CONTINUOUS LOGIC FOR THE CLASSICAL LOGICIAN

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1. A CLASS OF STRUCTURES

As a motivating example, consider real vector spaces. These are among the most simple strucures considered in model theory. Now expand them with a norm. The norm is a function that, given vector, outputs a real number, we may formalize this with a two sorted struture. Ideally, we would like to have that an elementary extension of a normed space mantain the usal notion of real numbers[1] but this is not possible with the usual notion of elementary extension. A way out has been proposed by Henson and Iovino: restrict the notion of elementarity to a smaller class of formulas (which they call positive bounded formulas). We elaborate on this idea generalizing it to arbitrary structures and a wider class of formulas.

1 **Definition.** Let L be a one-sorted (first-order) language. Let $L' \supseteq L$ be a two-sorted language. We consider the class of L'-structures of the form $\mathcal{M} = \langle M, R\rangle$, where M ranges over L-structures, while R is fixed.

We assume that R is endowed with a locally compact Hausdorff topology.

We require that function symbols only have one of these sorts

i. $R^n \to R$;

ii. $M^n \to M$;

iii. $M^n \to R$.

The interpretation of function symbolss of sort $R^n \to R$ is required to be continuous, the interpretation of function symbolss of sort $M^n \to R$ is required to be bounded, i.e. the range is contained in a compact set.

We only allow relation symbols of sorts M^n and R^n.

There might be models in the class described in Definition 1 that do not have a saturated elementary extension in the same class. As a remedy, below we carve out a set $\mathbb{L}$ of formulas, $L \subseteq \mathbb{L} \subseteq L'$, such that every model as in Definition 1 has an $\mathbb{L}$-elementary extension that is $\mathbb{L}$-saturated in the

[1] Non standard standard analists have no problem in expanding $\mathbb{R}$. In these notes, for a change, we insist as $\mathbb{R}$ should remain $\mathbb{R}$ throughout.

same class. Our choice of $\mathbb{L}$ is not the most general. It is a compromise that avoids eccessive complications.

For convenience we assume that the functions of sort $M^n \to M$ and the relation of sort M^n are all in L.

2 Definition. Formulas in $\mathbb{L}$ are constructed inductively from the following two sets of formulas

i. formulas as $t(x; y) \in C$, where $C \subseteq R^n$ is compact[2] and $t(x, y)$ is a tuple of terms of sort $M^{|x|} \times R^{|y|} \to R$;

ii. all formulas in L.

We require that $\mathbb{L}$ is closed under the Boolean connectives $\wedge$, $\vee$; the quantifiers $\forall$, $\exists$ of sort M; and the quantifier $\forall^C$, by which we mean a universal quantifier restricted to the compact set $C \subseteq R^m$.

2. Topological tools

We recall the standard definition of F-limits. Let I be a non-empty set. Let F be a filter on I. Let Y be a topological space. If $f : I \to Y$ and $\lambda \in Y$ we write

$$F\text{-}\lim_i f(i) = \lambda$$

if $f^{-1}[A] \in F$ for every $A \subseteq Y$ that is a neighborhood of λ. Such a λ is unique if Y is Hausdorff. When F is an ultrafilter, and Y is compact the limit always exists.

Let M^I denote the set of functions $\hat{a} : I \to M$.

3 Fact. Let $t(x; y)$ be a tuple of terms of sort $M^{|x|} \times R^{|y|} \to R$ such that

$$\{i \in I : t^{\mathcal{M}}(\hat{a}i; \alpha) \in U\} \quad \in \quad F$$

for some given $\hat{a} \in (M^I)^{|x|}$ and $\alpha \in R^{|y|}$. Then there is a an open $V \ni \alpha$ such that for everu $\alpha' \in V$

$$\{i \in I : t^{\mathcal{M}}(\hat{a}i; \alpha') \in U\} \quad \in \quad F.$$

Proof. By induction. If t is a function symbol f then x or y do not occor in t. If x does not occur in t the claim holds because $f^{\mathcal{M}} : R^{|y|} \to R$ is continuous. If y does not occur in t the claim is trivial. Finally, induction is is clear by the continuity of the functions of sort $R^n \to R$. $\square$

3. Henson-Iovino approximations

For $\varphi, \varphi' \in \mathbb{L}$ (free variables are hidden) we say that $\varphi' > \varphi$ if φ' can be obtained replacing each atomic formula $t \in C$ occurring in φ by $t \in D$ for some compact neighborhood D of C. If no such atomic formulas occurs in φ, then $\varphi > \varphi$.

[2] We confuse the relation symbols in L' of sort R^m with their interpretation and write $t \in C$ for $C(t)$

Note that this is a dense (pre)order of $\mathbb{L}$.

Formulas in as in (i) of Definition 2 do not occur under the scope of a negation, therefore we always have that $\varphi \to \varphi'$. Vice versa, if φ' for every $\varphi' > \varphi$, then φ.

The following lemma is required for the proof of Łŏś Theorem in the next section.

4 Lemma. Let $\alpha = F\text{-}\lim_i \alpha_i$, where $\langle \alpha_i : i \in I \rangle$ is a sequence in R and $F \in \beta I$. Let $\hat{a} : I \to M$. Let $\varphi(x; y) \in \mathbb{L}$ be such that $\{i : \mathcal{M} \vDash \varphi(\hat{a}i; \alpha)\} \in F$. Then $\{i : \mathcal{M} \vDash \varphi'(\hat{a}i\,; \alpha_i)\} \in F$ for every $\varphi' > \varphi$.

Proof. By induction on the syntax. When $\varphi(x; y)$ is in L, it does not depend on α, and the lemma is trivial. Suppose that $\varphi(x; y)$ is as in (i) of Definition 2, say it is the formula $t(x; y) \in C$.

Assume that $\{i : \mathcal{M} \vDash t(\hat{a}i; \alpha) \in C\} \in F$. Then $F\text{-}\lim_i t^{\mathcal{M}}(\hat{a}i; \alpha) \in C$. Let D be a compact neighborhood of C. By Fact 3, there is an open $V \ni \alpha$ such that $\{i : \mathcal{M} \vDash t(\hat{a}i; \alpha') \in D\} \in F$ for every $\alpha' \in D$ Then $\{i : \mathcal{M} \vDash t'(\hat{a}i\,; \alpha_i) \in D\} \in F$ follows. This completes the base case of the induction.

Induction clear for the connectives $\vee$, $\wedge$ and for the existential quantifier of sort M. To deal with the universal quantifier of sort M we assume inductively that for every $\varphi' > \varphi$

$$\left\{i : \mathcal{M} \vDash \varphi(\hat{a}i, \hat{b}i\,; \alpha)\right\} \in F \quad \Rightarrow \quad \left\{i : \mathcal{M} \vDash \varphi'(\hat{a}i, \hat{b}i\,; \alpha_i)\right\} \in F.$$

We prove

1. $$\{i : \mathcal{M} \vDash \forall y\, \varphi(\hat{a}i, y\,; \alpha)\} \in F \quad \Rightarrow \quad \left\{i : \mathcal{M} \vDash \forall y\, \varphi'(\hat{a}i, y\,; \alpha_i)\right\} \in F$$

Negate the r.h.s. of the implication. Using that F is an ultrafilter, there is a sequence $\hat{b}$ such that

$$\left\{i : \mathcal{M} \nvDash \varphi'(\hat{a}i, \hat{b}i\,; \alpha_i)\right\} \in F$$

Assume the l.h.s. of the implication, for a contradiction. Then $\left\{i : \mathcal{M} \vDash \varphi(\hat{a}i, \hat{b}i\,; \alpha)\right\} \in F$ and, by induction hypothesis, $\left\{i : \mathcal{M} \vDash \varphi'(\hat{a}i, \hat{b}i\,; \alpha_i)\right\} \in F$. A contradiction that proves (1).

Induction for the quantifier $\forall^C$ is similar. Assume inductively that for every $\varphi' > \varphi$

$$\left\{i : \mathcal{M} \vDash \varphi(\hat{a}i\,; \alpha, \beta)\right\} \in F \quad \Rightarrow \quad \left\{i : \mathcal{M} \vDash \varphi'(\hat{a}\,; \alpha_i, \beta_i)\right\} \in F.$$

We prove

2. $$\{i : \mathcal{M} \vDash \forall^C y\, \varphi(\hat{a}i, ; \alpha, y)\} \in F \quad \Rightarrow \quad \left\{i : \mathcal{M} \vDash \forall^C y\, \varphi'(\hat{a}i\,; \alpha_i, y)\right\} \in F$$

Negate the r.h.s. of the implication. Using that F is an ultrafilter, there is a sequence $\beta_i \in C$ such that

$$\left\{i : \mathcal{M} \nvDash \varphi'(\hat{a}i\,; \alpha_i, \beta_i)\right\} \in F$$

As C is compact, $F\text{-}\lim_i \beta_i$ exists, say it equals $\beta \in C$. Assume, for a contradiction, that the l.h.s. of the implication holds. Then $\big\{i : \mathcal{M} \vDash \varphi(\hat{a}\,;\alpha,\beta)\big\} \in F$ and, by induction hypothesis, $\big\{i : \mathcal{M} \vDash \varphi'(\hat{a}i\,;\alpha_i,\beta_i)\big\} \in F$. A contradiction that proves (2) and, with it, the lemma. □

4. Ultraproducts

Below we introduce a suitable notion of ultraproducts of some structures $\langle \mathcal{M}_i : i \in I\rangle$. We require that for each function symbol f of sort $M^n \to R$ there is a compact $C \subseteq R$ that contains the range of all the functions $f^{\mathcal{M}_i}$. Note that, otherwise, Fact 6 below may fail.

To keep notation tidy, we make two semplifications: (1) we only consider ultratpowers; (2) we do not consider formulas in L containing equality, so we need not take any quotient. The generalization is straightforward.

Let I be an infinite set. Let F be an ultrafilter on I. Let $\mathcal{M} = \langle M, R\rangle$ be an L-structure.

5 Definition. We define a structure $\mathcal{N} = \langle N, R\rangle$ that we call the ultrapower of $\mathcal{M}$.

1. $N = M^I$ that is, it is the set of sequences $\hat{a} : I \to M$.
2. If f is a function of sort $M^n \to M$ then $f^{\mathcal{N}}(\hat{a})$ is the sequence $\langle f^{\mathcal{M}}\big(\hat{a}i\big) : i \in I\rangle$.
3. The interpretation of functions of sort $R^n \to R$ is unchanged.
4. If f is a function of sort $M^n \to R$ then
$$f^{\mathcal{N}}\big(\hat{a}\big) \;=\; F\text{-}\lim_i f^{\mathcal{M}}\big(\hat{a}i\big).$$
5. if r is a relation symbol of sort M^n then
$$\mathcal{N} \vDash r(\hat{a}) \Leftrightarrow \big\{i \in I \;:\; \mathcal{M} \vDash r(\hat{a}i)\big\} \in F.$$
6. The interpretation of functions of sort R^n is unchanged.

The following is immediate but it needs to be noted.

6 Fact. The structure $\mathcal{N}$ satisfies Definition 1.

The following is easily proved by induction on the syntax

7 Fact. If $t(x)$ is a term of type $M^{|x|} \to M$
$$t^{\mathcal{N}}\big(\hat{a}\big) \;=\; \langle t^{\mathcal{M}}\big(\hat{a}i\big) : i \in I\rangle.$$
□

We also have that

8 Fact. If $t(x;y)$ has sort $M^{|x|} \times R^{|y|} \to R$
$$t^{\mathcal{N}}\big(\hat{a};\alpha\big) \;=\; F\text{-}\lim_i t^{\mathcal{M}}\big(\hat{a}i;\alpha\big).$$

Proof. By induction. If t is a function symbol then x or z do not occor in t. If x does not occur in t the claim is trivial. If y does not occur in t the claim holds by definition. Finally, induction is is clear by the continuity of the functions of sort $R^n \to R$. □

Finally, we prove Łǒś Theorem.

9 Theorem. Let $\mathcal{N}$ be as above and let $\varphi(x;y) \in \mathbb{L}$. Then for all $\hat{a} \in N^{|x|}$ and all $\alpha \in R^{|y|}$

$$\mathcal{N} \vDash \varphi(\hat{a};\alpha) \;\Leftrightarrow\; \big\{i \in I \;:\; \mathcal{M} \vDash \varphi'(\hat{a}i;\alpha)\big\} \in F \text{ for every } \varphi' > \varphi.$$

Proof. By induction on the syntax. If $\varphi(x;y) \in L$ then the theorem reduces to the classical Łǒś Theorem. Then, suppose that $\varphi(x;y)$ is as in (i) of Definition 2, say it is the formula $t(x;y) \in C$.

Assume $\mathcal{N} \vDash t(\hat{a},\alpha) \in C$. If D is a compact neighborhood of C then D is also a neighborhood of $t^{\mathcal{N}}(\hat{a},\alpha)$. Hence, by the definition of F-limit, $\big\{i \,:\, \mathcal{M} \vDash t(\hat{a}i,\alpha) \in D\big\} \in F$. Vice versa, assume $\mathcal{N} \vDash t(\hat{a},\alpha) \notin C$. Let D be a compact neighborhood of C such that $t^{\mathcal{N}}(\hat{a},\alpha) \notin D$. By Fact 8 and the definition of F-limit, $\big\{i \,:\, \mathcal{M} \vDash t(\hat{a}i,\alpha) \notin D\big\} \in F$.

This completes the proof of the base case of the induction.

Induction for the connectives $\vee$ and $\wedge$ is clear. To deal with the quantifiers of sort M we assume inductively that

$$\mathcal{N} \vDash \varphi(\hat{a},\hat{b}\,;\alpha) \;\Leftrightarrow\; \big\{i \in I \;:\; \mathcal{M} \vDash \varphi'(\hat{a}i,\hat{b}i\,;\alpha)\big\} \in F \text{ for every } \varphi' > \varphi.$$

First we prove

1. $\qquad \mathcal{N} \vDash \forall y\, \varphi(\hat{a},y\,;\alpha) \;\Leftrightarrow\; \big\{i \in I \;:\; \mathcal{M} \vDash \forall y\, \varphi'(\hat{a}i,y\,;\alpha)\big\} \in F$ for every $\varphi' > \varphi$.

($\Leftarrow$) Assume $\mathcal{N} \nvDash \varphi(\hat{a},\hat{b};\alpha)$ for some $\hat{b}$. By induction hypothesis, $\big\{i \,:\, \mathcal{M} \vDash \varphi'(\hat{a}i,\hat{b}i;\alpha)\big\} \notin F$ for some $\varphi' > \varphi$. A fortiori $\big\{i \,:\, \mathcal{M} \vDash \forall y\, \varphi'(\hat{a}i,y;\alpha)\big\} \notin F$ as required.

($\Rightarrow$) Assume that $\big\{i \,:\, \mathcal{M} \nvDash \forall y\, \varphi'(\hat{a}i,y;\alpha)\big\} \in F$. Choose $\hat{b}$ such that $\big\{i \,:\, \mathcal{M} \nvDash \varphi'(\hat{a}i,\hat{b}i;\alpha)\big\} \in F$. If for a contradiction $\mathcal{N} \vDash \forall y\, \varphi(\hat{a},y;\alpha)$, then in particular $\mathcal{N} \vDash \varphi(\hat{a},\hat{b};\alpha)$. By induction hypothesis, $\big\{i \,:\, \mathcal{M} \vDash \varphi'(\hat{a}i,\hat{b}i;\alpha)\big\} \in F$ a contradiction. This completes the proof of (1).

Now we prove (the argument, which we repeat for convinience, is dual to the one above)

2. $\qquad \mathcal{N} \vDash \exists y\, \varphi(\hat{a},y\,;\alpha) \;\Leftrightarrow\; \big\{i \in I \;:\; \mathcal{M} \vDash \exists y\, \varphi'(\hat{a}i,y\,;\alpha)\big\} \in F$ for every $\varphi' > \varphi$.

($\Rightarrow$) Assume $\mathcal{N} \vDash \varphi(\hat{a},\hat{b};\alpha)$ for some $\hat{b}$. By induction hypothesis, $\big\{i \,:\, \mathcal{M} \vDash \varphi'(\hat{a}i,\hat{b}i;\alpha)\big\} \in F$ for every $\varphi' > \varphi$. A fortiori $\big\{i \,:\, \mathcal{M} \vDash \exists y\, \varphi'(\hat{a}i,y\,;\alpha)\big\} \in F$ as required.

($\Leftarrow$) Assume that $\big\{i \,:\, \mathcal{M} \vDash \exists y\, \varphi'(\hat{a}i,y;\alpha)\big\} \in F$ for every $\varphi' > \varphi$. Choose some $\hat{b}$ such that $\big\{i \,:\, \mathcal{M} \vDash \varphi'(\hat{a}i,\hat{b}i;\alpha)\big\} \in F$. Suppose for a contradiction that $\mathcal{N} \nvDash \exists y\, \varphi(\hat{a},y\,;\alpha)$. Then, in particular, $\mathcal{N} \nvDash \varphi(\hat{a},\hat{b}\,;\alpha)$. By induction hypothesis, $\big\{i \,:\, \mathcal{M} \vDash \varphi'(\hat{a}i,\hat{b}i\,;\alpha)\big\} \notin F$ for some $\varphi' > \varphi$, a contradiction. This completes the proof of (2).

Finally, to deal with the quantifier $\forall^C$ we assume inductively that

$$\mathcal{N} \vDash \varphi(\hat{a}; \alpha, \beta) \;\Leftrightarrow\; \left\{ i \in I \;:\; \mathcal{M} \vDash \varphi'(\hat{a}i; \alpha, \beta) \right\} \in F \text{ for every } \varphi' > \varphi$$

and prove that

3. $\mathcal{N} \vDash \forall^C y\, \varphi(\hat{a}; \alpha, y) \;\Leftrightarrow\; \left\{ i \in I \;:\; \mathcal{M} \vDash \forall^C y\, \varphi'(\hat{a}i; \alpha, y) \right\} \in F$ for every $\varphi' > \varphi$.

($\Leftarrow$) Assume $\mathcal{N} \nvDash \varphi(\hat{a}; \alpha, \beta)$ for some β. By induction hypothesis, $\left\{ i \,:\, \mathcal{M} \vDash \varphi'(\hat{a}i; \alpha, \beta) \right\} \notin F$ for some $\varphi' > \varphi$. A fortiori $\left\{ i \,:\, \mathcal{M} \vDash \forall^C y\, \varphi'(\hat{a}i; \alpha, y) \right\} \notin F$ as required.

($\Rightarrow$) Assume that $\left\{ i \,:\, \mathcal{M} \nvDash \forall^C y\, \varphi'(\hat{a}i; \alpha, y) \right\} \in F$ for some $\varphi' > \varphi$. Choose some $\beta_i \in C$ such that $\left\{ i \,:\, \mathcal{M} \nvDash \varphi'(\hat{a}i; \alpha, \beta_i) \right\} \in F$ and let $\beta = F\text{-}\lim_i \beta_i$. If for a contradiction $\mathcal{N} \vDash \forall^C y\, \varphi(\hat{a}; \alpha, y)$, then $\mathcal{N} \vDash \varphi(\hat{a}; \alpha, \beta)$ and, by induction hypothesis, $\left\{ i \,:\, \mathcal{M} \vDash \varphi''(\hat{a}i; \alpha, \beta) \right\} \in F$ for every $\varphi'' > \varphi$. Fix φ'' such that $\varphi' > \varphi'' > \varphi$ and obtain a contradiction from Lemma 4 This completes the proof of (3) and, with it, of the theorem. □