

Standard analysis

C. L. C. L. Polymath

ABSTRACT. Let \mathcal{L} be a first-order two-sorted language. Let I be some fixed structure. A *standard* structure is an \mathcal{L} -structure of the form $\langle M, I \rangle$ where I is fixed. When I is a compact topological space (and \mathcal{L} meets a few requirements) it is possible to adapt a significant part of model theory to the restricted class standard structures. This has been demonstrated by Henson and Iovino for Banach spaces (see, e.g. [HI]) and has been generalized to arbitrary structures in [CLCL]. The starting point is to prove that every standard structure has a *positive* elementary extension that is standard and realizes all positive types that are finitely consistent. The main tool is the notion of approximations of positive formulas and of their negation. These have been introduced by Henson and Iovino.

We review and elaborate on the properties of positive formulas. In parallel, we introduce *continuous* formulas which are convenient to discuss examples and provide a better counterpart to Henson and Iovino theory and/or real-valued model theory. Finally, we discuss criteria for elimination of quantifiers, omitting types, ω -categoricity, stability, and indiscernibles within the setting of standard structures.

1. Standard structures

We refer to the introduction of [CLCL] for motivations. Aside from that, this paper is reasonably self-contained. In the first part we revisit some results of [CLCL]. We rephrase some theorems and add a few remarks and examples¹. Our notation and terminology diverges slightly where needed.

Let I be some fixed first-order structure which is endowed with a Hausdorff compact topology (in particular, a normal topology). The language L_I contains relation symbols for the compact subsets $C \subseteq I^n$ and a function symbol for each continuous functions $f : I^n \rightarrow I$. In particular, there is a constant for each element of I . According to the context, C and f denote either the symbols of L_I or their interpretation in the structure I . Such a language L_I is much larger than necessary but it is convenient because it uniquely associates a structure to a topological space. The notion of dense set of formulas (Definition 7) helps to reduce the size of the language when required.

The most straightforward examples of structures I are the unit interval $[0, 1]$ with the usual topology, and its homeomorphic copies $\mathbb{R}^+ \cup \{0, \infty\}$ and $\mathbb{R} \cup \{\pm\infty\}$.

We also fix a first-order language L_H which we call the language of the *home sort*.

Definition 1. Let \mathcal{L} be a two sorted language that expands both L_H and L_I . A *standard structure* is a two-sorted \mathcal{L} -structure of the form $\langle M, I \rangle$, where M is any L_H -structure, while I is the structure we fixed above. We write H and I to denote the two sorts of \mathcal{L} .

The language \mathcal{L} adds a relation symbol $R_\varphi(x)$ for every $\varphi(x) \in L_H$. All \mathcal{L} -structures are assumed to model $R_\varphi(x) \leftrightarrow \varphi(x)$. In other words, \mathcal{L} performs the Morleyzation of L_H .

Finally and most relevantly, \mathcal{L} contains arbitrarily many function symbols of sort $H^n \rightarrow I$.

Standard structures are denoted by the domain of their home sort.

¹In the final version of this paper we will omit Section 4 and refer to [CLCL] instead. We will also omit some proofs.

Clearly, saturated \mathcal{L} -structures exist but, with the exception of trivial cases (when I is finite), they are not standard. As a remedy, below we carve out a set of formulas \mathcal{L}^P , the set of positive formulas, such that every model has an positive elementary saturated extension that is also standard.

As usual, L_I , L_H , and \mathcal{L} denote both first-order languages and the corresponding set of formulas. We write \mathcal{L}_x when we restrict to formulas with free variables among x . If $\varphi(x) \in \mathcal{L}$ contains only terms of sort $H^n \rightarrow H$ and relations of sort H^n we will improperly say that $\varphi(x) \in L_H$ (which is only correct up to equivalence).

Note that \mathcal{L} has two types of atomic formulas:

1. atomic formulas in L_H (hence, up to equivalence, all formulas of L_H);
2. formulas of the form $\tau(x; \eta) \in C$, where $C \subseteq I^n$ is compact and $\tau(x; \eta)$ is a tuple of terms of sort $H^{|x|} \times I^{|\eta|} \rightarrow I$.

Definition 2. A formula in \mathcal{L} is **positive** if it uses only the Boolean connectives \wedge, \vee ; the quantifiers \forall^H, \exists^H of sort H ; and the quantifiers \forall^I, \exists^I of sort I .

The set of positive formulas is denoted by \mathcal{L}^P .

A **continuous** formula is a positive formula where only atomic formulas as in (2) above occur. The set of continuous formulas is denoted by \mathcal{L}^C .

We will use Latin letters x, y, z for variables of sort H and Greek letters η, ε for variables of sort I . Therefore we can safely drop the superscript from quantifiers if they are followed by variables.

The positive formulas of Henson and Iovino corresponds to those formulas in \mathcal{L}^C that do not have quantifiers of sort I .

Working within \mathcal{L}^P simplifies the comparison with classical model theory but comes at a price. Instead, allowing quantifiers of sort I comes almost for free. We will see (cf. Propositions 32) that the formulas in $\mathcal{L}^P / \mathcal{L}^C$ are approximated by formulas without quantifiers of sort I .

The extra expressive power offered by quantifiers of sort I is convenient. For instance, it is easy to see (cf. Example 3) that \mathcal{L}^C has at least the same expressive power as real valued logic

Example 3. Let $I = [0, 1]$, the unit interval in \mathbb{R} . Let $\tau(x)$ be a term of sort $H^{|x|} \rightarrow I$. Then there is a positive formula that says $\sup_x \tau(x) = \alpha$. Indeed, consider the formula

$$\forall x [\tau(x) \leq \alpha] \quad \wedge \quad \forall \varepsilon [\varepsilon \in \{0\} \vee \exists x [\alpha - (\tau(x) + \varepsilon) \in \{0\}]]$$

which, in a more legible form, becomes

$$\forall x [\tau(x) \leq \alpha] \quad \wedge \quad \forall \varepsilon > 0 \exists x [\alpha \leq \tau(x) + \varepsilon].$$

The following example is inspired by [HPP].

Example 4. Let \bar{M} be a saturated structure of signature L_H . The relevant part of \mathcal{L} contains symbols for the functions $f : \bar{M}^n \rightarrow I$ that are continuous in the following sense: the inverse image of every compact $C \subseteq I$ is type-definable in $L_H(\bar{M})$ for every $M \leq \bar{M}$. It is easy to verify that $\langle \bar{M}, I \rangle$ is positively saturated as defined in Section 5.

The theory of normed spaces is one of the motivating examples of standard structures. Essentially, functional analysis and model theory are only interested in the unit ball of normed spaces. To formalize the unit ball of a normed space as a standard structure (where I is the unit interval) is straightforward but cumbersome. Alternatively one can view a normed space as a many-sorted

structure: a sort for each ball of radius $n \in \mathbb{Z}^+$. Unfortunately, this also results into a bloated formalism.

A neater formalization is possible if one accepts that some positive elementary extensions (to be defined below) of a normed space could contain vectors of infinite norm hence not be themselves proper normed spaces. However these infinities are harmless if one is only interested in the unit ball. In fact, inside any ball of finite radius these nonstandard normed spaces are completely standard.

Example 5. Let $I = \mathbb{R} \cup \{\pm\infty\}$. Let L_H be the language of real (or complex) vector spaces. The language \mathcal{L} contains a function symbol $\|\cdot\|$ of sort $H \rightarrow I$. Normed space are standard structures with the natural interpretation of the language. It is easy to verify that the unit ball of a standard structure is the unit ball of a normed space. Note that the same remains true if we add to the language any continuous (equivalently, bounded) operator or functional.

We conclude this introduction advertising a question of [CLCL]. Is it possible to extend the Positive Compactness Theorem (Theorem 19) to a larger class of languages? E.g. can we allow in \mathcal{L} (and in \mathcal{L}^p) function symbols of sort $H^n \times I^m \rightarrow I$ with both n and m positive? These would have natural interpretations, e.g. a group acting on a compact set I .

2. Henson-Iovino approximations

For φ, φ' (free variables are hidden) positive formulas possibly with parameters we write $\varphi' > \varphi$ if φ' is obtained by replacing in φ each atomic formula of the form $t \in C$ with $t \in C'$, where C' is some compact neighborhood of C . If no such atomic formulas occurs in φ , then $\varphi > \varphi$. We call φ' a **weakening** of φ . Note that $>$ is a dense transitive relation and that $\varphi \rightarrow \varphi'$ in every \mathcal{L} -structure.

We write $\tilde{\varphi} \perp \varphi$ when $\tilde{\varphi}$ is obtained by replacing each atomic formula $t \in C$ occurring in φ with $t \in \tilde{C}$ where \tilde{C} is some compact set disjoint from C . The atomic formulas in L_H are replaced with their negation. Finally each connective is replaced by its dual i.e., $\vee, \wedge, \exists, \forall$ are replaced by $\wedge, \vee, \forall, \exists$, respectively. We say that $\tilde{\varphi}$ is a **strong negation** of φ . It is clear that $\tilde{\varphi} \rightarrow \neg\varphi$ in every \mathcal{L} -structure.

Lemma 6. For all positive formulas φ

1. for every $\varphi' > \varphi$ there is a formula $\tilde{\varphi} \perp \varphi$ such that $\varphi \rightarrow \neg\tilde{\varphi} \rightarrow \varphi'$;
2. for every $\tilde{\varphi} \perp \varphi$ there is a formula $\varphi' > \varphi$ such that $\varphi \rightarrow \varphi' \rightarrow \neg\tilde{\varphi}$.

Proof. If $\varphi \in L_H$ the claims are obvious. Suppose φ is of the form $t \in C$. Let φ' be $t \in C'$, for some compact neighborhood of C . Let O be an open set such that $C \subseteq O \subseteq C'$. Then $\tilde{\varphi} = (t \in I \setminus O)$ is as required by the lemma. Suppose instead that $\tilde{\varphi}$ is of the form $t \in \tilde{C}$ for some compact \tilde{C} disjoint from C . By the normality of I , there is C' , a compact neighborhood of C disjoint from \tilde{C} . Then $\varphi' = (t \in C')$ is as required. The lemma follows easily by induction. \square

For every type $p(x)$, we write

$$p'(x) = \{\varphi'(x) : \varphi' > \varphi \text{ for some } \varphi(x) \in p\}$$

in particular $\{\varphi(x)\}' = \{\varphi'(x) : \varphi' > \varphi\}$.

Definition 7. A set of formulas $\mathcal{F} \subseteq \mathcal{L}$ is **p-dense** modulo T , a theory, if for every positive $\varphi(x)$ and every $\varphi' > \varphi$, there is $\psi(x) \in \mathcal{F}$ such that $\varphi(x) \rightarrow \psi(x) \rightarrow \varphi'(x)$ holds in every standard structure that models T . If T is empty, we say that \mathcal{F} is p-dense modulo \mathcal{L} .

We say **c-dense** if the property above is required to hold only for continuous formulas.

Example 8. By Lemma 6, the set of negations of positive formulas is p-dense modulo \mathcal{L} .

Example 9. Let $I = [0, 1]$. The set of formulas build inductively from atomic formulas of the form $\tau \in \{0\}$, is c-dense modulo \mathcal{L} . In fact, as every compact subset of I is the intersection of finite unions of closed intervals, the set of formulas containing only atomic formulas of the form $\tau \in [\alpha, \beta]$ is c-dense. Finally note that $\tau \in [\alpha, \beta]$ is equivalent to $\tau \dot{-} \beta \in \{0\} \wedge \alpha \dot{-} \tau \in \{0\}$.

Example 10. In Section 8 we will prove that the set of positive/continuous formulas without quantifiers of sort I is p-dense/c-dense.

3. Morphisms

Let M and N be two standard structures. We say that a partial map $f : M \rightarrow N$ is **p-elementary** if for every $\varphi(x) \in \mathcal{L}^p$ and every $a \in (\text{dom } f)^{|x|}$

$$1. \quad M \models \varphi(a) \Rightarrow N \models \varphi(fa).$$

A p-elementary map that is total is called a p-elementary **embedding**. When the identity map $\text{id}_M : M \rightarrow M$ is a p-elementary embedding, we write $M \leq^p N$ and say that M is a p-elementary **substructure** of N .

The discussion of c-elementarity needs some extra care because \mathcal{L}^c does not contains equality in the home sort. Therefore we postpone it till Section 9.

On the other hand, as p-elementary maps are in particular L_H -elementary, they are injective. However, their inverse need not be p-elementary. In other words, the converse of the implication in (1) may not hold. Hence the following notion of elementarity which is more robust. We say that the map $f : M \rightarrow N$ is an **approximate p-elementary** if for every formula $\varphi(x) \in \mathcal{L}^p$, and every $a \in (\text{dom } f)^{|x|}$

$$2. \quad M \models \varphi(a) \Rightarrow N \models \{\varphi(fa)\}'.$$

One convenient feature of approximate p-elementarity is that it suffices verify (2) for any/some p-dense set of formulas. It is clear that p-elementarity implies its approximate variant. We will see that with a slight amount of saturation also the converse holds (Proposition 21). Finally, under full saturation, all differences disappear as these morphisms becomes \mathcal{L} -elementarity maps (Corollary 31).

The following holds in general.

Fact 11. If $f : M \rightarrow N$ is approximate p-elementary then

$$M \models \{\varphi(a)\}' \Leftrightarrow N \models \{\varphi(fa)\}'.$$

for every $\varphi(x) \in \mathcal{L}^p$, and every $a \in (\text{dom } f)^{|x|}$.

Proof. \Rightarrow Fix $\varphi' > \varphi$ and assume $M \models \varphi'(a)$. Let $\varphi' > \varphi'' > \varphi$. By the definition of approximate elementarity, $N \models \varphi''(fa)$ and $N \models \varphi'(fa)$ follows.

\Leftarrow Assume the r.h.s. of the equivalence. Fix $\varphi' > \varphi$ and prove $M \models \varphi'(a)$. Let $\varphi' > \varphi'' > \varphi$. By Lemma 6 there is some $\tilde{\varphi} \perp \varphi''$ such that $\varphi'' \rightarrow \neg \tilde{\varphi} \rightarrow \varphi'$. Then $N \models \neg \tilde{\varphi}(fa)$ and therefore $M \models \neg \tilde{\varphi}(a)$. Then $M \models \varphi'(a)$. \square

Finally, we consider the notion of partial embeddings. Though the definition seems weaker, we prove that the notion is completely classical. We say that the map $f : M \rightarrow N$ is a **partial embedding** if the implication in (1) holds for all atomic formulas $\varphi(x)$. Note that this is the same as requiring that (1) holds for all formulas without quantifiers of sort H .

Fact 12. If $f : M \rightarrow N$ is a partial embedding then

$$M \models \varphi(a) \Leftrightarrow N \models \varphi(f(a))$$

for every $a \in (\text{dom } f)^{|x|}$ and every formula $\varphi(x) \in \mathcal{L}^P$ without quantifiers of sort H .

Proof. The equivalence is trivial for formulas in L_H so we only consider atomic formulas of the form $t \in C$. Implication \Rightarrow holds by definition. Vice versa, if $M \models \tau(a) \notin C$ then, by normality, $M \models \tau(a) \in \tilde{C}$ for some compact \tilde{C} disjoint of C . By the definition of partial embedding, $N \models \tau(a) \in \tilde{C}$. Hence $N \models \tau(a) \notin C$. Induction is immediate. \square

4. The standard part

Our goal is to prove a compactness theorem for positive theories that only requires standard structures. To bypass lengthy routine applications of ultrafilters, ultrapowers, and ultralimits, we assume the Classical Compactness Theorem and built on that.

In this section we recall the notion of standard part of an element of the elementary extension of a compact Hausdorff topological space. Our goal is to prove Lemma 17 which in turn is required for the proof of the Positive Compactness Theorem (Theorem 19). The reader willing to accept it without proof may skip this section.

Let $\langle N, {}^*I \rangle$ be an \mathcal{L} -structure that extends \mathcal{L} -elementarily the standard structure M . Let η be a free variable of sort I . For each $\beta \in I$, we define the type

$$m_\beta(\eta) = \{\eta \in D : D \text{ compact neighborhood of } \beta\}.$$

The set of the realizations of $m_\beta(\eta)$ in *I is known to nonstandard analysts as the monad of β . The following fact is well-known.

Fact 13. For every $\alpha \in {}^*I$ there is a unique $\beta \in I$ such that ${}^*I \models m_\beta(\alpha)$.

Proof. Negate the existence of β . For every $\gamma \in I$ pick some compact neighborhood D_γ of γ , such that ${}^*I \models \alpha \notin D_\gamma$. By compactness there is some finite $\Gamma \subseteq I$ such that D_γ , with $\gamma \in \Gamma$, cover I . By elementarity, the interpretation in *I of these D_γ cover *I . A contradiction. The uniqueness of β follows from normality. \square

We denote by **st**(α) the unique $\beta \in I$ such that ${}^*I \models m_\beta(\alpha)$.

Fact 14. For every $\alpha \in {}^*I$ and every compact $C \subseteq I$

$${}^*I \models \alpha \in C \rightarrow \text{st}(\alpha) \in C.$$

Proof. Assume $\text{st}(\alpha) \notin C$. By normality there is a compact set D disjoint from C that is a neighborhood of $\text{st}(\alpha)$. Then ${}^*I \models \alpha \in D \subseteq \neg C$. \square

Fact 15. For every $\alpha \in ({}^*I)^{|a|}$ and every function symbol f of sort $|a| \rightarrow I$

$${}^*I \models \text{st}(f(\alpha)) = f(\text{st}(\alpha)).$$

Proof. By Fact 13 and the definition of $\text{st}(\cdot)$ it suffices to prove that $*I \models f(\alpha) \in D$ for every compact neighborhood D of $f(\text{st}(\alpha))$.

Fix one such D . Then $\text{st}(\alpha) \in f^{-1}[D]$. By continuity $f^{-1}[D]$ is a compact neighborhood of $\text{st}(\alpha)$. Therefore $*I \models \alpha \in f^{-1}[D]$ and, as $I \leq *I$ we obtain $*I \models f(\alpha) \in D$. \square

The standard part of $\langle N, *I \rangle$ is the standard structure $\langle N, I \rangle$ that interprets the symbols f of sort $H^n \rightarrow I$ as the functions

$$f^N(a) = \text{st}(*f(a)) \quad \text{for all } a \in N^n,$$

where $*f$ is the interpretation of f in $\langle N, *I \rangle$. Symbols in L_H maintain the same interpretation.

Fact 16. With the notation as above. Let $\tau(x; \eta)$ be a term of sort $H^{|x|} \times I^{|\eta|} \rightarrow I$. Then for every $a \in M^{|x|}$ and $\alpha \in (*I)^{|\eta|}$

$$\tau^N(a; \text{st}(\alpha)) = \text{st}(*\tau(a; \alpha))$$

Proof. When t is a function symbol of sort $H^{|x|} \rightarrow I$, the claim holds by definition. When t is a function symbol of sort $I^{|\eta|} \rightarrow I$, the claim follows from Fact 15. Now, assume inductively that

$$t_i^N(a; \text{st}(\alpha)) = \text{st}(*t_i(a; \alpha))$$

holds for the terms $t_1(x; \eta), \dots, t_n(x; \eta)$ and let $t = f(t_1, \dots, t_n)$ for some function f of sort $I^n \rightarrow I$. Then the claim follows immediately from the induction hypothesis and Fact 15. \square

Lemma 17. With the notation as above. For every $\varphi(x; \eta) \in \mathcal{L}^P$, $a \in N^{|x|}$ and $\alpha \in (*I)^{|\eta|}$

$$\langle N, *I \rangle \models \varphi(a; \alpha) \Rightarrow N \models \varphi(a; \text{st}(\alpha))$$

Proof. Suppose $\varphi(x; \eta)$ is \mathcal{L}^P -atomic. If $\varphi(x; \eta)$ is a formula of L_H the claim is trivial. Otherwise $\varphi(x; \eta)$ has the form $\tau(x; \eta) \in C$. Assume that the tuple $\tau(x; \eta)$ consists of a single term. The general case follows easily from this special case. Assume that $\langle N, *I \rangle \models \tau(a; \alpha) \in C$. Then $\text{st}(*\tau(a; \alpha)) \in C$ by Fact 14. Therefore $\tau^N(a; \text{st}(\alpha)) \in C$ follows from Fact 16. This proves the lemma for atomic formulas. Induction is immediate. \square

Corollary 18. Let M be a standard structure. Let $p(\eta) \subseteq \mathcal{L}^P(M)$ be a type that does not contain existential quantifiers of sort H . Then, if $p(\eta)$ is finitely consistent in M , it is realized in M .

The corollary has also a direct proof. This goes through the observation that the formulas in $p(\eta)$ define compact subsets of I .

Proof. Let $\langle *M, *I \rangle$ be an \mathcal{L} -elementary saturated superstructure of $\langle M, I \rangle$. Then $\langle *M, *I \rangle \models p(\alpha)$ for some $\alpha \in *I$. By the lemma above, $*M \models p(\text{st}(\alpha))$. Now observe that the truth of formulas without existential quantifiers of sort H is preserved by substructures. \square

The exclusion of existential quantifiers of sort H is necessary. For a counterexample take $M = I = [0, 1]$. Assume that \mathcal{L} contains a function symbol for the identity map $\iota : M \rightarrow I$. Let $p(\eta)$ contain the formulas $\exists x (x > 0 \wedge \iota x + \eta \in [0, 1/n])$ for all positive integers n .

5. Compactness

It is convenient to distinguish between consistency with respect to standard structures and consistency with respect to \mathcal{L} -structures. We say that a theory T is \mathcal{L} -consistent if $\langle M, *I \rangle \models T$ for some \mathcal{L} -structure $\langle M, *I \rangle$ (this is the classical notion of consistency). We say that T is standardly

consistent if $M \models T$ is for some standard structure M . By Lemma 17 these two notions coincide if T is positive. Therefore we have the following.

Theorem 19 (Positive Compactness Theorem). Let T be a positive theory. Then, if T is finitely \mathcal{L} -consistent, it is also standardly consistent.

An \mathcal{L} -structure N is **positively λ -saturated** if it realizes all types $p(x; \eta) \subseteq \mathcal{L}^P(N)$ with fewer than λ parameters that are finitely consistent in N . When $\lambda = |N|$ we simply say **p-saturated**. The existence of p-saturated standard structures is obtained from the classical case just as for Theorem 19.

Theorem 20. Every standard structure has a p-elementary extension to a p-saturated standard structure (possibly of inaccessible cardinality).

Proof. Let $\langle *M, *I \rangle$ be an \mathcal{L} -saturated \mathcal{L} -elementary extension of the standard structure $\langle M, I \rangle$. Let $\langle *M, I \rangle$ be its standard part as defined in Section 4. By Lemma 17, $\langle *M, I \rangle$ realizes all finitely consistent positive types with fewer than $|*M|$ parameters. \square

The following proposition shows that a slight amount of saturation tames the positive formulas.

Proposition 21. Let N be a positively ω -saturated standard structure. Then

$$\{\varphi(x; \eta)\}' \leftrightarrow \varphi(x; \eta)$$

holds in N for every formula $\varphi(x; \alpha) \in \mathcal{L}^P(N)$.

Proof. We prove \rightarrow , the non trivial implication. The claim is clear for atomic formulas. Induction for conjunction, disjunction and the universal quantifiers is immediate. We consider case of the existential quantifiers of sort H. Assume inductively

$$\text{ih.} \quad \{\varphi(x, z; \eta)\}' \rightarrow \varphi(x, z; \eta)$$

We need to prove

$$\{\exists z \varphi(x, z; \eta)\}' \rightarrow \exists z \varphi(x, z; \eta)$$

From (ih) we have

$$\exists z \{\varphi(x, z; \eta)\}' \rightarrow \exists z \varphi(x, z; \eta)$$

Therefore it suffices to prove

$$\{\exists z \varphi(x, z; \eta)\}' \rightarrow \exists z \{\varphi(x, z; \eta)\}'$$

Replace the variables $x; \eta$ with parameters, say $a; \alpha$, and assume that $N \models \exists z \varphi'(a, z; \alpha)$ for every $\varphi' > \varphi$. We need to prove the consistency of the type $\{\varphi'(a, z; \alpha) : \varphi' > \varphi\}$. By saturation, finite consistency suffices. This is clear if we show that the antecedent is closed under conjunction. Indeed it is easy to verify that if $\varphi_1, \varphi_2 > \varphi$ then $\varphi_1 \wedge \varphi_2 > \varphi'$ for some $\varphi' > \varphi$. In words, the set of approximations of φ is a directed set.

For existential quantifiers of sort I we argue similarly. \square

By Corollary 18, when $\varphi(x; \eta)$ does not contains existential quantifiers of sort H, the proposition above does not require the assumption of saturation. In general, some saturation is necessary: consider the model presented after Corollary 18 and the formula $\exists x (x > 0 \wedge \iota(x) \in \{0\})$.

A consequence of Proposition 21 is that the approximate morphisms defined in Section 3 coincide with their unapproximate version when the codomain is positively ω -saturated.

6. The monster model

We denote by \mathcal{U} some large p-saturated standard structure which we call the **positive monster model**. Truth is evaluated in \mathcal{U} unless otherwise is specified. We denote by T the positive theory of \mathcal{U} . The density of a set of formulas is understood modulo T . Below we say **p-model** for p-elementary substructure of \mathcal{U} . We stress once again that the truth of some $\varphi \in \mathcal{L}^p(M)$ in a p-model M implies the truth of φ (in \mathcal{U}) but not vice versa. If also the converse implication holds we say M a **strong p-model**. However, all p-models agree on the approximated truth, see Fact 11,

$$M \models \{\varphi\}' \Leftrightarrow \{\varphi\}'$$

Strong p-models are those that realize the equivalence in Proposition 21, e.g. ω -saturated p-models are strong p-models.

The following fact demonstrates how positive compactness applies. There are some subtle differences from the classical setting. Let $A \subseteq \mathcal{U}$ be a small set throughout this section.

Fact 22. Let $p(x) \subseteq \mathcal{L}^p(A)$ be a type. Then for every $\varphi(x) \in \mathcal{L}^p(\mathcal{U})$

1. if $p(x) \rightarrow \neg\varphi(x)$ then $\psi(x) \rightarrow \neg\varphi(x)$ for some $\psi(x)$ conjunction of formulas in $p(x)$;
2. if $p(x) \rightarrow \varphi(x)$ and $\varphi' > \varphi$ then $\psi(x) \rightarrow \varphi'(x)$ for some conjunction of formulas in $p(x)$.

Proof. (1) is immediate by saturation; (2) follows from (1) by Lemma 6. \square

We write $S_x^p(A)$ for the set of maximally consistent subsets of $\mathcal{L}_x^p(A)$. We define **p-tp(a/A)**, the positive type of a over A , to be the set of formulas $\{\varphi(x) \in \mathcal{L}^p(A) : \varphi(a)\}$. Similarly, we define $S_x^c(A)$ and **c-tp(a/A)**.

In general, if \mathcal{F} is any set of formulas, we write **\mathcal{F} -tp(a/A)**, for the type $\{\varphi(x) \in \mathcal{F}(A) : \varphi(a)\}$. The undecorated symbol **tp(a/A)** denotes the \mathcal{L} -type.

Fact 23. Let $p(x) \subseteq \mathcal{L}^p(A)$. The following are equivalent

1. $p(x)$ is a maximally consistent subsets of $\mathcal{L}_x^p(A)$;
2. $p(x) = \text{p-tp}(a/A)$ for some $a \in \mathcal{U}^{|x|}$.

Proof. (1 \Rightarrow 2) By the saturation of \mathcal{U} , there is an $a \in \mathcal{U}^{|x|}$ such that $p(x) \subseteq \text{p-tp}(a/A)$. By maximality $p(x) = \text{p-tp}(a/A)$.

(2 \Rightarrow 1) From Lemma 6 and Proposition 21 we obtain

$$\neg\varphi(x) \rightarrow \bigvee_{\tilde{\varphi} \perp \varphi} \tilde{\varphi}(x).$$

Suppose $\varphi(x) \in \mathcal{L}^p(A) \setminus p$. Then $\neg\varphi(a)$. Hence $\tilde{\varphi}(a)$ holds for some $\tilde{\varphi} \perp \varphi$ and $p(x) \rightarrow \neg\varphi(x)$ follows. \square

Note that in the proof above we could replace \mathcal{L}^p with any set of positive formulas closed under strong negation. Therefore we can also claim the following.

Fact 24. Let $p(x) \subseteq \mathcal{F}(A)$, where \mathcal{F} is a set of positive formulas closed under strong negation. Then the following are equivalent

1. $p(x)$ is a maximally consistent subset of $\mathcal{F}_x(A)$;
2. $p(x) = \mathcal{F}\text{-tp}(a/A)$ for some $a \in \mathcal{U}^{|x|}$.

7. Cauchy completeness and c-models

For $\tau(x, z)$ a term of sort $H^{|x|+|z|} \rightarrow I$ we define the formula

$$x \sim_{\tau} y = \forall z \tau(x, z) = \tau(y, z),$$

where the expression $\alpha = \beta$ is shorthand for $\langle \alpha, \beta \rangle \in \Delta$, where Δ is the diagonal of I^2 . We also define the type

$$x \sim y = \{x \sim_{\tau} y : \tau(x, z) \text{ as above}\}.$$

Fact 25. For any $a = \langle a_i : i < \lambda \rangle$ and $b = \langle b_i : i < \lambda \rangle$

$$a \sim b \Leftrightarrow a_i \sim b_i \text{ for every } i < \lambda.$$

Proof. Only implication \Leftarrow requires a proof. Assume $a_i \sim b_i$ for every i . Let $|a| = |b| = \lambda$ and assume inductively that

$$\forall y, z \tau(a, y, z) = \tau(b, y, z)$$

holds for every term $\tau(x, y, z)$, with $|x| = \lambda$ (universal quantification over the free variables is understood throughout the proof). In particular for any a_{λ}

$$1. \quad \forall z \tau(a, a_{\lambda}, z) = \tau(b, a_{\lambda}, z).$$

As $a_{\lambda} \sim b_{\lambda}$ then

$$\forall x, z \tau(x, a_{\lambda}, z) = \tau(x, b_{\lambda}, z)$$

and in particular

$$2. \quad \forall z \tau(b, a_{\lambda}, z) = \tau(b, b_{\lambda}, z).$$

From (1) and (2) we obtain

$$\forall z \tau(a, a_{\lambda}, z) = \tau(b, b_{\lambda}, z).$$

For limit ordinals induction is trivial. □

Note that the approximations of the formula $x \sim_{\tau} y$ have the form

$$x \sim_{\tau, D} y = \forall z \langle \tau(x, z), \tau(y, z) \rangle \in D$$

for some compact neighborhood D of Δ . Hence we define

$$x \sim' y = \{x \sim_{\tau, D} y : \tau(x, z) \text{ as above } D \text{ compact neighborhood of } \Delta\}.$$

If $\tau(x, z) = \tau_1(x, z), \dots, \tau_n(x, z)$ is a tuple of terms, by $x \sim_{\tau, D} y$ we denote the conjunction of the formulas $x \sim_{\tau_i, D} y$.

The formulas $x \sim_{\tau, D} y$, as D ranges over the compact neighborhoods of Δ and $\tau(x, z)$ ranges over the finite tuples parameter-free terms, define a system of entouages on $\mathcal{U}^{|x|}$. We refer to this uniformity and the topology associated as the **I-topology**. Though not needed in the sequel, it is worth mentioning that the *I*-topology on $\mathcal{U}^{|x|}$ coincides with the product of the *I*-topology on \mathcal{U} . This can be verified by an argument similar to the proof of Fact 25.

Fact 26. For every $\varphi(x) \in \mathcal{L}^c$

$$x \sim y \rightarrow \varphi(x, \eta) \leftrightarrow \varphi(y, \eta)$$

Proof. By induction on $\varphi(x, \eta)$. Suppose $\varphi(x, \eta)$ as the form $\tau(x, \eta) \in C$. Then clearly

$$x \sim_{\tau} y \rightarrow \varphi(x, \eta) \leftrightarrow \varphi(y, \eta)$$

Induction is easy. As an example, we spell out the proof for the quantifier \exists^H . Assume inductively that

$$x, x' \sim y, y' \rightarrow \varphi(x, x', \eta) \leftrightarrow \varphi(y, y', \eta)$$

Then in particular

$$x \sim y \rightarrow \varphi(x, z, \eta) \leftrightarrow \varphi(y, z, \eta).$$

Therefore

$$x \sim y \rightarrow \exists z \varphi(x, z, \eta) \leftrightarrow \exists z \varphi(y, z, \eta). \quad \square$$

The following proposition corresponds to the Perturbation Lemma [HI, Proposition 5.15].

Proposition 27. For every $\varphi(x) \in \mathcal{L}^c(\mathcal{U})$

$$x \sim y \rightarrow [\varphi(x) \leftrightarrow \varphi(y)]$$

hence, by compactness, for every $\varphi' > \varphi$ there are a tuple of terms τ and a compact neighborhood D of Δ such that

$$x \sim_{\tau, D} y \rightarrow [\varphi(x) \rightarrow \varphi'(y)].$$

We say that $p(x) \subseteq \mathcal{L}^c(\mathcal{U})$ is a **Cauchy type** if it is consistent and $p(x) \wedge p(y) \rightarrow x \sim y$. Equivalently, $p(x)$ is a Cauchy type if $p(x) \leftrightarrow a \sim x$ for some/any $a \models p(x)$. We say that a set $A \subseteq \mathcal{U}$ is **Cauchy complete** if $p(\mathcal{U}) \subseteq A^{|x|}$ for every Cauchy type $p(x) \subseteq \mathcal{L}^c(A)$. Note that Cauchy complete sets are in particular closed under \sim -equivalence. We say that $M \subseteq \mathcal{U}$ is a **c-model** if it is Cauchy complete and

$$c. \quad M \models \varphi(a) \Rightarrow \varphi(a) \quad \text{for all formulas } \varphi(x) \in \mathcal{L}^c \text{ and } a \in M^{|x|}.$$

Note that \mathcal{L}^c is closed under weakening and strong negation. Therefore the argument in the proof of Fact 11 proves that for every c-model M

$$ac. \quad M \models \{\varphi(a)\}' \Leftrightarrow \{\varphi(a)\}' \quad \text{for all formulas } \varphi(x) \in \mathcal{L}^c \text{ and } a \in M^{|x|}.$$

We say what a type $q(x)$ is **finitely satisfiable** in M if every conjunction of formulas in $q(x)$ has a solution in M .

Fact 28. Let $M \subseteq \mathcal{L}^c(M)$ satisfy (c) above. Then the following are equivalent

1. M is Cauchy complete, hence it is a c-model;
2. $a \in M$ whenever $a \sim' x$ is finitely satisfied in M .

Proof. (1 \Rightarrow 2) Assume that $a \sim' x$ is finitely satisfied in M . Let $a_{\tau, D} \in M$ be a solution of $a \sim_{\tau, D} x$ where D ranges over the compact neighborhoods of the diagonal and $\tau(x, z)$ ranges over the finite tuples parameter-free terms. Then, by the uniqueness of the limit (up to \sim -equivalence), the type $p(x)$ containing the formulas $x \sim_{\tau, D} a_{\tau, D}$ is a Cauchy type. By (1), $p(x)$ is realized in M . Then all its realizations belong to M .

(2 \Rightarrow 1) Let $p(x) \subseteq \mathcal{L}^c(M)$ be a Cauchy type. Then $p(x) \leftrightarrow a \sim x$ for some $a \models p(x)$. By elementarity $p'(x)$ is finitely satisfied in M . Then also $a \sim' x$ is finitely satisfied. Then $p(x)$ is realized in M . \square

Fact 29. Let M be a c-model. Then M is a substructure of \mathcal{U} .

Proof. Let $a \in M^n$ and let f be a function symbol of sort $H^n \rightarrow H$. We need to prove that $fa \in M$. By Fact 28, it suffices to prove that $fa \sim' x$ is finitely satisfied in M . This is the case because $\{\exists x fa \sim_\tau x\}'$ holds in \mathcal{U} hence, by (ac), it holds also in M . \square

8. Elimination of quantifiers of sort I for positive formulas

We show that the quantifiers of sort I can be eliminated up to some approximation. Precisely, we prove that $\mathcal{L}_{\text{lqf}}^p$, the set of positive formulas without quantifiers of sort I , is p -dense modulo T (the theory of \mathcal{U}).

A partial map is $\mathcal{L}_{\text{lqf}}^p$ -elementary if it preserves the truth of formulas in $\mathcal{L}_{\text{lqf}}^p$.

Proposition 30. Every $\mathcal{L}_{\text{lqf}}^p$ -elementary map $f : \mathcal{U} \rightarrow \mathcal{U}$ of small cardinality extends to an automorphism of \mathcal{U} .

Proof. By Fact 24, the inverse of an $\mathcal{L}_{\text{lqf}}^p$ -elementary map is also $\mathcal{L}_{\text{lqf}}^p$ -elementary. Then we can extend the map by back-and-forth as usual. \square

Let $A \subseteq \mathcal{U}$ be a small set throughout this section. We apply the proposition above to obtain a strengthening of Fact 24. For $a, b \in \mathcal{U}^{|x|}$ we write $a \equiv_A b$ if a and b satisfy the same \mathcal{L} -formulas over A .

Corollary 31. Let $p(x) = \mathcal{L}_{\text{lqf}}^p\text{-tp}(a/A)$ and $q(x) = \text{tp}(a/A)$. Then $p(x) \leftrightarrow q(x)$.

Proof. Only \rightarrow requires a proof. If $b \models p(x)$ then there is an $\mathcal{L}_{\text{lqf}}^p$ -elementary map $f \supseteq \text{id}_A$ such that $fa = b$. Then f extends to an automorphism. As every automorphism is \mathcal{L} -elementary, $a \equiv_A b$, and the corollary follows. \square

The corollary says that \mathcal{U} does not distinguish between \mathcal{L} , \mathcal{L}^p , and $\mathcal{L}_{\text{lqf}}^p$ types. In the classical setting, from an equivalence between types one derives an equivalence between formulas. Without negation, this is not true. Still, we can infer an approximate form of equivalence.

Proposition 32. The set $\mathcal{L}_{\text{lqf}}^p$ is p -dense modulo T .

Proof. Let $\varphi(x)$ be a positive formula. We need to prove that for every $\varphi' > \varphi$ there is some formula $\psi(x) \in \mathcal{L}_{\text{lqf}}^p$ such that $\varphi(x) \rightarrow \psi(x) \rightarrow \varphi'(x)$. By Corollary 31 and Proposition 21

$$\neg\varphi(x) \rightarrow \bigvee_{p'(x) \rightarrow \neg\varphi(x)} p'(x)$$

where $p(x)$ ranges over the maximally consistent $\mathcal{L}_{\text{lqf}}^p$ -types. By Fact 22 and Lemma 6

$$\neg\varphi(x) \rightarrow \bigvee_{\neg\tilde{\psi}(x) \rightarrow \neg\varphi(x)} \neg\tilde{\psi}(x),$$

where $\tilde{\psi}(x) \in \mathcal{L}_{\text{lqf}}^p$. Equivalently,

$$\varphi(x) \leftarrow \bigwedge_{\tilde{\psi}(x) \leftarrow \varphi(x)} \tilde{\psi}(x).$$

By compactness, see Fact 22, for every $\varphi' > \varphi$ there are some finitely many $\tilde{\psi}_i(x) \in \mathcal{L}_{\text{lqf}}^p$ such that

$$\varphi'(x) \leftarrow \bigwedge_{i=1, \dots, n} \tilde{\psi}_i(x) \leftarrow \varphi(x)$$

which yields the interpolant required by the proposition. \square

Proposition 33. Let \mathcal{F} be a p-dense set of positive formulas. Then for every $\varphi(x) \in \mathcal{L}^p$

$$\neg\varphi(x) \leftrightarrow \bigvee \{\psi(x) \in \mathcal{F} : \psi'(x) \rightarrow \neg\varphi(x) \text{ for some } \psi' > \psi\}.$$

Proof. Only \rightarrow requires a proof. We will make repeated use of the equivalence $p(x) \leftrightarrow p'(x)$ that holds for all $p(x) \in \mathcal{L}^p$. Let $a \in \mathcal{U}^{|x|}$ be such that $\neg\varphi(a)$. Let $p(x) = \mathcal{L}_{\text{lqf}}^p\text{-tp}(a)$. By Corollary 31, $p(x) \rightarrow \neg\varphi(x)$. As \mathcal{F} is p-dense, $p'(x) \leftrightarrow q(x) = \mathcal{F}\text{-tp}(a)$. Then $q'(x) \rightarrow \neg\varphi(x)$ and, by compactness, $\psi'(x) \rightarrow \neg\varphi(x)$ for some $\psi' > \psi \in \mathcal{F}$. \square

We will need a similar result for larger class formulas. We write Σ^p for the set of formulas of the form $\exists y \varphi(x, y)$ where $\varphi(x, y)$ is a positive Boolean combination of formulas such as $\neg\psi(x, y)$ and $\psi'(x, y)$ for $\psi(x, y)$ positive and $\psi' > \psi$. The following follows easily from the proposition above by induction on the syntax of $\varphi(x)$.

Proposition 34. For every $\varphi(x) \in \Sigma^p$

$$\varphi(x) \leftrightarrow \bigvee \{\psi(x) \in \mathcal{L}^p : \psi'(x) \rightarrow \varphi(x) \text{ for some } \psi' > \psi\}.$$

9. Elimination of quantifiers of sort I for continuous formulas

We adapt the argument in the previous section to continuous formulas. But first we need some definitions.

Let \mathcal{U}/\sim be the quotient of \mathcal{U} by the equivalence relation defined in Section 7. The equivalence class of $a \in \mathcal{U}$ is denoted by $[a]$. A **c-elementary** map is a (partial) map $f : \mathcal{U}/\sim \rightarrow \mathcal{U}/\sim$ such that $\varphi(a) \rightarrow \varphi(b)$ for every $\varphi(x) \in \mathcal{L}^c$ and a, b such that $f([a]) = [b]$.

The class $\mathcal{L}_{\text{lqf}}^c$ and the **$\mathcal{L}_{\text{lqf}}^c$ -elementary** maps are defined in analogy to the respective positive variant. An automorphism of \mathcal{U}/\sim is a total and surjective $\mathcal{L}_{\text{lqf}}^c$ -elementary map (which is also c-elementary).

For brevity we will often confuse $[a]$ with a .

Proposition 35. All $\mathcal{L}_{\text{lqf}}^c$ -elementary maps of small cardinality extend to automorphisms of \mathcal{U}/\sim .

Proof. By Fact 24, the inverse of an $\mathcal{L}_{\text{lqf}}^c$ -elementary map is also $\mathcal{L}_{\text{lqf}}^c$ -elementary. Then we can extend the map by back-and-forth as usual..... \square

10. The Tarski-Vaught test and the Löwenheim-Skolem theorem

The following proposition is our version of the Tarski-Vaught test.

Proposition 36. Let M be a subset of \mathcal{U} . Let \mathcal{F} be a p-dense set of positive formulas. Then the following are equivalent

1. M is a p-model;
2. for every formula $\psi(x) \in \mathcal{F}(M)$

$$\exists x \psi(x) \Rightarrow \text{for every } \psi' > \psi \text{ there is an } a \in M \text{ such that } \psi'(a);$$
3. for every formula $\psi(x) \in \mathcal{F}(M)$

$$\exists x \neg\psi(x) \Rightarrow \text{there is an } a \in M \text{ such that } \neg\psi(a).$$

If M is Cauchy complete and \mathcal{F} is a c-dense set of continuous formulas then (2) and (3) above are equivalent to

1'. M is a c-model.

Proof. (1 \Rightarrow 2) Assume $\exists x \psi(x)$ and let $\psi' > \psi$ be given. By Lemma 6 there is some $\tilde{\psi} \perp \psi$ such that $\psi(x) \rightarrow \neg \tilde{\psi}(x) \rightarrow \psi'(x)$. Then $\neg \forall x \tilde{\psi}(x)$ hence, by (1), $M \models \neg \forall x \tilde{\psi}(x)$. Then $M \models \neg \tilde{\psi}(a)$ for some $a \in M$. Hence $M \models \psi'(a)$ and $\psi'(a)$ follows from (1).

(2 \Rightarrow 3) Assume (2) and let $\psi(x) \in \mathcal{F}(M)$ be such that $\exists x \neg \psi(x)$. By Proposition 37, there are a consistent $\varphi(x) \in \mathcal{F}(M)$ and some $\varphi' > \varphi$ such that $\varphi'(x) \rightarrow \neg \psi(x)$. Then (3) follows.

(2 \Rightarrow 1) Assume (2). By the classical Tarski-Vaught test $M \leq_H \mathcal{U}$. Then M is the domain of a substructure of \mathcal{U} . Then $\varphi(a) \Leftrightarrow M \models \varphi(a)$ holds for every atomic formula $\varphi(x)$ and for every $a \in M^{|x|}$. Now, assume inductively

$$M \models \varphi(a, b) \Rightarrow \varphi(a, b).$$

Using (2) and the induction hypothesis we prove by contraposition that

$$M \models \forall y \varphi(a, y) \Rightarrow \forall y \varphi(a, y).$$

Indeed,

$$\begin{aligned} \neg \forall y \varphi(a, y) &\Rightarrow \exists y \neg \varphi(a, y) \\ &\Rightarrow \exists y \neg \varphi'(a, y) \quad \text{for some } \varphi' > \varphi \\ &\Rightarrow \exists y \neg \psi(a, y) \quad \text{for some } \psi \in \mathcal{F} \text{ such that } \varphi(a, y) \rightarrow \psi(a, y) \rightarrow \varphi'(a, y) \\ &\Rightarrow \neg \psi(a, b) \quad \text{for some } b \in M \text{ by (2)} \\ &\Rightarrow \neg \varphi(a, b) \\ &\Rightarrow M \models \neg \varphi(a, b) \quad \text{by induction hypothesis} \\ &\Rightarrow M \not\models \forall y \varphi(a, y). \end{aligned}$$

Induction for the connectives $\vee, \wedge, \exists^H, \exists^I$, and \forall^I is straightforward.

Finally, note that the proof of (1 \Rightarrow 2) also proves (1' \Rightarrow 2) while the proof of (3 \Rightarrow 1) proves (3 \Rightarrow 1') if we can show that M is a substructure of \mathcal{U} . But this the case by Fact 29. \square

Classically, the main application of the Tarski-Vaught test is in the proof of the downward Löwenheim-Skolem Theorem. Note that here the classical downward Löwenheim-Skolem Theorem holds in full for all \mathcal{L} -structures. In particular every $A \subseteq \mathcal{U}$ is contained in a standard structure of cardinality $|\mathcal{L}(A)|$. In this form the Löwenheim-Skolem Theorem is not very informative. In fact, the cardinality of \mathcal{L} is excessively large because of the abundance of symbols in L_1 .

We say that \mathcal{L} is **separable** modulo T if there is a countable set of positive formulas that is p-dense modulo T .

Proposition 37. Assume that \mathcal{L} is separable modulo the theory of \mathcal{U} . Let $A \subseteq \mathcal{U}$ be countable. Then there is a countable p-model M containing A . (The size of a p-model is the size of the domain of its home sort.)

Proof. As in the classical proof of the Löwenheim-Skolem Theorem, we construct $M \subseteq \mathcal{U}$ that contains a witness for every consistent formula in $\mathcal{F}(M)$. By separability and Proposition 36, M is a p-model. \square

Proposition 38. Assume that L_H is countable and that \mathcal{L} has at most countably many symbols of sort $H^n \rightarrow I$. Then, if I is a second countable (the topology has a countable base), \mathcal{L} is separable modulo \mathcal{L} .

Proof. Fix a countable filter of compact neighborhoods of the diagonal of I^2 . □

11. Omitting types and countable categoricity

A type $p(x)$ is isolated by $\varphi(x)$, a consistent formula, if $\varphi(x) \rightarrow p(x)$. If $p(x)$ is isolated by $\neg\varphi(x)$ for some $\varphi(x) \in \mathcal{L}^P(A)$ we say that it is **p-isolated** over A . Note that, by Proposition 36, if $p(x)$ is p-isolated over A , then $p(x)$ is realized in every p-model containing A .

Proposition 39. Let \mathcal{F} be a p-dense set of positive formulas. Then the following are equivalent

1. $p(x)$ is p-isolated over A ;
2. $p(x)$ is isolated by $\neg\psi(x)$ for some $\psi(x) \in \mathcal{F}(A)$;
3. $p(x)$ is isolated by some $\psi'(x)$ such that $\psi' > \psi$ for some consistent $\psi(x) \in \mathcal{F}(A)$;
4. $p(x)$ is isolated by some formula $\varphi(x) \in \Sigma^P(A)$.

Proof. $1 \Leftrightarrow 2$ For the nontrivial direction, note that by density

$$\varphi(x) \leftrightarrow \bigwedge \{ \psi(x) \in \mathcal{F} : \varphi(x) \rightarrow \psi(x) \}$$

therefore, negating both sides of the equivalence,

$$\neg\varphi(x) \leftrightarrow \bigvee \{ \neg\psi(x) : \psi(x) \in \mathcal{F} \text{ and } \neg\psi(x) \rightarrow \neg\varphi(x) \}.$$

If $\neg\varphi(x)$ isolates $p(x)$ then any consistent formula in the disjunction on the l.h.s. also isolates $p(x)$.

$1 \Leftrightarrow 3$ By Proposition 33 and Fact 6.

$3 \Leftrightarrow 4$ By Proposition 34. □

Lemma 40. Let \mathcal{L} be separable and let A be countable. Assume that $p(x) \subseteq \mathcal{L}^P(A)$ is not p-isolated over A . Then every consistent formula $\neg\psi(z)$, with $\psi(z) \in \mathcal{L}^P(A)$, has a solution a such that $p(x)$ is not isolated over A, a .

Proof. We construct a sequence of $\mathcal{L}^P(A)$ -formulas $\langle \gamma_i(z) : i < \omega \rangle$ such that any realization a of the type $\{ \gamma_i(z) : i < \omega \}$ is the required solution of $\neg\psi(z)$.

Let $\langle \xi_i(x; z) : i < \omega \rangle$ enumerate a countable p-dense subset of $\mathcal{L}_{x; z}^P(A)$. Let $\gamma_0(z)$ be a consistent positive formula such that $\gamma'_0(z) \rightarrow \neg\psi(z)$ for some $\gamma'_0 > \gamma_0$, which exists by Proposition 33. Define $\gamma_{i+1}(z)$ and $\gamma'_{i+1}(z)$ inductively as follows.

1. If $\neg\xi_i(x; z) \wedge \gamma'_i(z)$ is inconsistent, let $\gamma_{i+1}(z) = \gamma_i(z)$ and $\gamma'_{i+1}(z) = \gamma'_i(z)$;
2. otherwise, pick $\varphi(x) \in p$ such that (#) below is consistent

$$(\#) \quad \gamma'_i(z) \wedge \exists x [\neg\xi_i(x; z) \wedge \neg\varphi(x)].$$

Finally, let $\gamma_{i+1}(z)$ and $\gamma'_{i+1} > \gamma_{i+1}$ consistent positive formulas such that $\gamma'_{i+1}(z)$ implies (#) —this exists by Proposition 34.

Let $a \models \{ \gamma_i(z) : i < \omega \}$. We claim that A, a does not p-isolate $p(x)$. Otherwise, by density, $\neg\xi_i(x; a) \rightarrow p(x)$ for some $i < \omega$, where $\neg\xi_i(x; a)$ is consistent. This contradicts $a \models \gamma_{i+1}(z)$.

Therefore the proof is complete if we can show that it is always possible to find the formula $\varphi(x)$ required in (2).

Suppose for a contradiction that $\neg\xi_i(x; z) \wedge \gamma'_i(z)$ is consistent while $(\#)$ is inconsistent for all formulas $\varphi(x) \in p$, that is,

$$\neg\xi_i(x; z) \wedge \gamma'_i(z) \rightarrow \varphi(x).$$

This immediately implies that

$$\exists z [\neg\xi_i(x; z) \wedge \gamma'_i(z)] \rightarrow p(x).$$

Then $p(x)$ is isolated by a formula in $\Sigma^P(A)$. By Proposition 39, this is a contradiction. \square

Theorem 41 (Positive Omitting Types). Assume that \mathcal{L} is separable and that A is countable. Assume also that $p(x) \subseteq \mathcal{L}(A)$ is not p -isolated. Then there is a p -model M containing A that omits $p(x)$.

Proof. As in the classical proof, apply the lemma above and the Tarski-Vaught test (Proposition 36) to obtain a countable p -model M that does not isolate $p(x)$. For p -models, isolating and realizing are equivalent. \square

Assume that \mathcal{L} is separable modulo T . A theory T is **positively ω -categorical** if any two countable p -models $M, N \models T$ are isomorphic. The following analogue of Ryll-Nardzewski's Theorem follows as usual.

Theorem 42. Assume that \mathcal{L} is separable modulo T . The following are equivalent

1. T is positively ω -categorical;
2. every positive type $p(x) \subseteq \mathcal{L}^P$, for x any finite tuple of variables, is p -isolated over \emptyset .

The classical argument proves also the following.

Proposition 43. Fix a finite tuple of variables x . The following are equivalent

1. every positive type $p(x) \subseteq \mathcal{L}^P(A)$ is p -isolated over A ;
2. there are finitely many complete types.

Proof. (1 \Rightarrow 2) Let $p_i(x) = p\text{-tp}(a_i/A)$, for $i < \lambda$, be an enumeration without repetitions of all positive types. Let $\neg\varphi_i(x)$ be the negative formulas that isolate the $p_i(x)$. As these are complete types, $\neg\varphi_i(x) \leftrightarrow p_i(x)$. If λ is infinite then the positive type $\{\varphi_i(x) : i < \lambda\}$ is consistent. Any realization of this type yield a contradiction.

(2 \Rightarrow 1) Let $p_i(x) = p\text{-tp}(a_i/A)$, for $i < n$, be an enumeration without repetitions of all positive types. Pick a formula $\varphi_i(x) \in p_i \setminus \bigcup \{p_j : j \in n \setminus \{i\}\}$. Then the formula $\neg \bigvee \{\varphi_i(x) : j \in n \setminus \{i\}\}$ isolates $p_i(x)$. \square

12. Example: metric spaces

We discuss a simple example. Let I be $\mathbb{R}^+ \cup \{0, \infty\}$, with the topology that makes it homeomorphic to the unit interval. Let M, d is a metric space. Let L_H contain symbols for functions $M^n \rightarrow M$ that are uniformly continuous. Let \mathcal{L} contain a symbol for d and possibly for some functions of $M^n \rightarrow I$ that are uniformly continuous w.r.t. the metric d .

Let $\langle M, I \rangle$ be the structure that interprets the symbols of the language as natural.

Let \mathcal{U} be a positive monster model that is an \mathcal{L}^p elementary extension of M . Clearly, d does not define a metric on \mathcal{U} as there are pairs of elements at infinite distance. However, when restricted to a ball of finite radius, d defines a pseudometric on \mathcal{U} . Therefore the notion of convergent sequence makes perfectly sense in \mathcal{U} . As all functions have been required to be uniformly continuous, it is immediate that $x \sim_1 y$ is equivalent to $d(x, y) = 0$.

Fact 44. Let \mathcal{U} be as above. Then for every p -model N and $a \in \mathcal{U}$ the following are equivalent

1. $p(x) = p\text{-tp}(a/N)$ is a Cauchy type;
2. there is a sequence $\langle a_i : i \in \omega \rangle$ of elements of N that converges to a .

Proof. (2 \Rightarrow 1) Let $\langle \varepsilon_i : i \in \omega \rangle$ be a sequence of reals that converges to 0 and such that $d(a_i, a) \leq \varepsilon_i$ for every $i \in \omega$. Then the formulas $d(a_i, x) \leq \varepsilon_i$ are in $p(x)$. Then every element realizing $p(x)$ is at distance 0 from a . Therefore $p(x) \rightarrow a \sim x$.

(1 \Rightarrow 2) As $p(x)$ is Cauchy type, $p(x) \rightarrow a \sim x$. Then $p'(x) \rightarrow d(a, x) < 2^{-i}$ for all i . By compactness (see Fact 22) there are formulas $\varphi_i(x) \in p$ such that $\varphi'_i(x) \rightarrow d(a, x) < 2^{-i}$ for some $\varphi'_i > \varphi_i$. By \mathcal{L}^p -elementarity there is an $a_i \in N$ such that $\varphi'_i(a_i)$. As $d(a, a_i) < 2^{-i}$ for all i , the sequence $\langle a_i : i \in \omega \rangle$ converges to a . \square

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