

Scratch paper

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April 2019

Abstract Poche idee, ben confuse.

1 Introduction

2 Abstract samples

Let M be a structure of signature L . The **fractional multiset expansion** of M is a many-sorted expansion that has a sort for M , which we call the home-sort, a sort for \mathbb{R} , and a **sample-sort** for the set of functions $s : M \rightarrow \mathbb{R}$ that are almost always 0. We write $\bar{M} = \langle M, \mathbb{R}, M^s \rangle$ for the expansion above.

Below x, y, z are always tuples of variables of home-sort, x^s, y^s, z^s are tuples of sample-sort of the same length of x, y , respectively z .

The language of \bar{M} is denoted by \bar{L} . It will be defined in the next section as it is not relevant for at present.

2.1 Definition Let \mathcal{U} be a monster model of cardinality $\kappa > |L|$ and let $\bar{\mathcal{U}} = \langle \mathcal{U}, \mathbb{R}, \mathcal{U}^s \rangle$ be the corresponding expansion. We denote by $\bar{\mathcal{U}}^*$ a saturated elementary extension of $\bar{\mathcal{U}}$ of cardinality κ . As all saturated models of cardinality κ are isomorphic, we can assume that $\bar{\mathcal{U}}^* = \langle \mathcal{U}, \mathbb{R}^*, \mathcal{U}^{s*} \rangle$, where \mathbb{R}^* and \mathcal{U}^{s*} are suitable saturated extensions of \mathbb{R} , respectively \mathcal{U}^s . Elements \mathcal{U}^s are called **finite samples**, elements in \mathcal{U}^{s*} are called **internal samples**.

Finally, a **global sample** is a type $p(x^s) \in S(\mathcal{U}, \bar{M})$, where M is a model which will be clear from the context. □

2.2 Notation For any global type $p(x^s) \in S(\mathcal{U}, \bar{M})$, formula $\psi(x^s; z) \in \bar{L}(\bar{M})$, and $b \in \mathcal{U}^{|z|}$ we write $\psi(p; b)$ for $\psi(x^s; b) \in p$. We also write

$$\psi(p; \mathcal{U}) = \left\{ b \in \mathcal{U}^{|z|} : \psi(p; b) \right\}$$

(the same notation applies with x for x^s). This notation intentionally confuses p with any of its realizations in some elementary extension of $\bar{\mathcal{U}}$. Sets of this form are called **externally definable**. □

2.3 Definition A global sample $p(x^s)$ is **smooth** if it is realized in $\bar{\mathcal{U}}^*$. □

The following notions are standard

2.4 Definition Let M be given. A global sample $p(x^s)$ is

1. *invariant* if for any $\varphi(x^s; z) \in \bar{L}(\bar{M})$ the set $\varphi(p; \mathcal{U})$ is invariant over \bar{M} ;
2. *finitely satisfiable* if for every formula in $p(x^s)$ is satisfied in \bar{M} ;
3. *definable* if, for every $\psi(x^s; z) \in \bar{L}(\bar{M})$, the set $\psi(p; \mathcal{U})$ is definable over \bar{M} . □

2.5 Fact Let M be given. Let $p(x^s)$ be a global sample. Then, if p is finitely satisfiable, it is invariant. □

2.6 Fact Let M be given. Let $p(x^s)$ be a smooth sample. Then, if p is invariant, it is also finitely satisfiable and definable.

Proof Let s be an internal sample that realizes $p(x^s)$. Let $\varphi(x^s; b) \in p$ for some $\varphi(x^s; z) \in \bar{L}(\bar{M})$ and $b \in \mathcal{U}^{|z|}$. Let b' be such that $s \restriction_{\bar{M}} b' \equiv_{\bar{M}} b$. By invariance, $\varphi(s; b')$. Therefore there is an $r \in M^s$ such that $\varphi(r; b')$. As $b' \equiv_{\bar{M}} b$, we obtain $\varphi(r; b)$. This proves finite satisfiability.

Now, let $\psi(x^s; z) \in \bar{L}(\bar{M})$. As $\psi(p; \mathcal{U}) = \psi(s; \mathcal{U})$ is definable in $\bar{\mathcal{U}}^*$. By invariance it is definable in \bar{M} . □

2.7 Lemma Let M be given. For every global sample $p(x^s)$ the following are equivalent

1. p is smooth and invariant;
2. p is definable and for every $\varphi(x^s; z) \in L$ there are some finitely many $r_i \in \bar{M}$, say $0 \leq i < n$, such that for every $b \in \mathcal{U}^{|z|}$ we have $\varphi(p; b) \leftrightarrow \varphi(r_i; b)$ for some i ;
3. p is definable and finitely satisfiable.

Proof $1 \Rightarrow 2$ definability has been proved above. Let s be an internal sample that realizes $p(x^s)$. Let $\varphi(x^s; z) \in \bar{L}(\bar{M})$. The type

$$q(z) = \left\{ \varphi(s; z) \nleftrightarrow \varphi(r; z) : r \in \bar{M} \right\}$$

is inconsistent by Fact 2.6. Hence compactness yields the required $r_i \in \bar{M}$.

$2 \Rightarrow 3$ Is clear.

$3 \Rightarrow 1$ Invariance has been proved above. For any $\varphi(x^s; z) \in \bar{L}(\bar{M})$ and $r \in M^s$ there is a formula $\vartheta(z) \in L(M)$ defining the set $\{b \in \mathcal{U}^{|z|} : \varphi(p; b) \leftrightarrow \varphi(r; b)\}$. Let $q(x^s)$ be the type containing all the formulas

$$\forall z \left[\vartheta(z) \wedge \varphi(r; z) \rightarrow \varphi(x^s; z) \right].$$

as $\varphi(x^s; z)$ and r range as above. This type is consistent and is equivalent to $p(x^s)$. As $q(x^s)$ is a type over \bar{M} , it is realized in $\bar{\mathcal{U}}^*$. □

3 Less abstract samples

, the language of ordered rings (on \mathbb{R}), the language of real vector spaces (on M^S). Moreover, for every $\varphi(x; z) \in L$ there is a symbol for a function

$$\bar{\varphi}(x^S; z) : S^{|x|} \times M^{|z|} \longrightarrow \mathbb{R}.$$

Below, ε always ranges over the positive standard reals. If a and b are (hyper)reals, we write $a \approx_\varepsilon b$ for $|a - b| < \varepsilon$. We write $a \approx b$ if $a \approx_\varepsilon b$ holds for every ε .

In this section we assume that for every $\varphi(x), \psi(x) \in L(\mathcal{U})$ if $\varphi(x) \rightarrow \psi(x)$ then $\bar{\varphi}(x^S) \leq \bar{\psi}(x^S)$.

3.1 Fact *Let M be given. Let $p(x^S)$ be global sample. Suppose for every $\varphi(x) \in L(\mathcal{U})$ and ε there are $\vartheta_1(x), \vartheta_2(x) \in L(M)$ such that $\vartheta_1(x) \rightarrow \varphi(x) \rightarrow \vartheta_2(x)$ and $\bar{\vartheta}_2(p) \approx_\varepsilon \bar{\vartheta}_1(p)$. Then p is finitely satisfiable.*

Proof Let $\varphi_i(x)$, for $0 \leq i < n$, be given. We claim that there is an $r \in \bar{M}$ such that $\bar{\varphi}_i(p) \approx_{3\varepsilon} \bar{\varphi}_i(r)$ for every i .

Let $\vartheta_{i,1}(x)$ and $\vartheta_{i,2}(x)$ be as in the fact. As $\vartheta_{i,1}(p) \leq \varphi_i(p) \leq \vartheta_{i,2}(p)$, then $\vartheta_{i,1}(p) \approx_\varepsilon \varphi_i(p)$. By elementarity there is an $r \in \bar{M}$ such that $\vartheta_{i,1}(r) \approx_\varepsilon \vartheta_{i,1}(p)$ and $\vartheta_{i,2}(r) \approx_\varepsilon \vartheta_{i,2}(p)$. Then the claim follows immediately. \square

3.2 Lemma *The following are equivalent for every global sample $p(x^S)$*

1. p is smooth and invariant;
2. for every finite $B \subseteq \mathcal{U}^{|z|}$ and every ε , there is an $r \in \bar{M}$ such that $\bar{\varphi}(p; b) \approx_\varepsilon \bar{\varphi}(r; b)$ for all $b \in B$;
2. for every $\varphi_i(x; z) \in L$, every $b_i \in \mathcal{U}^{|z|}$, and every ε , there is an $r \in \bar{M}$ such that $\bar{\varphi}_i(p; b_i) \approx_\varepsilon \bar{\varphi}_i(r; b_i)$, for every $0 \leq i < n$;
2. for every $\psi_0(x), \dots, \psi_{n-1}(x) \in L(\mathcal{U})$ and every ε , there is an $r \in \bar{M}$ such that $\bar{\psi}_i(p) \approx_\varepsilon \bar{\psi}_i(r)$, for every $i < n$;
4. there are finitely many formulas $\vartheta_i(x) \in L(M)$ such that for every $b \in \mathcal{U}^{|z|}$ we have that $\vartheta_i(x) \rightarrow \varphi(x; b) \rightarrow \vartheta_j(x)$ and $\bar{\vartheta}_j(p) - \bar{\vartheta}_i(p) < \varepsilon$ for some i, j .

Proof Let s be an internal sample that realizes $p(x^S)$.

$1 \Rightarrow 2$. Let B and ε be given. Let $\bar{b} = \langle b_i : i < n \rangle$ be an enumeration of B . Let $\mu_i \in \mathbb{R}$ be such that $\bar{\varphi}(p; b_i) \approx \mu_i$ for every $i < n$. Let \bar{b}' be such that $s \restriction_{\bar{M}} \bar{b}' \equiv_{\bar{M}} \bar{b}$. By invariance, $\bar{\varphi}(s; b'_i) \approx \mu_i$. Therefore there is an $r \in \bar{M}$ such that $\bar{\varphi}(r; b'_i) \approx_\varepsilon \mu_i$ for every $i < n$. As $\bar{b}' \equiv_{\bar{M}} \bar{b}$, we obtain $\bar{\varphi}(r; b_i) \approx_\varepsilon \mu_i$.

$1 \Rightarrow 2$. Let $\psi_i(x) = \varphi_i(x; b_i)$ for some $\varphi_i(x; z) \in L$ and $b_i \in \mathcal{U}^{|z|}$. Let $\bar{b} = \langle b_i : i < n \rangle$. Let $\mu_i \in \mathbb{R}$ be such that $\bar{\varphi}_i(p; b_i) \approx \mu_i$. Let \bar{b}' be such that $s \restriction_{\bar{M}} \bar{b}' \equiv_{\bar{M}} \bar{b}$. By invariance, $\bar{\varphi}_i(s; b'_i) \approx \mu_i$. Therefore there is an $r \in \bar{M}$ such that $\bar{\varphi}_i(r; b'_i) \approx_\varepsilon \mu_i$ for every $i < n$. As $\bar{b}' \equiv_{\bar{M}} \bar{b}$, we obtain $\bar{\varphi}_i(r; b_i) \approx_\varepsilon \mu_i$.

1 \Rightarrow 3. By smoothness we it suffices to prove 3 with s for p . The type

$$p(z) = \left\{ \bar{\varphi}(s; z) \not\approx_\varepsilon \bar{\varphi}(r; z) : r \in \bar{M} \right\}$$

is inconsistent by 2. Hence compactness yields the required $r_1, \dots, r_n \in \bar{M}$.

3 \Rightarrow 2. Clear.

2 \Rightarrow 1 Assume 2. We prove that p is invariant. Pick some $b \equiv_{\bar{M}} b'$ and some ε . Let $r, r' \in \bar{M}$ be such that $\bar{\varphi}(p; b) \approx_\varepsilon \bar{\varphi}(r; b)$ and $\bar{\varphi}(p; b') \not\approx_\varepsilon \bar{\varphi}(r'; b')$. As $\bar{\varphi}(r; b) \approx \bar{\varphi}(r'; b')$ follows from $b \equiv_{\bar{M}} b'$, we obtain $\bar{\varphi}(p; b) \approx_\varepsilon \bar{\varphi}(p; b')$.

We prove that p is smooth.

$$p(x^s) = \left\{ \bar{\varphi}(x^s; b) \approx_\varepsilon \mu_b : b \in \mathcal{U}^{|z|} \right\}$$

□

3.3 Definition Let $\varphi(x; z) \in L$ and M be given. A global sample $p(x^s)$ is

1. *invariant* if $\bar{\varphi}(p; b) \approx \bar{\varphi}(p; b')$ for every $b \equiv_{\bar{M}} b'$;
2. (pointwise) *approximable* if, for every $b \in \mathcal{U}^{|z|}$ and every ε , there is an $r \in \bar{M}$ such that $\bar{\varphi}(p; b) \approx_\varepsilon \bar{\varphi}(r; b)$;
3. *definable* if, for every ε , the set $\{b \in \mathcal{U}^{|z|} : \bar{\varphi}(p; b) < \varepsilon\}$ is definable over \bar{M} .

□

The following is a useful characterization of smooth samples.

4 Old stuff/garbage

We write $\text{supp}(p)$ for the *support* of p , that is, the set of those a in \mathcal{U} such that $p \vdash (a \in x^s) > \varepsilon$ for some standard positive ε . If s is a smooth sample $\text{supp}(s)$ is defined to be $\text{supp}(p)$ for $p(x^s) = \text{tp}(s/\bar{U})$.

Let s be an external sample. For every formula $\varphi(x; z) \in L$ and every $b \in \mathcal{U}^{|z|}$ we define

$$\text{Av}_{x/s} \varphi(x; b) = \frac{|\{a \in s : \varphi(a; b)\}|}{|s|},$$

When possible we abbreviate $\text{Av}_{x/s} \varphi(x; b)$ with $\bar{\varphi}(s; b)$.

We write $\text{ft}(a)$, for the standard part of the hyperrational number a . That is, the unique real number μ such that $\mu \approx a$.

The standard part of Av_s induces a finite probability measure on the algebra of definable subsets of $\mathcal{U}^{|x|}$. This measure has an unique extension to a Lebesgue probability measure on a σ -algebra. This is known as the *Loeb measure*.

All definitions and facts in this section are relative to some given formula $\varphi(x; z) \in L$ and some model M .

4.1 Definition Let $\varphi(x; z) \in L$ and M be given. We say that a sample s is *smooth* if, for every

$s' \equiv_M s$ and every $b \in \mathcal{U}^{|\mathcal{Z}|}$, we have $\bar{\varphi}(s'; b) \approx \bar{\varphi}(s; b)$. \square

4.2 Definition Let $\varphi(x; z) \in L$ and M be given. An external sample s is

1. *invariant* if, for every $b, b' \in \mathcal{U}^{|\mathcal{Z}|}$ such that $b \equiv_M b'$, we have $\bar{\varphi}(s; b) \approx \bar{\varphi}(s; b')$;
2. *definable* if, for every ε , the set $\{b \in \mathcal{U}^{|\mathcal{Z}|} : \bar{\varphi}(s; b) < \varepsilon\}$ is definable over M ;
3. *finitely satisfiable* if, for all $b \in \mathcal{U}^{|\mathcal{Z}|}$ there is an $r \in \bar{M}$ such that $\bar{\varphi}(s; b) \approx_\varepsilon \bar{\varphi}(r; b)$;
4. *generically stable* if all of the above hold. \square

Smooth roughly means internal and invariant.

4.3 Fact Let $\varphi(x; z) \in L$ and M be given. The following are equivalent for every external sample s

1. s is smooth;
2. there is an invariant internal sample $s' \equiv_M s$.

Proof $1 \Rightarrow 2$. Let s be smooth and let $s' \equiv_M s$ be any internal sample. If $b, b' \in \mathcal{U}^{|\mathcal{Z}|}$ and $b \equiv_M b'$, then $b' = fb$ for some $f \in \text{Aut}(\bar{\mathcal{U}}^*/M)$. Then $\bar{\varphi}(s'; fb) \approx \bar{\varphi}(f^{-1}s'; b)$. Moreover, by smoothness $\bar{\varphi}(f^{-1}s'; b) \approx \bar{\varphi}(s'; b)$. The invariance in s' follows.

$2 \Rightarrow 1$. It suffices to prove that if s is internal and invariant then it is smooth. Suppose for a contradiction that there is an $s' \equiv_M s$ such that $\bar{\varphi}(s'; b) \not\approx_\varepsilon \bar{\varphi}(s; b)$. Pick a internal sample $s'' \equiv_{M, s} s'$. Then $\bar{\varphi}(s''; b) \not\approx_\varepsilon \bar{\varphi}(s; b)$. As $s'' \equiv_M s$ are both in $\bar{\mathcal{U}}^*$, then $s'' = fs$ for some $f \in \text{Aut}(\bar{\mathcal{U}}^*/M)$. Hence we obtain $\bar{\varphi}(s; f^{-1}b) \not\approx_\varepsilon \bar{\varphi}(s; b)$ which contradicts the invariance of s . \square

4.4 Definition Let $\varphi(x; z) \in L$ and M be given. Let $\mathcal{B} \subseteq \mathcal{U}^{|\mathcal{Z}|}$ be arbitrary. We say that s is *(uniformly) approximable* on \mathcal{B} if for every ε there is a finite sample $r \in \bar{M}$ such that $\bar{\varphi}(s, b) \approx_\varepsilon \bar{\varphi}(r, b)$ for every $b \in \mathcal{B}$. (The sample r depends on ε , not on b). \square

4.5 Lemma Let $\varphi(x; z) \in L$ and M be given. Let s be approximable on \mathcal{B} and such that $\bar{\varphi}(s; b) > \varepsilon$ for every $b \in \mathcal{B}$. Then there is a finite cover of \mathcal{B} , say $\mathcal{B}_1, \dots, \mathcal{B}_n$, such that all the types $p_i(x) = \{\varphi(x; b) : b \in \mathcal{B}_i\}$ are consistent.

Proof Let $r \in \bar{M}$ be as in Definition 4.4. As r is finite, we may assume that $\text{supp}(r) = \{a_1, \dots, a_n\}$. Let $\mathcal{B}_i = \{b \in \mathcal{B} : \varphi(a_i; b)\}$. As $\bar{\varphi}(r; b) > 0$ for all $b \in \mathcal{B}$, these \mathcal{B}_i are the required cover of \mathcal{B} . \square

4.6 Corollary Let $\varphi(x; z) \in L$ and M be given. If s be approximable on $\langle b_i : i < \omega \rangle$, where $\langle b_i : i < \omega \rangle$ is a sequence of indiscernibles such that $\bar{\varphi}(s; b_i) > \varepsilon$ for every $i < \omega$, then the type $\{\varphi(x; b_i) : i < \omega\}$ is consistent. \square

4.7 Corollary Let $\varphi(x; z) \in L$ and M be given. Let s be approximable on \mathcal{C} . Then for every ε there is a pair of distinct $c, c' \in \mathcal{C}$ such that $\text{Av}_{x/s}[\varphi(x; c) \nleftrightarrow \varphi(x; c')] < \varepsilon$

Proof Suppose for a contradiction that $\text{Av}_{x/s}[\varphi(x; c) \nleftrightarrow \varphi(x; c')] \geq \varepsilon$ for all distinct $c, c' \in \mathcal{C}$. Apply Lemma 4.5 to the formula $\psi(x; z, z') = [\varphi(x; z) \nleftrightarrow \varphi(x; z')]$ and the set $\mathcal{B} = \{\langle c, c' \rangle \in \mathcal{C}^2 : c \neq c'\}$. The sets \mathcal{B}_i obtained from Lemma 4.5 induce a finite coloring of the complete graph on \mathcal{C} . By the Ramsey theorem there is an infinite monochromatic set $A \subseteq \mathcal{C}$. Hence $\{\varphi(x; a) \nleftrightarrow \varphi(x; a') : a, a' \in A, a \neq a'\}$ is consistent. As $|A| > 2$, this is impossible. \square

5 The nip formulas

5.1 Theorem Let $\varphi(x; z) \in L$ and M be given and assume that $\varphi(x; z)$ is nip. Then every sample is approximable on M over M .

Proof Questo è Vapnik-Chervonenkis. \square

For smooth samples the Vapnik-Chervonenkis Theorem can be strengthened as follows. (The difference is that below b ranges over $\mathcal{U}^{|z|}$.)

5.2 Corollary Let $\varphi(x; z) \in L$ be nip. Every smooth sample s is approximable on \mathcal{U} over M .

Proof By Theorem 5.1, there is an $r \in \bar{M}$ such that $\bar{\varphi}(s; b) \approx_\varepsilon \bar{\varphi}(r; b)$ for all $b \in M^{|z|}$.

Suppose for a contradiction that $\bar{\varphi}(s; b') \not\approx_\varepsilon \bar{\varphi}(r; b')$ for some $b' \in \mathcal{U}^{|z|}$. Pick a $s' \subseteq \mathcal{U}^{|x|}$ such that $b' \downarrow_M s' \equiv_M s$. By the smoothness of s , we obtain $\bar{\varphi}(s'; b') \not\approx_\varepsilon \bar{\varphi}(r; b')$. As $b' \downarrow_M s'$, the same formula holds for some $b \in M^{|z|}$. Once again by smoothness, $\bar{\varphi}(s; b) \not\approx_\varepsilon \bar{\varphi}(r; b)$. A contradiction. \square

5.3 Definition ?? We say that $\varphi(x; z) \in L$ is *distal* if there is a formula $\psi(x; z_1, \dots, z_n) \in L$ such that for every finite set $B \subseteq \mathcal{U}$ and every $a \in \mathcal{U}^{|x|}$ there are $b_1, \dots, b_n \in B$ such that $\psi(a; b_1, \dots, b_n)$ and $\psi(x; b_1, \dots, b_n)$ decides all formulas $\varphi(x; b)$ for $b \in B$. \square

5.4 Definition ??* We say that $\varphi(x; z) \in L$ is *distal* if there is a formula $\psi(x_1, \dots, x_n; z) \in L$ such that for every finite set $A \subseteq \mathcal{U}^{|x|}$ and every $b \in \mathcal{U}^{|z|}$ there are $a_1, \dots, a_n \in A$ such that $\psi(a_1, \dots, a_n, z)$ and $\psi(x_1, \dots, x_n, z)$ decides all formulas $\varphi(a; z)$ for $a \in A$. \square

For every finite sample $r \in \bar{M}$ and every $\mu \in \mathbb{R}$ there is a formula $\psi(z) \in L(\text{supp } r)$ such that $\bar{\varphi}(r; z) = \mu \leftrightarrow \psi(z)$. The formula $\psi(z)$ depends on r .

When $\varphi(x; z)$ is distal

If $\varphi(x; z)$ is distal then there is a formula ψ such that for every $r \in M^f$ there is $r_0 \in M$

5.5 Theorem (false) The following are equivalent

1. $\varphi(x; z) \in L$ is distal;
2. for every sample $s \in \mathcal{U}^{f*}$, if s is generically stable then s is smooth.

There is a formula $\psi(x_1, \dots, x_n; z)$ such that for every $r \in \bar{M}$
there are a_1, \dots, a_n such that $\varphi(r; b) = \mu \psi(x_1, \dots, x_n; z)$