}^n; \in, A_{J_\alpha}^{n,p}).$$

By the downward extension of embeddings lemma there are unique π, \bar{M}, \bar{p} such that

1. $\pi: \bar{M} \rightarrow_{\Sigma_1^{(n)}} J_\alpha$,
2. $\pi \upharpoonright H_M^n = \text{id}$,
3. $\pi(\bar{p}) = p$,
4. $\bar{p} \in R_M^n$ and
5. $\bar{M}^{n, \bar{q}} = (H_{J_\alpha}^n; \in, A_{J_\alpha}^{n, p})$.

By condensation we have that $\bar{M} = J_{\bar{\alpha}}$ for some $\bar{\alpha} \leq \alpha$.

Claim 1.10.2. $\bar{\alpha} = \alpha$.

Proof. Let \bar{a} be the $\Sigma_1^{(n-1)}(J_{\bar{\alpha}})$ set in q via the definition for a , call it ϕ . Let $\xi < a \cap \omega\rho_{J_\alpha}^n = \omega\rho_{J_{\bar{\alpha}}}^n$. We have

$$\begin{aligned}
\xi \in \bar{a} &\iff J_{\bar{\alpha}} \models \phi[\xi, q] \\
&\iff J_\alpha \models \phi[\underbrace{\pi(\xi)}_{=\xi}, \underbrace{\pi(q)}_{=p}] \\
&\iff \xi \in a,
\end{aligned}$$

i.e. $a \cap \omega\rho_{J_\alpha}^n = \bar{a} \cap \omega\rho_{J_{\bar{\alpha}}}^n$. If $\bar{\alpha} < \alpha$, then $\bar{a} \cap \omega\rho_{J_{\bar{\alpha}}}^n \in J_{\bar{\alpha}+1} \subseteq J_\alpha$, which is absurd. Hence $\bar{\alpha} = \alpha$. ■

Since $\pi(q) = p$, we have $q \leq^* p$. On the other hand p is the $<^*$ -least good n th parameter and thus $p = q$. By $q \in R_{J_{\bar{\alpha}}}^n = R_{J_\alpha}^n$. Contradiction! □

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2 More on Downward Extensions of Embeddings

Talk 3, first draft

Definition 2.0.1. Let $M = (|M|; A_1, \dots, A_n)$ and $X \subseteq |M|$. Then

$$M|X := (|M| \cap X; A_1 \cap X, \dots, A_n \cap X).$$

Lemma 2.0.1. Let $M = (J_\alpha^A; \in, A, B)$ be an acceptable structure and let $X \subseteq M$ be closed under good $\Sigma_1^{(n)}(M)$ -functions with $X \cap P_M^n \neq \emptyset$. Let \bar{M} be the transitive collapse of X and let σ be the inverse of the collapsing map. Then

$$\sigma: \bar{M} \rightarrow_{\Sigma_1^{(n)}} M.$$

Proof. $\vec{x} \in X$ and let ϕ be a $\Sigma_0^{(n)}$ -formula such that

$$M \models \exists y^n \phi[y^n, \vec{x}].$$

By $\Sigma_1^{(n)}(M)$ -uniformization, leveraging that X is closed under good $\Sigma_1^{(n)}(M)$ -functions, we obtain that

$$M|X \models \exists y^n \phi[y^n, \vec{x}]$$

and thus that $M|X \prec_{\Sigma_1^{(n)}} M$. Now, for $i \leq n$, define

1. $H^i := \sigma'' H_M^i$ and
2. $\omega\rho^i := H^i \cap \text{Ord}$.

We establish a pseudo-interpretation of $\Sigma_1^{(n)}$ -formulae over \bar{M} by declaring that variables of type i ($i \leq n$) range over H^i . For this pseudo-interpretation we obtain

$$\sigma: \bar{M} \rightarrow_{\Sigma_1^{(n)}} M$$

as above. It now suffices to show

Exercise 2.0.1. $\omega\rho_{\bar{M}}^i = \omega\rho^i$ for all $i \leq n$.

□

Lemma 2.0.2. *Let*

$$\sigma: M \rightarrow_{\Sigma_1^{(n)}} N$$

be such that $\sigma \upharpoonright \omega\rho_N^{n+1} = \text{id}$ and $\text{ran}(\sigma) \cap P_N^ \neq \emptyset$. Then σ is $\Sigma^*(= \bigcup_{k < \omega} \Sigma_1^{(k)})$ -elementary.*

Proof. By induction on $m > n$ we prove that

1. $\omega\rho_M^m = \omega\rho_N^m$ and
2. $\sigma: M \rightarrow_{\Sigma_1^{(m)}} N$.

For this it suffices to prove the following two claims.

Claim 2.0.1. *Suppose $\sigma: M \rightarrow_{\Sigma_1^{(m)}} N$, $m \geq n$. Then $\omega\rho_M^{m+1} = \omega\rho_N^{m+1}$.*

Proof. Let $\bar{p} \in P_M^*$ be such that $\sigma(\bar{p}) \in P_N^*$. Let A be $\Sigma_1^{(m)}(N)$ in $\sigma(\bar{p})$ such that $A \cap \omega\rho_N^{m+1} \notin N$. Let \bar{A} be $\Sigma_1^{(m)}(M)$ in \bar{p} by the same definition. We have $\bar{A} \cap \omega\rho_N^{m+1} \notin M$ as otherwise

$$\sigma(\bar{A} \cap \omega\rho_N^{m+1}) \cap \omega\rho_N^{m+1} = A \cap \omega\rho_N^{m+1} \in N.$$

Hence $\omega\rho_M^{n+1} \leq \omega\rho_N^{n+1}$.

Conversely let \bar{A} be $\Sigma_1^{(m)}(M)$ in parameter \bar{p} and let $\alpha < \omega\rho_N^{m+1}$. Let A be $\Sigma_1^{(m)}(N)$ in parameter $\sigma(\bar{p})$ via the same definition. Then

$$\bar{A} \cap \alpha = A \cap \alpha \in \mathcal{J}_{\omega\rho_N^{m+1}}^N.$$

Since $\sigma \upharpoonright \omega\rho_N^{m+1} = \text{id}$, we have $\mathcal{J}_{\omega\rho_M^{m+1}}^M = \mathcal{J}_{\omega\rho_N^{m+1}}^N$, so that $\bar{A} \cap \alpha \in M$ and hence $\omega\rho_N^{m+1} \leq \omega\rho_M^{m+1}$. ■

Claim 2.0.2. *Suppose $\omega\rho_M^m = \omega\rho_N^m$ and $\sigma: M \rightarrow_{\Sigma_1^{(m-1)}} N$, $m > n$. Then*

$$\sigma: M \rightarrow_{\Sigma_1^{(m)}} N.$$

Proof. By induction on the complexity of $\Sigma_1^{(m)}$ -formulae. The only nontrivial step is the introduction of an existential quantifier of type m . So, suppose $\vec{x} \in M$, ϕ is preserved by σ and

$$N \models \exists x^m \phi[x^m, \sigma(\vec{x})].$$

Pick some such $x \in H_N^m$. Since $\sigma \upharpoonright H_N^m = \text{id}$, we have $\sigma(x) = x$ and

$$M \models \phi[x, \vec{x}].$$

Since $\omega\rho_M^m = \omega\rho_N^m$, it follows that

$$M \models \exists x^m \phi[x^m, \vec{x}].$$

■

□

3 Witnesses and Solidity

Problem 3.0.1. *Let*

$$\sigma: \bar{M} \rightarrow_{\Sigma_1^{(n)}} M^3$$

In general we might have that

$$p_{M,n+1} <^* \sigma(p_{\bar{M},n+1}),$$

i.e. that standard parameters are moved incorrectly by fine structural maps. In this section we introduce the concept of solidity that, provided it holds for \bar{M} , implies that standard parameters will be moved correctly.

³In a typical application, σ will be the canonical embedding associated to a fine structural ultrapower of \bar{M} .

Remark 3.0.1. *Fine structure theory and its later refinement $\Sigma^{(*)}$ -theory was developed by Ronald Jensen. The concept of solidity, however, is due to Bill Mitchell and later, independently, Sy Friedman.*

Definition 3.0.1. *Let $p \in [o(M)]^{<\omega}$. (Q, r) is a generalized witness for $\nu \in o(M)$ w.r.t. M, p iff*

1. Q is acceptable and $\nu \subseteq Q$,
2. $r \in [o(Q)]^{<\omega}$ and
3. Let n be such that $\omega\rho_M^{n+1} \leq \nu < \omega\rho_M^n$. Then for every $\Sigma_1^{(n)}$ -formula ϕ and $\xi_0, \dots, \xi_l < \nu$

$$M \models \phi[p \setminus (\nu + 1), \xi_0, \dots, \xi_l] \implies Q \models \phi[r, \xi_0, \dots, \xi_l].$$

Lemma 3.0.1. *There is a $\Sigma_1^{(n)}$ -formula ψ such that for every M, p, n, ν as above (Q, r) is a generalized witness for ν w.r.t. M, p if for all $\xi_0, \dots, \xi_l < \nu$*

$$M \models \psi[p \setminus (\nu + 1), \xi_0, \dots, \xi_l] \implies Q \models \psi[r, \xi_0, \dots, \xi_l].$$

Proof. Let

$$\psi(i, q, \langle l, \langle \xi_0, \dots, \xi_l \rangle \rangle) \equiv M^{n, q} \models \phi_i(q \cap \omega\rho_M^n, \xi_0, \dots, \xi_l),$$

where $(\phi_i \mid i < \omega)$ is the fixed recursive enumeration of all Σ_1 -formulae in the language of acceptable \mathcal{J} -structures. \square

Exercise 3.0.1. *Verify that ψ is as desired.*

Theorem 3.0.1. *Let $p \in P_M^n$ be such that for every $\nu \in p$ there is a generalized witness (Q, r) for ν w.r.t. M, p such that $Q \in M$. Then $p = p_{M, n}$.*

Proof. Suppose not. Then $p_{M, n} <^* p$. Hence there is some $\nu \in p \setminus p_{M, n}$ with

$$q := p \setminus (\nu + 1) = p_{M, n} \setminus (\nu + 1).$$

Fix $i < n$ such that $\omega\rho_M^{i+1} \leq \nu < \omega\rho_M^i$ and let A be a $\Sigma_1^{(i)}(M)$ set in $p_{M, n}$ such that $A \cap \omega\rho_M^{i+1} \notin M$. Now fix a generalized witness (Q, r) for ν w.r.t. M, p such that $Q \in M$.

Let X be the closure of $\nu \cup q$ under good $\Sigma_1^{(i)}(M)$ functions and let

$$\sigma: W \rightarrow X \prec_{\Sigma_1^{(i)}} M$$

be the transitive collapse. Let $\bar{q} = \sigma^{-1}(q)$. W is the closure of $\nu \cup \bar{q}$ under good $\Sigma_1^{(i)}(W)$ functions, so that

$$W = \bar{h}_W^{i+1}(\nu \cup \{\bar{q}\}).$$

Claim 3.0.1. $p_{M,n} \in \text{ran}(\sigma)$.

Proof.

$$p_{M,n} = \underbrace{p_{M,n} \setminus (\nu + 1)}_{=q} \cup (p_{M,n} \cap [0, \nu)).$$

Since $q \in X$, $\nu \subseteq X$ and X is closed under pairing, we have $p_{M,n} \in X = \text{ran}(\sigma)$. \blacksquare

Now let \bar{A} be the $\Sigma_1^{(i)}(W)$ set in $\bar{p} = \sigma^{-1}(p_{M,n})$ by the same definition as A .

Define

$$\sigma^*: W \rightarrow Q, f_W(\xi_0, \dots, \xi_l, q) \mapsto f_Q(\xi_0, \dots, \xi_l, r),$$

where $\xi_0, \dots, \xi_l \in \nu$ and f_W, f_Q are the corresponding interpretation of the same functionally absolute definition of a good $\Sigma_1^{(i)}$ -function f in W, Q .

Exercise 3.0.2. σ^* is a well-defined $\Sigma_0^{(i)}$ -elementary embedding such that

1. $\sigma^* \upharpoonright \nu = \text{id}$ and

2. $\sigma^*(\bar{q}) = r$.

Let $\omega\rho^* := \sup \sigma^{**} \omega\rho_W^i$ and $A^* := A_Q^{i, r \upharpoonright i} \cap \mathcal{J}_{\rho^*}^Q$. We have that $Q^* := (\mathcal{J}_{\rho^*}^Q, A^*) \in M$ and

$$\sigma^* \upharpoonright H_W^i: W^{i, \bar{q} \upharpoonright i} \rightarrow_{\Sigma_0} Q^*$$

cofinally.

Note that $\bar{A} \cap \omega\rho_W^i$ is $\Sigma_1(W^{i, \bar{q} \upharpoonright i})$ in the parameter $\bar{p} \cap \omega\rho_W^i$. Let \tilde{A} be $\Sigma_1(Q^*)$ in $\sigma^*(\bar{p} \cap \omega\rho_W^i)$ by the same definition. Since $\bar{Q}^* \in M$, we have that $\tilde{A} \in M$. On the other hand, since $\sigma \upharpoonright \nu = \sigma^* \upharpoonright \nu = \text{id}$, we have that

$$\tilde{A} \cap \omega\rho_M^{i+1} = \bar{A} \cap \omega\rho_M^{i+1} = A \cap \omega\rho_M^{i+1} \notin M.$$

Contradiction! \square

As with good parameters, we can restrict ourselves to a natural, representative subclass of solidity witnesses.

Definition 3.0.2. Let M be acceptable, $p \in [o(M)]^{<\omega}$ and $\nu \in o(M)$. Let

$$W_M^{\nu, p}$$

be the transitive collapse of $M \upharpoonright X$, where X is the closure of $\nu \cup (p \setminus (\nu + 1))$ under good $\Sigma_1^{(n)}(M)$ -functions where $n \in \omega$ is such that $\omega\rho_M^{n+1} \leq \nu < \omega\rho_M^n$.

$W_M^{\nu,p}$ is the standard witness for ν w.r.t. M, p and the corresponding inverse of the collapsing map

$$\sigma: W_M^{\nu,p} \rightarrow M$$

is the canonical witness map of $W_M^{\nu,p}$.

Lemma 3.0.2. *Let $p \in P_M^n$. Then for every $\nu \in p$*

$$W_M^{\nu,p} \in M \iff \text{there is a generalized witness } Q \in M \text{ for } \nu \text{ w.r.t. } M, p.$$

Proof. Zeman, Lemma 1.12.3. □

Corollary 3.0.1. *Let M be acceptable, $p \in P_M^n$ and suppose that every $\nu \in p$ has a generalized witness w.r.t. M, p in M . Then $p \restriction i = p_{M,i}$ for all $i \leq n$.*

Definition 3.0.3. *An acceptable \mathcal{J} -structure M is solid iff $W_M^{\nu,p_M} \in M$ for all $\nu \in p_M$.*

M is solid above α iff $W_M^{\nu,p_M} \in M$ whenever $\nu \in p_M \setminus \alpha$.

Exercise 3.0.3. *J_α is solid for all α .*

The main interest in solid \mathcal{J} -structures is captured in the following

Theorem 3.0.2. *Let $\sigma: M \rightarrow N$ be $\Sigma_1^{(n)}$ -preserving, $\bar{p} \in M$, $p = \sigma(\bar{p})$, $\bar{\nu} \in o(M)$, $\nu = \sigma(\bar{\nu})$ with $\omega\rho_M^{n+1} \leq \bar{\nu}$ and $\omega\rho_N^{n+1} \leq \nu$.*

Let (\bar{Q}, \bar{r}) be a generalized witness for $\bar{\nu}$ w.r.t. M, \bar{p} such that $\bar{Q} \in M$. Then $(Q, r) := \sigma((\bar{Q}, \bar{r}))$ is a generalized witness for ν w.r.t. N, p .

Proof. Fix $i < n$ such that $\omega\rho_M^{i+1} \leq \bar{\nu} < \omega\rho_M^{i+1}$ and $\omega\rho_N^{i+1} \leq \nu < \omega\rho_N^i$.⁴ Let ϕ be a $\Sigma_1^{(i)}$ -formula. Then

$$M \models \forall \xi_0^i, \dots, \xi_l^i < \bar{\nu} \left(\phi(\xi_0^i, \dots, \xi_l^i, \bar{p} \restriction (\bar{\nu} + 1)) \implies \bar{Q} \models \phi(\xi_0^i, \dots, \xi_l^i, \bar{r}) \right).$$

This is a $\Pi_1^{(i)}$ statement and hence preserved upwards. □

Corollary 3.0.2. *Let $\sigma: M \rightarrow N$ be Σ^* -elementary and $p = \sigma(p_M) \in P_N^*$. If M is solid, then $p = p_N$ and N is solid.*

⁴such an i exists by Exercise 3.0.4.

Bonus Exercises

Exercise 3.0.4. Let $\pi: M \rightarrow N$ be $\Sigma_1^{(n)}$ -elementary. Then either

1. $\omega\rho_M^n = o(M)$ and $\omega\rho_N^n = o(N)$ or
2. $\omega\rho_M^n < o(M)$ and $\pi(\omega\rho_M^n) = \omega\rho_N^n$.

Corollary 3.0.3. Let $\pi: M \rightarrow N$ be $\Sigma_1^{(n)}$ -elementary. Then for all $k \leq n$ either

1. $\omega\rho_M^k = o(M)$ and $\omega\rho_N^k = o(N)$ or
2. $\omega\rho_M^k < o(M)$ and $\pi(\omega\rho_M^k) = \omega\rho_N^k$.

In particular this holds if $\pi: M \rightarrow N$ is Σ^* -elementary.

Proof of Corollary. If $\pi: M \rightarrow N$ is $\Sigma_1^{(n)}$ -elementary, then π is also $\Sigma_1^{(l)}$ -elementary for all $l \leq n$. \square