A PRESENTATION THEOREM FOR CONTINUOUS LOGIC AND METRIC ABSTRACT ELEMENTARY CLASSES

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ABSTRACT. In recent years, the model theory of metric objects has seen much activity by widening the class of models the real-valued models whose underlying set is a complete metric space. We show that it is possible to carry out this work by giving presentation theorems of two main frameworks (continuous first order logic and Metric Abstract Elementary Classes) into discrete model-theoretic settings (a nice fragment of $\mathbb{L}_{\omega_1,\omega}$ and Abstract Elementary Classes, respectively). We also translate various notions of classification theory.

1. INTRODUCTION

In the spirit of Chang and Shelah's presentation results (from [Cha68] and [Sh88], respectively), we prove a presentation theorem for classes of continuous structures, both those axiomatized by first-order and beyond, in terms of a class of discrete structures. The thrust of this presentation theorem is the basic analytic fact that the behavior of continuous functions is determined by their values on a dense subset of their domain. Focusing on dense subsets is key because it allows us to drop the requirement that structures be complete, which is not a property expressible by discrete (classical) logic, even in the broader contexts of $\mathbb{L}_{\lambda,\omega}$ or Abstract Elementary Classes.

The specific statements of the presentation theorems appear below (see Theorem 2.1 for continuous first-order logic and Theorem 6.1 for Metric Abstract Elementary Classes), but the general idea is the same in both cases: given a continuous language τ, we define a discrete language τ^+ that allows us to approximate the values of the functions and relations by a countable dense subset of values, namely $\mathbb{Q} \cap [0,1]$. Note that the specification that this dense set (and its completion) is standard already requires an $\mathbb{L}_{\omega_1,\omega}(\tau^+)$ sentence, even if we are working in continuous first-order logic. Then, given a continuous τ-structure M and a nicely dense (see Definition 1.1 below) subset of it A, we can form a discrete τ^+-structure $\mathcal{A}$ with universe A that encodes all of M.

This allows us to define a functor between the continuous class and their discrete approximations that witnesses that these two classes are equivalent as categories. We investigate this equivalent further by considering various model-theoretic properties and finding analogues for them in the class of approximations. We consider types, saturation, (and for Metric Abstract Elementary Classes), amalgamation, joint embedding, and d-tameness.

We present two applications for this functor. In the realm of Metric Abstract Elementary Classes, it allows us to reduce many foundational questions to the same questions about Abstract Elementary Classes, where there are known answers. For instance, Theorem 6.4 answers an open question about the existence of Hanf numbers for Metric Abstract Elementary Classes, and shows that it is the same as for normal Abstract Elementary Classes. On the discrete side, the functor allows for the applications of results about countable fragments of $\mathbb{L}_{\omega_1,\omega}$ to continuous first-order logic.

Throughout we assume that the reader is familiar with the basics of the continuous contexts–either first-order or Metric Abstract Elementary Classes–but try to provide references and reminders when discussing the concepts.

Many of the arguments in the two cases are similar. In order to avoid repeating the same arguments twice in slightly different contexts, we provide the details only once. We have chosen to provide the details for continuous first-order logic because this context often allows more specific formulations of the correspondence.

Dense sets are not quite the right context because they need not be substructures of the larger structure. Instead, we introduce nicely dense sets to require them to be closed under functions.

Definition 1.1. *Given a continuous model M and a set $A \subset |M|$, we say that A is* nicely dense *iff A is dense in the metric structure $(|M|, d^M)$ and A is closed under the functions of M.*

In the what follows, we will often want to prove similar results for both "greater than" and "less than." In order to avoid writing everything twice, we often use $\square$ to stand in for both $\geq$ and $\leq$. Thus, asserting a statement for "$r \square s$" means that that statement is true both for "$r \geq s$" and for "$r \leq s$."

Our goal is to translate the real-valued formulas of τ into classic, true/false formulas of τ^+. We do this by encoding relations into τ^+ that are intended to specify the value of ϕ by deciding if it is above or below each possible value. To ensure that the size of the language doesn't grow, we take advantage of the separability or $\mathbb{R}$ and only compare each ϕ to the rationals in $[0,1]$. For notational ease, we set $\mathbb{Q}' := [0,1] \cap \mathbb{Q}$.

We would like to thank Pedro Zambrano for helpful comments on this paper. After posting drafts of this paper, the author discovered a similar project by Ackerman [Ack] (done independently). Ackerman also encodes metric notions in $\mathbb{L}_{\omega_1,\omega}$, but does so by encoding the category of complete metric spaces and uniformly

continuous maps in this logic and having the encoding of metric structures fall out of this, rather than focusing on continuous logic from the start (as we do here). Additionally, our focus is primarily on applications dealing with classification theory (saturation, etc.), while Ackerman applies his methods to explore set-theoretic absoluteness.

A final note is that some of the arguments are straightforward arguments with δ's and ϵ's. Thus, we omit the proofs and only reference the axioms of T_{dense} that are needed. Full proofs can be found on the author's website [Bonc].

2. Models and Theories

The main thesis of the presentation of continuous first-order logic is that model-theoretic properties of continuous first order structures can be translated to model-theoretic (but typically quantifier free) properties of discrete structures that model a specific theory in an expanded language. We use cFml τ to denote the continuous formulas of the language τ. The main theorem about this presentation is the following:

Theorem 2.1. *Let τ be a continuous language. Then there is*

(a) *a discrete language τ^+;*
(b) *an $\mathbb{L}_{\omega_1,\omega}(\tau^+)$ theory T_{dense};*
(c) *a map that takes continuous τ-structures M and nicely dense subsets A to discrete τ^+-structures M_A that model T_{dense};*
(d) *a map that takes discrete τ^+ structures A that model T_{dense} to continuous τ-structures $\overline{A}$*

with the properties that

(1) *$M_A \vDash T_{dense}$ has universe A and, for any $\mathbf{a} \in A$, $\phi(\mathbf{x}) \in cFml\,\tau$, $r \in \mathbb{Q}'$, and $\square$ standing for $\geq$ and $\leq$, we have*
$$M_A \vDash R_{\phi\square r}[\mathbf{a}] \iff \phi^M(\mathbf{a})\square r$$

(2) *A is a dense subset of $\overline{A}$ and, for any $\mathbf{a} \in A$, $\phi(\mathbf{x}) \in cFml\,\tau$, $r \in \mathbb{Q}'$, and $\square$ standing for $\geq$ and $\leq$, we have*
$$A \vDash R_{\phi\square r}[\mathbf{a}] \iff \phi^{\overline{A}}(\mathbf{a})\square r$$

(3) *these maps are (essentially) each other's inverse. That is, given any nicely dense $A \subset M$, we have $M \cong_A \overline{M_A}$ and, given any τ^+-structure $A \vDash T_{dense}$, we have $(\overline{A})_A = A$.*

The "essentially" in the last clause comes from the fact that completions are not technically unique as the objects selected as limits can vary, but this fairly pedantic point is the only obstacle.

Restricting to dense subsets and their completions have already been considered in continuous first-order logic, where it goes by the name *prestructure* (see [BBHU08, Section 3]). The key difference here is that, while prestructures are

still continuous objects with uniformly continuous functions and relations, M_A is a discrete object with the relations on it being either true or false.

Proof: Our proof is long, but straightforward. First, we will define τ^+ and T_{dense}. Then, we will introduce the map $(M, A) \mapsto M_A$ and prove it satisfies (1). After this, we will introduce the other map $A \mapsto \overline{A}$ and prove (2). Finally, we will prove that they satisfy (3).

Defining the new language and theory

We define the language τ^+ to be

$$\langle F_i^+, R_{\phi(\mathbf{x}) \geq r}, R_{\phi(\mathbf{x}) \leq r} \rangle_{i < n_F, \phi(\mathbf{x}) \in \text{cFml } \tau, r \in \mathbb{Q}'}$$

with the arity of F_i^+ matching the arity of F_i and the arity of $R_{\phi(\mathbf{x}) \square r}$ matching $\ell(\mathbf{x})$. Since we only use a full (dense) set of connectives (see [BBHU08, Definition 6.1]), we have ensured that $|\tau^+| = |\tau| + \aleph_0$.

We define $T_{dense} \subset \mathbb{L}_{\omega_1, \omega}(\tau^+)$ to be the universal closure of all of the following formulas ranging over all continuous formulas $\phi(\mathbf{z})$ and $\psi(\mathbf{z}')$, all terms $\mathfrak{t}(z, \mathbf{z}'')$, and all $r, s \in \mathbb{Q}'$ and $t \in \mathbb{Q}' - \{0\}$. We have divided them into headings so that their meaning is (hopefully) more clear. When we refer to specific sentences of T_{dense} later, we reference the ordering in this list. As always, a $\square$ in a formula means that it should be included with both a '$\geq$' and a '$\leq$' replacing the $\square$.

(1) **The ordered structure of $\mathbb{R}$**
   - (a) $\neg R_{\phi(\mathbf{z}) \geq r}(\mathbf{x}) \to R_{\phi(\mathbf{z}) \leq r}(\mathbf{x})$
   - (b) $\neg R_{\phi(\mathbf{z}) \leq r}(\mathbf{x}) \to R_{\phi(\mathbf{z}) \geq r}(\mathbf{x})$
   - (c) If $r > s$, then include $\neg R_{\phi(\mathbf{z}) \geq r}(\mathbf{x}) \vee \neg R_{\phi(\mathbf{z}) \leq s}(\mathbf{x})$
   - (d) If $r \geq s$, then include
       - $R_{\phi(\mathbf{z}) \leq s}(\mathbf{x}) \to R_{\phi(\mathbf{z}) \leq r}(\mathbf{x})$; and
       - $R_{\phi(\mathbf{z}) \geq r}(\mathbf{x}) \to R_{\phi(\mathbf{z}) \geq s}(\mathbf{x})$
   - (e) $R_{\phi(\mathbf{z}) \geq r}(\mathbf{x}) \vee R_{\phi(\mathbf{z}) \leq r}(\mathbf{x})$
   - (f) $\wedge_{n < \omega} \vee_{r, s \in \mathbb{Q}', |r - s| < \frac{1}{n}} R_{\phi \leq r}(\mathbf{x}) \wedge R_{\phi \geq s}(\mathbf{x})$
   - (g) $(\wedge_{n < \omega} R_{\phi(\mathbf{z}) \geq r - \frac{1}{n}}(\mathbf{x})) \to R_{\phi(\mathbf{z}) \geq r}(\mathbf{x})$
   - (h) $(\wedge_{n < \omega} R_{\phi(\mathbf{z}) \leq r + \frac{1}{n}}(\mathbf{x})) \to R_{\phi(\mathbf{z}) \leq r}(\mathbf{x})$

(2) **Construction of formulas**
   - (a) $R_{\phi(\mathbf{z}) \geq 0}(\mathbf{x}) \wedge R_{\phi(\mathbf{z}) \leq 1}(\mathbf{x})$
   - (b) $\neg R_{0 \geq t}(\mathbf{x}) \wedge \neg R_{1 \leq 1 - t}(\mathbf{x})$;
   - (c) $R_{\frac{\phi(\mathbf{z})}{2} \geq r}(\mathbf{x}) \leftrightarrow R_{\phi(\mathbf{z}) \geq 2r}(\mathbf{x})$
   - (d) $R_{\frac{\phi(\mathbf{z})}{2} \leq r}(\mathbf{x}) \leftrightarrow R_{\phi(\mathbf{z}) \leq 2r}(\mathbf{x})$;
   - (e) $R_{\phi(\mathbf{z}) \dot- \psi(\mathbf{z}') \geq r}(\mathbf{x}, \mathbf{x}') \leftrightarrow \vee_{s \in \mathbb{Q}'}(R_{\psi(\mathbf{z}') \leq s}(\mathbf{x}') \wedge R_{\phi(\mathbf{z}) \geq r + s}(\mathbf{x}))$
   - (f) $R_{\phi(\mathbf{z}) \dot- \psi(\mathbf{z}') \leq r}(\mathbf{x}, \mathbf{x}') \leftrightarrow \vee_{s \in \mathbb{Q}'}(\neg R_{\psi(\mathbf{z}') \leq s}(\mathbf{x}') \wedge R_{\phi(\mathbf{z}) \leq r + s}(\mathbf{x}))$;
   - (g) $R_{\sup_y \mathfrak{t}(y, \mathbf{y}) \leq r}(\mathbf{x}) \leftrightarrow \forall x R_{\mathfrak{t}(y, \mathbf{y}) \leq r}(x, \mathbf{x})$
   - (h) $R_{\sup_y \mathfrak{t}(y, \mathbf{y}) \geq r}(\mathbf{x}) \leftrightarrow \wedge_{n < \omega} \exists x R_{\mathfrak{t}(y, \mathbf{y}) \geq r - \frac{1}{n}}(x, \mathbf{x})$;

(i) $R_{\inf_y \mathfrak{t}(y,\mathbf{y}) \leq r}(\mathbf{x}) \leftrightarrow \wedge_{n<\omega} \exists x R_{\mathfrak{t}(y,\mathbf{y}) \leq r + \frac{1}{n}}(x, \mathbf{x})$;

(j) $R_{\inf_y \mathfrak{t}(y,\mathbf{y}) \geq r}(\mathbf{x}) \leftrightarrow \forall x R_{\phi(y,\mathbf{y}) \geq r}(x, \mathbf{x})$;

(k) $R_{\phi(y,\mathbf{y}) \square r}(\mathfrak{t}(\mathbf{x}'), \mathbf{x}) \leftrightarrow R_{\phi(\mathfrak{t}(\mathbf{y}'), \mathbf{x}) \square r}(\mathbf{x}', \mathbf{x})$

(3) **Metric structure**

(a) $R_{d(y,y') \leq 0}(x, x') \leftrightarrow x = x'$;

(b) $R_{d(y,y') \square r}(x, x') \leftrightarrow R_{d(y,y') \square r}(x', x)$;

(c) $\wedge_{r \in \mathbb{Q}'} (R_{d(y,y') \geq r}(x, x') \rightarrow \forall x'' \vee_{s \in \mathbb{Q}' \cap [0,r]} R_{d(y,y') \geq s}(x, x'') \wedge R_{d(y,y') \geq r-s}(x'', x'))$

(4) **Uniform Continuity**

(a) For each $r, s \in \mathbb{Q}'$ and $i < \tau_F$ such that $s < \Delta_{F_i}(r)$, we include the sentence

$$\wedge_{i<n} R_{d(z,z') \leq s}(x_i, y_i) \rightarrow R_{d(z,z') \leq r}(F_i(\mathbf{x}), F_i(\mathbf{y}))$$

(b) For each $r, s \in \mathbb{Q}'$ and $j < \tau_R$ such that $s < \Delta_{R_j}(r)$, we include the sentence

$$\wedge_{i<n} R_{d(z,z') \leq s}(x_i, y_i) \rightarrow (R_{R_j(\mathbf{z}) \dot{-} R_j(\mathbf{z}') \leq r}(\mathbf{x}, \mathbf{y}) \wedge R_{R_j(\mathbf{z}) \dot{-} R_j(\mathbf{z}') \leq r}(\mathbf{y}, \mathbf{x}))$$

We have been careful about the specific enumeration of these axioms for a reason. If the original continuous language is countable, then T_{dense} is countable. In particular, we could take the conjunction of it and make it a single $\mathbb{L}_{\omega_1,\omega}(\tau^+)$ sentence. This means that it is expressible in a countable fragment of $\mathbb{L}_{\omega_1,\omega}(\tau^+)$. In general, T_{dense} is expressible in a $|\tau| + \aleph_0$ sized fragment of $\mathbb{L}_{\omega_1,\omega}(\tau^+)$.

Countable fragments are the most well-studied infinitary languages and many of the results in, say, Keisler [Kei71] use these fragments. These results are then applicable to countable theories in continuous first-order logic. Such an application is an improvement on finding generalized indiscernibles: in [Ben05, Lemma 3.35], Ben-Yaacov appeals to (essentially) Morley's omitting types theorem to find appropriate indiscernibles that look like a long enough sequence. Even for countable theories T, "long enough" is bounded by $\beth_{(2^\omega)^+}$. However, using our correspondence (including the analysis of types from Section 5) and the Hanf number for $\mathbb{L}_{\omega_1,\omega}$ [Kei71, Theorem 21], this bound can be brought down to $\beth_{\omega_1}$.

From continuous to discrete...

This is the easier of the directions. We define the structure M_A so that all of the "intended" correspondences hold and everything works out well.

Suppose we have a continuous τ-structure M and a nicely dense subset A. Now we define an τ^+ structure M_A by

(1) the universe of M_A is A;

(2) $(F_i^+)^{M_A} = F_i^M \upharpoonright A$ for $i < n_F$; and

(3) for $r \in \mathbb{Q}'$ and $\phi(\mathbf{x}) \in \text{cFml } \tau$, set

$$R^{M_A}_{\phi \square r} = \{\mathbf{a} \in A : \phi^M(\mathbf{a}) \square r\}$$

This is an τ^+-structure since it is closed under functions. The real meat of this part is the following claim, which is (1) from the theorem.

Claim: $M_A \vDash T_{dense}$ and, for any $\mathbf{a} \in A$, $\phi(\mathbf{x}) \in \text{cFml } \tau$, $r \in \mathbb{Q}'$, and $\square = \geq, \leq$, we have

$$M_A \vDash R_{\phi \square r}[\mathbf{a}] \iff \phi^M(\mathbf{a}) \square r$$

Proof of Claim: This is all straightforward. From the definition, we know that, for any $\mathbf{a} \in A$ and formula $\phi(\mathbf{x}) \in \text{cFml } \tau$ and $\square \in \{\geq, \leq\}$, we have

$$M_A \vDash R_{\phi \square r}[\mathbf{a}] \iff \phi^M(\mathbf{a}) \square r$$

This gives an easy proof of the fact that $M_A \vDash T_{dense}$ because they are all just true facts if '$R_{\phi \square r}(\mathbf{a})$' is replaced by '$\phi(\mathbf{a}) \square r$.' $\dagger_{Claim}$

...and back again

This is the harder direction. We want to 'read out' the τ-structure that A is a dense subset of from the τ^+ structure. First, we use the axioms of T_{dense} to show that we can read out the metric and relations of τ from the relations of τ^+ and that these are well-defined. Then we complete A and use the uniform continuity of the derived relations to expand them to the whole structure. In the first direction, T_{dense} could have been any collection of true sentences about continuous structures and the real line, but this direction makes it clear that the axioms chosen are sufficient.

Suppose that we have an τ^+-structure A that models T_{dense}. The following claim is an important step in reading out the relations of the completion of A from A.

Claim 2.2. *For any $\phi(\mathbf{x}) \in cFml \ \tau$ and $\mathbf{a} \in A$, we have*

$$\sup\{t \in \mathbb{Q}' : A \vDash R_{\phi(\mathbf{x}) \leq t}(\mathbf{a})\} = \inf\{t \in \mathbb{Q}' : A \vDash R_{\phi(\mathbf{x}) \geq t}(\mathbf{a})\}$$

As mentioned, the proofs are typically straightforward. We give this proof to give the reader the flavor of the arguments.

Proof: We show this equality by showing two inequalities.

- Let $r \in \{t \in \mathbb{Q}' : A \vDash R_{\phi(\mathbf{x}) \leq t}(\mathbf{a})\}$ and $s \in \{t \in \mathbb{Q}' : A \vDash R_{\phi(\mathbf{x}) \geq t}(\mathbf{a})\}$. Then

$$A \vDash R_{\phi(\mathbf{x}) \geq r}(\mathbf{a}) \wedge R_{\phi(\mathbf{x}) \leq s}(\mathbf{a})$$

  Then, since M^+ satisfies (1c), we must have $r \leq s$. Thus $\sup\{t \in \mathbb{Q}' : A \vDash R_{\phi(\mathbf{x}) \leq t}(\mathbf{a})\} \leq \inf\{t \in \mathbb{Q}' : A \vDash R_{\phi(\mathbf{x}) \geq t}(\mathbf{a})\}$.
- By (1f), we have

$$A \vDash \bigwedge_{n < \omega} \bigvee_{r,s \in \mathbb{Q}'; |r-s| < \frac{1}{n}} R_{\phi(\mathbf{x}) \leq r}(\mathbf{a}) \wedge R_{\phi(\mathbf{x}) \geq s}(\mathbf{a})$$

Let $\epsilon > 0$. Then there is $n_0 < \omega$ such that $\epsilon > \frac{1}{n_0}$. By the above, there are $r, s \in \mathbb{Q}'$ such that $|r - s| < \frac{1}{n_0}$ and

$$M^+ \models R_{\phi(\mathbf{x}) \leq r}(\mathbf{a}) \wedge R_{\phi(\mathbf{x}) \geq s}(\mathbf{a})$$

As above, (1c) implies $r \geq s$, so we have $r - s < \frac{1}{n_0} < \epsilon$. Thus $r < s + \epsilon$ and $s \in \{t \in \mathbb{Q}' : A \models R_{\phi(\mathbf{x}) \leq t}(\mathbf{a})\}$ and $r \in \{t \in \mathbb{Q}' : A \models R_{\phi(\mathbf{x}) \geq t}(\mathbf{a})\}$. Then, $\inf\{t \in \mathbb{Q}' : A \models R_{\phi(\mathbf{x}) \geq t}(\mathbf{a})\} \leq \sup\{t \in \mathbb{Q}' : A \models R_{\phi(\mathbf{x}) \leq t}(\mathbf{a})\}$. $\dagger_{Claim}$

The first relation that we need is the metric. Given $a, b \in A$, we set

$$\begin{aligned} D(a, b) &:= \sup\{r \in \mathbb{Q}' : A \models R_{d(x,y) \geq r}[a, b]\} \\ &= \inf\{r \in \mathbb{Q}' : A \models R_{d(x,y) \leq r}[a, b]\} \end{aligned}$$

These definitions are equivalent by Claim 2.2. We show that this is indeed a metric on A.

Claim 2.3. $(|A|, D)$ *is a metric space.*

Proof: See [Bonc]; the proof uses axioms (1d), (1h), (3b), and (3c). $\dagger_{Claim}$

Now we define partial functions and relations on $(|A|, D)$ such that they are uniformly continuous. In particular,

(1) for $i < n_F$, set $f_i := F_i^A$ with modulus $\Delta_{f_i}(r) = \sup\{s \in \mathbb{Q}' : A \models \forall x_0, \ldots, x_{n(F_i)-1}; \forall y_0, \ldots, y_{n(F_i)-1} (\wedge_{i < n(F_i)} R_{d(z,z') \leq s}(x_i, y_i) \rightarrow R_{d(z,z') \leq r}(F_i(\mathbf{x}), F_i(\mathbf{y})))\}$.

(2) for $j < n_R$, set $r_j(\mathbf{a}) := \sup\{r \in \mathbb{Q}' : A \models R_{R_j(\mathbf{z}) \leq r}[\mathbf{a}]\}$ with modulus $\Delta_{r_j}(r) = \sup\{s \in \mathbb{Q}' : A \models \forall \mathbf{x} \forall \mathbf{y} (\wedge_{i < n(R_j)} R_{d(z,z') \leq s}(x_i, y_i) \rightarrow (R_{R_j(\mathbf{z}) \dot{-} R_j(\mathbf{z}') \leq r}(\mathbf{x}, \mathbf{y}) \wedge R_{R_j(\mathbf{z}) \dot{-} R_j(\mathbf{z}') \leq r}(\mathbf{y}, \mathbf{x})))\}$.

These functions are not defined on the desired structure (ie the completion of A), but they already fulfill our goal in terms of agreeing with the discrete relations in the following sense.

Claim 2.4. *For all* $\mathbf{a} \in A$ *and all formulas* $\phi(\mathbf{x})$ *built up from these functions and* D, *we have that*

$$\phi(\mathbf{a}) \square r \iff A \models R_{\phi(\mathbf{z}) \square r}[\mathbf{a}]$$

Proof: See [Bonc]; this proof uses axioms (1d), (1g), (1h), (2k), (2e), (2g), (2h), (2i), and (2j). $\dagger$

We have given these functions moduli, but do not know they are uniformly continuous. We show this now. It is also worth noting that these moduli might not be the same moduli in the original signature τ. Instead, these are the optimal moduli, while the original language might have moduli that could be improved.

Claim 2.5. *The functions* f_i *and* r_j *are continuous.*

Proof: See [Bonc]; this proof uses (1d).   †

Now we have a prestructure. Now we complete $|A|$ to $|\overline{A}|$ in the standard way; see Munkries [Mun00] for a reference for the topological facts. In particular, we define the continuous τ-structure $\overline{A}$ by

- the universe $|\overline{A}|$ is the completion of $(|A|, D)$;
- the metric $d^{\overline{A}}$ is the extension of D to $|\overline{A}|$;
- for $i < n_F$, $F_i^{\overline{A}}$ is the unique extension of f_i to $|\overline{A}|$; and
- for $j < n_R$, $R_j^{\overline{A}}$ is the unique extension of r_j to $|\overline{A}|$.

Essential inverses

Proposition 2.6. *Given any continuous τ-structure M and dense subset A, we have that $M \cong_A \overline{M_A}$ and, given any τ^+ structure A that models T_{dense}, we have that $(\overline{A})_A = A$.*

Proof: First, let M be a continuous τ-structure and $A \subset |M|$ be nicely dense. We define a map $f : M \to \overline{(M_A)}$ as follows: if $a \in A$, then $f(a) = a$. For $a \in M - A$, fix some (any) sequence $\langle a_n \in A : n < \omega \rangle$ such that $\lim_{n \to \infty} a_n = a$ (this limit computed in M). We know that $\langle a_n : n < \omega \rangle$ is Cauchy in M, so it's Cauchy in $\overline{(M_A)}$. Then set $f(a) = \lim_{n \to \infty} a_n$, where that limit is computed in $\overline{(M_A)}$. This is well-defined and a bijection because A is dense in both sets. That this is an τ-isomorphism follows from applying the correspondence twice: for all $\mathbf{a} \in A$ and $\phi(\mathbf{x}) \in \mathrm{cFml}\ \tau$

$$\phi^M(\mathbf{a}) \square r \iff M_A \vDash R_{\phi(\mathbf{x}) \square r}[\mathbf{a}] \iff \phi^{\overline{(M_A)}}(\mathbf{a}) \square r$$

and the fact that the values of ϕ on A determines its values on M and $\overline{(M_A)}$.

Second, let A be a τ^+ structure that models T_{dense}. Clearly, the universes are the same, ie, $|(\overline{A})_A| = |A|$. For any relation $R_{\phi \square r}$ and $\mathbf{a} \in |A|$, we have

$$A \vDash R_{\phi \square r}[\mathbf{a}] \iff \phi^{\overline{A}}(\mathbf{a}) \square r \iff (\overline{A})_A \vDash R_{\phi \square r}[\mathbf{a}]$$

Given a function F_i^+ and $\mathbf{a}, a \in A$, we have that

$$(F_i^+)^A(\mathbf{a}) = a \iff A \vDash R_{d(F_i^+(\mathbf{x}), x) \leq 0}[\mathbf{a}, a]$$

$$\iff (\overline{A})_A \vDash R_{d(F_i^+(\mathbf{x}), x) \leq 0}[\mathbf{a}, a] \iff (F_i^+)^{(\overline{A})_A}(\mathbf{a}) = a$$

                                                                                †

We can extend this correspondence to theories. Suppose that T is a continuous theory in τ. Following [BBHU08, Definition 4.1], theories are sets of closed τ-conditions; that is, a set of "$\phi = 0$," where ϕ is a formula with no free variables. The following is immediate from Theorem 2.1.

Corollary 2.7. *If "$\phi = 0$" is a closed τ-condition, then*

$$\phi^M = 0 \iff M_A \vDash R_{\phi \leq 0}$$

With our fixed theory T, set T^* to be $T_{dense} \cup \{R_{\phi \leq 0} : \text{"}\phi = 0\text{"} \in T\}$. Then our representation of continuous τ-structures as discrete τ^+-structures modeling T_{dense} can be extended to a representation of continuous models of T and discrete models of T^*.

3. Elementary Substructure

We now discuss translating the notion of elementary substructure between our two contexts. Depending on the generality needed, this is either easy or difficult.

For the easy case, we have the following.

Theorem 3.1. *Let M, N be continuous τ structures. Then $M \prec_\tau N$ iff, for every nicely dense $A \subset M$ and $B \subset N$ such that $A \subset B$, we have that $M_A \subset_{\tau^+} N_B$.*

Note that the relation between M_A and N_B is just substructure. So even though they are models of infinitary theories, their relation just concerns atomic formulas. This is because we have built the quantifiers of τ into the relations of τ^+.

Proof: $\leftarrow$: Let $A = M$ and $B = N$. Then $M \subset N$, so $M_M \subset_{\tau^+} N_N$ by assumption. Thus they agree on all relations concerning elements of M. Now we want to show that $M \prec_\tau^c N$. Let $\phi(\mathbf{x}) \in \text{cFml } \tau$ and $\mathbf{a} \in M$. From the theorems proved last section, we have, for each $r \in \mathbb{Q}'$,

$$
\begin{array}{lll}
\phi^M(\mathbf{a}) \square r & \iff M_M \vDash R_{\phi(\mathbf{x}) \square r}[\mathbf{a}] & \text{Theorem 2.1} \\
& \iff N_N \vDash R_{\phi(\mathbf{x}) \square r}[\mathbf{a}] & M_M \subset_{\tau^+} N_N \\
& \iff \phi^N(\mathbf{a}) \square r & \text{Theorem 2.1}
\end{array}
$$

Thus $\phi^M(\mathbf{a}) = \phi^N(\mathbf{a})$ and $M \prec_\tau N$ as desired.

$\rightarrow$: Let $A \subset M$ and $B \subset N$ be nicely dense so $A \subset B$. We want to show that $M_A \subset_{\tau^+} N_B$.

- Let $F^+ \in \tau^+$ and $\mathbf{a} \in A$. Then, by definition of the structures,

$$(F^+)^{M_A}(\mathbf{a}) = F^M(\mathbf{a}) = F^N(\mathbf{a}) = (F^+)^{N_B}(\mathbf{a})$$

- Let $R_{\phi \square r}(\mathbf{x}) \in \tau^+$ and $\mathbf{a} \in A$.

$$
\begin{array}{lll}
M_M \vDash R_{\phi(\mathbf{x}) \square r}[\mathbf{a}] & \iff \phi^M(\mathbf{a}) \square r & \text{Theorem 2.1} \\
& \iff \phi^N(\mathbf{a}) \square r & M \prec N \\
& \iff N_N \vDash R_{\phi(\mathbf{x}) \square r}[\mathbf{a}] & \text{Theorem 2.1}
\end{array}
$$

$$\dagger$$

Similarly, we have the following.

Theorem 3.2. *Given $A, B \vDash T_{dense}$, if $A \subset_{\tau^+} B$, then $\overline{A} \prec_\tau \overline{B}$.*

However, relying on just these theorems would not allow these relations alone do not capture the entirety of the relation between $\overline{A}$ and $\overline{B}$ via the analysis of A and B alone. For instance, the completion of $\mathbb{Q} \cap [0,1]$ is a subset of the completion of $\mathbb{Q} + \sqrt{2}$, but this relation isn't picked up by the previous theorems. Thus, we develop a criterion for L^+ structures $A, B \vDash T_{dense}$ that is equivalent to $\overline{A} \prec_\tau \overline{B}$.

To this end, we define inessential extensions of models of T_{dense}.

Definition 3.3. *Given $A \subset_{\tau_A^+} B$, we say that B is an* inessential extension *of A iff for every $b \in |B|$ and $n < \omega$, there is some $a \in |A|$ such that $B \vDash R_{d(x,y) < \frac{1}{n}}[b, a]$.*

Briefly, we have that B is an inessential extension of A if $A \subset B$ and $\overline{A} = \overline{B}$. This gives us our desired criterion.

Theorem 3.4. *Let $A, B \vDash T_{dense}$. Then TFAE*

    (1) *$\overline{A} \prec_\tau \overline{B}$.*
    (2) *There is an τ^+ structure C such that $A, B \prec_{\tau^+} C$ and C is an inessential extension of B.*
    (3) *There is an τ^+ structure $C' \vDash T_{dense}$ such that $A, B \subset_{\tau^+} C$ and C is an inessential extension of B.*
    (4) *There is an extension of the functions and relations of τ^+ to $A \cup B$ such that $A \cup B \vDash T_{dense}$ that are still uniformly continuous and such that for every $a \in |A \cup B|$ and $n < \omega$, there is some $b \in |B|$ such that $A \cup B \vDash R_{d(x,y) < \frac{1}{n}}[b, a]$.*

Proof:

$\underline{(1) \implies (2)}$ Take $C = (\overline{B})_{A \cup B}$.

$\underline{(2) \implies (3)}$ Immediate.

$\underline{(3) \implies (4)}$ Take the extension inherited from C.

$\underline{(4) \implies (1)}$ We have $\overline{A}, \overline{B} \prec \overline{A \cup B}$ from the first condition and $\overline{B} = \overline{A \cup B}$ form the second.

4. T_{dense} AS AN ABSTRACT ELEMENTARY CLASS

In this section, we view the discrete side of things as an Abstract Elementary Class; see Baldwin [Bal09] or Grossberg [Gro1X].

Theorem 4.1. *Let T be a complete, continuous first order τ-theory. Then let τ^+ and T_{dense} be from Theorem 2.1. Set $K = (Mod\,(T^*), \subset_{\tau^+})$. Then*

    (1) *K is an AEC;*
    (2) *K has amalgamation over sets, joint embedding, and no maximal models; and*
    (3) *Galois types in K correspond to continuous, syntactic types in T.*

Note that if T were not complete, then amalgamation over sets would not hold. However, the other properties will continue to hold, including the correspondence between Galois types and sequence types.

Proof: $T_{dense} \cup T^+$ is a $\mathbb{L}_{\omega_1,\omega}(\tau^+)$ theory, so all of the axioms of AECs hold except perhaps the chain axioms (which might fail because strong substructure is not elementary according to the fragment). For those, consider a $\subset_{\tau^+}$-increasing chain $\langle M_{A_i} : i < \alpha \rangle$. Then, by Theorem 2.1 and Theorem 3.2, the sequence $\langle \overline{M_{A_i}} : i < \alpha \rangle$ is $\prec_\tau$-increasing chain that each model T. Then by the chain axiom for continuous logic, there is $M = \overline{\cup_{i<\alpha}(\overline{M_{A_i}})}$ that models T. Additionally, $A := \cup_{i<\alpha} A_i$ is nicely dense in M. Thus, $M_A = \cup_{i<\alpha} M_{A_i}$ is as desired. Additionally, if $M_{A_i} \subset_{\tau^+} M_B$ for some B, then $M \prec_\tau \overline{M_B}$, so $M_A \subset_{\tau^+} M_B$.

These properties all follow from the corresponding properties of continuous first-order logic. For instance, considering amalgamation, suppose $M_A \subset_{\tau^+} M_B, M_C$. Then we have $\overline{M_A} \prec_\tau \overline{M_B}, \overline{M_C}$. By amalgamation for continuous first-order logic, there is some $N \succ_\tau \overline{M_B}$ and elementary $f : \overline{M_C} \to_{\overline{M_A}} N$. Let $D \subset N$ be nicely dense that contains $B \cup C$. Then we have $M_B \subset_{\tau^+} N_D$ and $f \restriction M_C : M_C \to_{M_A} N_D$; this is an amalgamation of the original system.

Finally, we wish to show that Galois types are syntactic types and vice versa. Note that there are monster models in each class. Further more, we may assume that, if $\mathfrak{C}$ is the monster model of T, that there is some nicely dense $U \subset \mathfrak{C}$ such that the monster model of K is M_U; in fact, we could take $U = |\mathfrak{C}|$. Let continuous $M \vDash T$ and $A \subset M$ be nicely dense. If we have tuples $\mathbf{a}$ and $\mathbf{b}$, then

$$
\begin{aligned}
gtp_K(\mathbf{a}/M_A) = gtp_K(\mathbf{b}/M_A) &\iff \exists f \in Aut_{M_A} M_U.f(\mathbf{a}) = \mathbf{b} \\
&\iff \exists f \in Aut_{\overline{M_A}} \mathfrak{C}.f(\mathbf{a}) = \mathbf{b} \\
&\iff tp_T(\mathbf{a}/M) = tp_T(\mathbf{b}/M)
\end{aligned}
$$

$\dagger$

We pause here only briefly to point out a strange occurence: first-order continuous logic is compact (see [BBHU08, Theorem 5.8]), but $\mathbb{L}_{\omega_1,\omega}$ is incompact. Yet, we have seen that continuous logic can be embedded into $\mathbb{L}_{\omega_1,\omega}$. The solution to this incongruity is that the compactness of continuous logic comes from a different ultraproduct than the model-theoretic one, namely the Banach space ultraproduct. In model theoretic terms, the Banach space ultraproduct avoids having elements of nonstandard norm by explicitly excluding all sequences with unbounded norm from the product. This is put into a general framework for type omission in the author's thesis [Bona] (see [Bonb, Section 4.1] for details).

We conclude with a basic example relevant to the next section. I thank Ilijas Farah for discussions around this example.

Example 4.2. *The model theory of probability spaces (X, B, μ) is developed in [BBHU08, Section 16] by defining a metric structure where the universe consists of*

the elements of B modulo μ-equivalence; adding 0, 1, complement, meet, and join to the language; and setting the distance $d(A, B) = \mu(A \triangle B)$. An axiomatization PrA is given in [BBHU08, Theorem 16.1].

Then PrA^* consists of the normal axioms of T_{dense} along with the appropriately relativized axioms of PrA: each "universal axiom" $\sup_{\mathbf{x}} \phi(\mathbf{x})$ becomes $\forall \mathbf{x} R_{\phi \leq 0}(\mathbf{x})$. This means that a model M of PrA^* will have a naturally induced structure of a boolean algebra on it, along with a distance function d that gives rise to a probability measure via $\mu(x) = d(x, 0)$.

Probability spaces can be seen as a metric version of boolean algebras, and any model of PrA^* is a boolean algebra with some extra structure. However, this correspondence does not go backwards: there are many boolean algebras that cannot be expanded to a model of PrA^*. In particular, any boolean algebra $\mathcal{B}$ with an increasing sequence $\langle b_\alpha : \alpha < \omega_1 \rangle$ cannot be a reduct of a model of PrA^* because $\langle \mu(b_\alpha) : \alpha < \omega_1 \rangle$ would be $\aleph_1$-increasing sequence of reals.

PrA is stable (see [BBHU08, Proposition 16.9] or [FHS13, Proposition 4.6]) and, thus, doesn't have the (properly defined) order property. However, there *is* an order extractable from the syntax. Set $x \prec y$ iff $\mu(x \cap y) \dot{-} \mu(x) = 0$. Looking in the the probability space of Lebesgue measurable subsets of $[0, 1]$, we can find sequences $\langle X_i \mid \alpha \rangle$ that are increasing according to this measure for any $\alpha < \omega_1$. However, this does not contradict the above because the proper definition of the order property [FHS13, Definition 2.3] requires a uniform separation of the values of the formula (rather than only detecting when a formula takes the value 0).

This represents a common theme of studying the order property in general AECs. When defining the order property in an AEC (see, for instance, [Sh394, Section 4]), an extra parameter of *how long* the order is must be included as there is no compactness to make it arbitrarily long. Then the order property with no parameters means that there are arbitrarily long order or, equivalently, that there is an order of length $\beth_{(2^{LS(K)})^+}$. Thus, PrA^* has the α-order property for every $\alpha < \omega_1$, does not have the $\aleph_1$-order property, and is stable (see Corollary 5.2 below). The compactness of continuous logic from the metric ultrapower offers a better criteria in terms uniform order property from [FHS13]: T^* has the order property (as an AEC) iff T has arbitrary long finite orders (as a metric theory).

5. Types

Fix a continuous τ-theory T, and let T^* be it's discrete equivalent (described at the end of Section 2).

In Theorem 4.1, we showed that Galois types on the discrete side correspond to the normal definition of syntactic on the continuous side. We can characterize Galois types more precisely by looking at the quantifier-free syntactic type in τ^+.

Proposition 5.1. *In $(Mod(T^*), \subset_{\tau^+})$, two elements have the same Galois type iff they have the same quantifier-free τ^+-type.*

Proof: In all AECs, two tuples having the same Galois type implies having the same quantifier-free type. Suppose that $\mathbf{a}, \mathbf{b} \in D \vDash T^*$ have the same quantifier-free type over $C \subset |D|$. Then, by Theorem 2.1.(2), $\mathbf{a}, \mathbf{b} \in \bar{D}$ have the same continuous τ-type over C. By Theorem 4.1.(3), this means that $\mathbf{a}$ and $\mathbf{b}$ have the same Galois type in $(\text{Mod}\,(T^*), \subset_{\tau^+})$. †

Of course, not every finitely consistent quantifier-free τ^+-type is realized in a model. For instance, the partial type $\{\neg R_{d(x',y') \geq 0}(x,y), R_{d(x',y') \leq \frac{1}{n}}(x,y) \mid n < \omega\}$ is finitely satisfiable, but describes the type of two elements that are an infinitesimal, positive distance from each other. Clearly, no element in a model of T_{dense} can satisfy this.

The correspondence allows us to connect the stability of the discretization with the stability of the continuous class because we've established a bijection between the types. An important distinction in the study of stability in continuous first-order logic is *discrete stability* (counting the cardinality of the type space [BBHU08, Definition 14.1]) and *stability* (counting the density character of the type space under a natural metric [BBHU08, Definition 14.4]).

Corollary 5.2. *T is λ-discrete stable iff $(\text{Mod}\,(T^*), \subset_{\tau^+})$ is λ-Galois stable.*

Proof: Theorem 4.1.(3) has established a bijection between the relevant sets. †

The density character notion of stability turns out to be the better measure of a class' behavior (although they are equivalent gloablly by [BBHU08, Theorem 14.6]). Additionally, in the discrete context, we could develop a notion of distance between types paralleling the notion on the continuous side. However, it doesn't seem as though there's a natural way to recover the density character of the type space in this context.

We now turn to saturation. While stability is a property of theories, saturation is a property of models. Thus, it requires a finer analysis to determine the transfer between continuous notions and T_{dense}. In particular, it is clear that we cannot expect a characterization along the lines of "the continuous structure M is saturated iff the discrete structure M_A is saturated for every nicely dense subset A." The failure comes from the fact that nicely dense subsets can miss many elements. Thus, we introduce the notion of a sequence type below. This notion allows us to give a characterization of the desired form in terms of saturation for sequence types (see Theorem 5.6). Note this notion appears elsewhere, e.g., in Farah and Magidor [FaMa] as the type p_ω, although they formalize it as a type in infinitely many free variables, rather than infinitely many types in 2 free variables.

Definition 5.3.   • *We say that $\langle r_n : n < \omega \rangle$ is a* sequence ℓ-type over B' iff $r_0(\mathbf{x})$ is an ℓ-type over B' and $r_{n+1}(\mathbf{x}, \mathbf{y})$ is a 2ℓ-type over B' such that there is some index set I, (possibly repeating) formulas $\langle \phi_i : i \in I \rangle$; and (possibly

repeating) Cauchy sequences $\langle\langle\mathbf{b}_n^i \in B'\rangle_{n<\omega} : i \in I\rangle$ *so* $d(\mathbf{b}_n^i, \mathbf{b}_{n+1}^i) \leq \frac{1}{2^n}$ *such that*

- $r_0(\mathbf{x}) = \{R_{\phi_i(\mathbf{z},\mathbf{z}')\leq w^{\phi_i}(2)}(\mathbf{x}, \mathbf{b}_0^i) : i \in I\}$; *and*
- $r_{n+1}(\mathbf{x}, \mathbf{y}) = \{R_{\phi_i(\mathbf{z},\mathbf{z}')\leq w^{\phi_i}(\frac{1}{2^n})}(\mathbf{x}, \mathbf{b}_{n+1}^i) : i \in I\} \cup \{R_{d(z,z')\leq \frac{1}{2^n}}(x_k, y_k) : k < \ell\}$

- *A* realization *of a sequence type* $\langle r_n : n < \omega\rangle$ *is* $\langle\mathbf{a}_n : n < \omega\rangle$ *such that*
  - $\mathbf{a}_0$ *realizes* r_0; *and*
  - $\mathbf{a}_{n+1}\mathbf{a}_n$ *realizes* r_{n+1}.

Note that the use of $\frac{1}{2^n}$ is not necessary; this could be replaced by any summable sequence for an equivalent definition (also replacing $\frac{1}{2^{n-1}}$ by the trailing sums). However, we fix $\frac{1}{2^n}$ for computational ease. The fundamental connection between continuous types and sequence types is the following.

Theorem 5.4. *Let* $A \subset |M|$ *be nicely dense.*

(1) *If* $B \subseteq |M|$ *and* $r(\mathbf{x})$ *is a partial* ℓ-*type over* B, *then for any* $B' \subset A$ *such that* $\overline{B'} \supset B$, *there is a sequence* ℓ *type* $\langle r_n : n < \omega\rangle$ *over* B' *such that*

$$M \text{ realizes } r \text{ iff } M_A \text{ realizes } \langle r_n : n < \omega\rangle$$

(2) *If* $B' \subset A$ *and* $\langle r_n : n < \omega\rangle$ *is a partial sequence* ℓ-*type over* B', *then there is a unique* ℓ-*type* r *over* $\overline{B'}$ *such that*

$$M \text{ realizes } r \text{ iff } M_A \text{ realizes } \langle r_n : n < \omega\rangle$$

We can denote the type in (2) by $\lim_{n\to\infty} r_n$. In each case, we have that $\langle\mathbf{a}_n \in M_A : n < \omega\rangle$ realizes $\langle r_n : n < \omega\rangle$ implies $\lim_{n\to\infty} \mathbf{a}_n$ realizes $\lim_{n\to\infty} r_n$.

Proof: See [Bonc].   †

We now connect type-theoretic concepts in continuous logic (e.g. saturation and stability) with concepts in our discrete analogue.

Recall (see [BBHU08, Definition 7.5]) that a continuous structure M is κ-saturated iff, for any $A \subset M$ of size $< \kappa$ and any continuous type $r(\mathbf{x})$ over A, if every finite subset of $r(\mathbf{x})$ is satisfiable in M, then so is $r(\mathbf{x})$.

Definition 5.5.

- *If* $\langle r_n : n < \omega\rangle$ *is a sequence type defined by an index set* I *and* $I_0 \subset I$, *then* $\langle r_n : n < \omega\rangle^{I_0}$ *is the sequence type defined by* I_0.
- *We say that* $M_A \vDash T_{dense}$ *is* κ-*saturated for sequence types iff, for all* $B' \subset A$ *and sequence type* $\langle r_n : n < \omega\rangle$ *over* B' *that is defined by* I, *if* $\langle r_n : n < \omega\rangle^{I_0}$ *is realized in* M_A *for all finite* $I_0 \subset I$, *then* $\langle r_n : n < \omega\rangle$ *is realized in* M_A.

Theorem 5.6. *Let* $M \vDash T$ *and* $A \subset M$ *be nicely dense.*

(1) *If* M *is* κ-*saturated and* $\lambda^{\aleph_0} < \kappa$, *then* M_A *is* λ^+ *saturated for sequence types.*

(2) *If* M_A *is* κ *saturated, then* M *is* κ *saturated.*

Proof:

(1) Let M be κ-saturated and $A \subset M$ be nicely dense. Let $B' \subset M_A$ of size λ and let $\langle r_n : n < \omega \rangle$ be a sequence type over B' that is finitely satisfiable in M_A. Set $r = \lim_{n \to \infty} r_n$ from Theorem 5.4; this is a type over $\overline{B'}$ where $|\overline{B'}| \leq \lambda^{\aleph_0} < \kappa$. We claim that r is finitely satisfiable in M. Any finite subset of r^- of

$$r = \{\phi_i(\mathbf{x}, \lim_{n \to \infty} \mathbf{b}_n^i) : i \in I\}$$

corresponds to a finite $I_0 \subset I$. Then, by Theorem 5.4, r_0 is realized in M iff $\langle r_n : n < \omega \rangle^{I_0}$ is realized in M_A. Then, since each $\langle r_n : n < \omega \rangle^{I_0}$ is realized in M_A by assumption, we have that r is finitely satisfiable in M. By the κ-saturation of M, r is realized in M. By Theorem 5.4, $\langle r_n : n < \omega \rangle$ is realized in M_A. So M_A is λ^+-saturated.

(2) Let M_A be κ-saturated for sequence types. Let $B \subset M$ of size $< \kappa$ and r be a type over B that is finitely satisfied in B. Find $B' \subset A$ such that $\overline{B'} \supset B$; this can be done with $|B'| \leq |B| + \aleph_0 < \kappa$. Then form the sequence type $\langle r_n : n < \omega \rangle$ over B' that converges to r_n as in Theorem 5.4. As before, since r is finitely satisfiable in M, so is $\langle r_n : n < \omega \rangle$ in M_A. So $\langle r_n : n < \omega \rangle$ is realized in M_A by saturation. Thus, r is realized in M. †

We immediately get the following corollary.

Corollary 5.7. *If $\kappa = (\lambda^{\aleph_0})^+$ or, more generally, $\kappa = \sup_{\lambda < \kappa}(\lambda^{\aleph_0})^+$ and M is of size κ, then M is saturated iff M_A is saturated for some nicely dense $A \subset M$ of size κ.*

6. Metric Abstract Elementary Classes

In this section, we extend the above representation to Metric Abstract Elementary Classes. Recall from Hirvonen and Hyttinen [HH09] or that a Metric Abstract Elementary Class (MAEC) is a class of continuous $\tau(K)$-structures K and a strong substructure relation $\prec_K$ satisfying the following axioms:

(1) $\prec_K$ is a partial order on K;

(2) for every $M, N \in K$, if $M \prec_K N$, then $M \subseteq_\tau N$;

(3) $(K, \prec_K)$ respects $\tau(K)$ isomorphisms, if $f : N \to N'$ is an $\tau(K)$ isomorphism and $N \in K$, then $N' \in K$ and if we also have $M \in K$ with $M \prec_K N$, then $f(M) \in K$ and $f(M) \prec_K N'$;

(4) *(Coherence)* if $M_0, M_1, M_2 \in K$ with $M_0 \prec_K M_2$; $M_1 \prec_K M_2$; and $M_0 \subseteq M_1$, then $M_0 \prec M_1$;

(5) *(Tarski-Vaught chain axioms)* suppose $\langle M_i \in K : i < \alpha \rangle$ is a $\prec_K$-increasing continuous chain, then

(a) $\overline{\cup_{i<\alpha} M_i} \in K$ and, for all $i < \alpha$, we have $M_i \prec_K \overline{\cup_{i<\alpha} M_i}$; and

(b) if there is some $N \in K$ such that, for all $i < \alpha$, we have $M_i \prec_K N$,
    then we also have $\cup_{i<\alpha} M_i \prec_K N$; and

(6) *(Löwenheim-Skolem number)* There is an infinite cardinal $\lambda \geq |\tau(K)|$ such
    that for any $M \in K$ and $A \subset M$, there is some $N \prec_K M$ such that $A \subset |N|$
    and $dc(N) \leq |A| + \lambda$. We denote the minimum such cardinal by $LS(K)$.

These axioms were first given in Hirvonen and Hyttinen [HH09].

A key difference is that the functions and relations τ are no longer required to be
uniformly continuous, but just continuous. This is due to the lack of compactness
in the MAEC context. This initially seems problematic because functions must
be uniformly continuous on a set to be guaranteed an extension to its closure.
However, we get around this by simply defining K_{dense} to be all the structures
that happen to complete to a member of K, then use the MAEC axioms to show
that K_{dense} satisfies the AEC axioms.

For this reason, when we refer to continuous languages, structures, etc. in this
section, we will not mean that they are uniformly continuous.

Theorem 6.1. *Let τ be a continuous language. Then there is a discrete language
τ^+ such that, for every MAEC K with $\tau(K) = \tau$, there is*

(1) *an AEC K_{dense} with $\tau(K_{dense}) = \tau^+$ and $LS(K_{dense}) = LS(K)$;*
(2) *a map from $M \in K$ and nicely dense subsets A of M to $M_A \in K_{dense}$; and*
(3) *a map from $\mathcal{A} \in K_{dense}$ to $\overline{\mathcal{A}} \in K$*

with the properties that

(1) *M_A has universe A and for each $\mathbf{a} \in A$, $r \in \mathbb{Q}'$, and $\square \in \{\leq, \geq\}$, we have
    that*

$$M_A \vDash R_{R_j(\mathbf{z})\square r}[\mathbf{a}] \iff R_j^M(\mathbf{a})\square r$$

(2) *$\overline{\mathcal{A}}$ has universe that is the completion of A with respect to the derived metric
    and for each $\mathbf{a} \in A$, $r \in \mathbb{Q}'$, and $\square \in \{\leq, \geq\}$, we have that*

$$R_j^{\overline{\mathcal{A}}}(\mathbf{a})\square r \iff \mathcal{A} \vDash R_{R_j(\mathbf{z})\square r}[\mathbf{a}]$$

(3) *The maps above are essentially inverses, in the since of Theorem 2.1.3*
(4)   • *Given $M_\ell \in K$ and A_ℓ nicely dense in M_ℓ for $\ell = 0, 1$, if $f : M_0 \to M_1$
        is a K-embedding such that $f(A_0) \subset A_1$, then $f \upharpoonright A_0$ is a K_{dense}-
        embedding from $(M_0)_{A_0}$ to $(M_1)_{A_1}$.*
       • *Given $\mathcal{A}, \mathcal{B} \in K_{dense}$ and a K_{dense}-embedding $f : \mathcal{A} \to \mathcal{B}$, this lifts
        canonically to a K-embedding $\overline{f} : \overline{\mathcal{A}} \to \overline{\mathcal{B}}$.*

Proof: The proof proceeds similar to the first-order version, Theorem 2.1. In
particulalr, many of the definitions of continuous structures from discrete approx-
imations (such as getting the metric and relations from their approximations) did
not use compactness and only used uniform continuity to ensure that a completion
existed, which will be guaranteed by the definition of K_{dense} in this case.

Given continuous $\tau = \langle F_i, R_j \rangle_{i < n_f, j < n_r}$, define

$$\tau^+ := \langle F_i^+, R_{R_j(\mathbf{z}) \geq r}, R_{R_j(\mathbf{z}) \leq r} \rangle_{i < n_f, j < n_r, r \in \mathbb{Q}'}$$

Given an MAEC K, we define the AEC K_{dense} as follows:

- $\tau(K_{dense}) = \tau^+$;
- Given an τ^+ structure $\mathcal{A}$, we use the following procedure to determine membership in K_{dense}: define D on $A \times A$ by

$$\begin{aligned} D(a,b) &:= \sup\{r \in \mathbb{Q}' : \mathcal{A} \vDash R_{d(x,y) \geq r}[a,b]\} \\ &= \inf\{r \in \mathbb{Q}' : \mathcal{A} \vDash R_{d(x,y) \leq r}[a,b]\} \end{aligned}$$

  The proof that this is a well-defined and is a metric proceeds exactly as in the previous case. We can similarly define the relations R_j on A and complete the universe (A, D) to $\overline{A}$. We call the structure $\mathcal{A}$ *completable* iff
  (1) for every $\mathbf{a} \in \overline{A}$ and every Cauchy sequence $\langle \mathbf{a}^n \in A : n < \omega \rangle$ converging to to $\mathbf{a}$, the value of $\lim_{n \to \infty} R_j(\mathbf{a}^n)$ is independent of the choice of the sequence; and similarly
  (2) for every $\mathbf{a} \in \overline{A}$ and every Cauchy sequence $\langle \mathbf{a}^n \in A : n < \omega \rangle$ converging to to $\mathbf{a}$, the value of $\lim_{n \to \infty} F_i^+(\mathbf{a}^n)$ is independent of the choice of the sequence.
  If $\mathcal{A}$ is completable, then we define $\overline{\mathcal{A}}$ to be the τ^+-structure where F_i and R_j are defined on $\overline{A}$ according to the independent value given above. Finally, we say that $\mathcal{A} \in K_{dense}$ iff
  (1) $\mathcal{A}$ is completable; and
  (2) $\overline{\mathcal{A}} \in K$.
- Given $\mathcal{A}, \mathcal{B} \in K_{dense}$, we say that $\mathcal{A} \prec_{dense} \mathcal{B}$ iff
  (1) $\mathcal{A} \subset_{\tau^+} \mathcal{B}$; and
  (2) $\overline{\mathcal{A}} \prec_K \overline{\mathcal{B}}$.

Now that we have the definition of K_{dense}, we must show that it is in fact an AEC. The verification of the axioms are routine; we give the arguments for coherence and the chain axioms as templates.

For coherence, suppose that $\mathcal{A}, \mathcal{B}, \mathcal{C} \in K_{dense}$ such that $\mathcal{A} \prec_{dense} \mathcal{C}$; $\mathcal{B} \prec_{dense} \mathcal{C}$; and $\mathcal{A} \subset_{\tau^+} \mathcal{B}$. Then, taking completions, we get that

$$\overline{\mathcal{A}} \prec_K \overline{\mathcal{C}}; \overline{\mathcal{B}} \prec_K \overline{\mathcal{C}}; \text{ and } \overline{\mathcal{A}} \subset_\tau \overline{\mathcal{B}}$$

By coherence in K, we then have that $\overline{\mathcal{A}} \prec_K \overline{\mathcal{B}}$. Then, by definition, $\mathcal{A} \prec_{dense} \mathcal{B}$, as desired.

For the chain axioms, suppose that $\langle \mathcal{A}_i \in K_{dense} : i < \alpha \rangle$ is a continuous, $\prec_{dense}$-increasing chain such that, for all $i < \alpha$, $\mathcal{A}_i \prec_{dense} \mathcal{B} \in K_{dense}$. Again, taking completions, we get that $\langle \overline{\mathcal{A}}_i \in K : i < \alpha \rangle$ is a continuous, $\prec_K$-increasing chain such that, for all $i < \alpha$, $\overline{\mathcal{A}}_i \prec_K \overline{\mathcal{B}} \in K$. Then, by the union axioms for K, we have that $\cup_{i < \alpha} \overline{\mathcal{A}}_i \in K$ and $\cup_{i < \alpha} \overline{\mathcal{A}}_i \prec_K \overline{\mathcal{B}}$. Note that the existence of

$\overline{\cup_{i<\alpha}\overline{\mathcal{A}_i}}$ shows that $\cup_{i<\alpha}\mathcal{A}_i$ is completable and that an easy computation shows that $\overline{\cup_{i<\alpha}\overline{\mathcal{A}_i}} = \overline{\cup_{i<\alpha}\mathcal{A}_i}$. Thus, $\cup_{i<\alpha}\mathcal{A}_i \in K_{dense}$ and, for all $j < \alpha$,

$$\mathcal{A}_j \prec_{dense} \cup_{i<\alpha}\mathcal{A}_i \prec_{dense} \mathcal{B}$$

Once we have defined the maps and shown that K_{dense} is an AEC, the rest of the proof proceeds exactly as in the continuous first-order case, in some ways simpler since τ^+ only has relations for each relation of τ, rather than each formula of τ.

We now turn to an application. Both Hirvonen and Zambrano have proved versions of Shelah's Presentation Theorem for MAECs in their theses. The more general is Zambrano's [Zam, Theorem 1.2.7]:

Theorem 6.2. *Let K be a MAEC. There is $\tau_1 \supset \tau$ and a continuous[1] τ_1-theory T_1 and a set of T_1-types Γ such that $K = PC(T_1, \Gamma, \tau)$.*

An immediate corollary to our presentation theorem is a discrete presentation theorem.

Corollary 6.3 (Discrete Presentation Theorem for Metric AECs)**.** *Let K be a MAEC. Then there is a (discrete) language τ_1 of size $LS(K)$, an τ_1-theory T_1, and a set of T_1-types Γ such that $K = \{\overline{M_1 \restriction \tau(K)} : M_1 \vDash T_1 \text{ and omits } \Gamma\}$, where the completion is taken with respect to a canonically definable metric.*

Proof: Apply Theorem 6.1 to represent K as a discrete AEC K_{dense} and then apply Shelah's Presentation Theorem from Shelah [Sh88].

Additionally, Zambrano asks [Zam, Question 1.2.9] if there exists is a Hanf number for model existence in MAECs. Using our presentation theorem, we can answer this questions in the affirmative. Furthermore, the Hanf number for MAECs is the same as for AECs.

Theorem 6.4. *If K is a MAEC with $LS(K) = \kappa$ and has models of size or density character cofinal in $\beth_{(2^\kappa)^+}$, then K has models with density character arbitrarily large.*

Proof: For every, $\lambda < \beth_{(2^\kappa)^+}$, let $M_\lambda \in K$ have size $\geq \lambda$. $|M_\lambda|$ is nicely dense in itself, so $(M_\lambda)_{|M_\lambda|} \in K_{dense}$ has size $\geq \lambda$. By the definition of Hanf number for discrete AECs, this means that K_{dense} has arbitrarily large models. Taking completions, this means K has arbitrarily large models. The proof for density character is the same.   †

Given this representation, we can determine basic structural properties of K by looking at K_{dense} and vice versa. The above theorem already shows how to transfer arbitrary large models and the other properties transfer similarly.

Proposition 6.5. *Suppose K is an MAEC. For P being amalgamation, joint embedding, or no maximal models, K has P iff K_{dense} has P.*

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[1]But not *uniformly* continuous.

The fourth clause of the conclusion of Theorem 6.1 is stated as it is to make the proof of this proposition easy to see.

We now look at the notion of type in K_{dense} that corresponds to Galois types in K. Similar to the examination in Section 5, we see that the

To study saturation, we pass to a sequence of types representing a Cauchy sequence for a realization of the Galois type we wish to represent.

Definition 6.6.
- *Given $\mathcal{A} \in K_{dense}$, $\langle r_n : n < \omega \rangle$ is a* sequence Galois type over $\mathcal{A}$ *iff*
  (1) $r_0 \in gS^\ell(\mathcal{A})$; *and*
  (2) $r_{n+1} \in gS^{\ell 2}(\mathcal{A})$ *such that*
      (a) *if $\mathbf{ab} \vDash r_{n+1}$, then $d(\mathbf{a}, \mathbf{b}) \leq \frac{1}{2^n}$; and*
      (b) $r_{n+1}^{\{\ell,...,\ell 2-1\}} = r_n^\ell$, *i. e. the first ℓ coordinates of r_n are the same as the final ℓ coordinates of r_{n+1}.*
- *Given a sequence Galois type $\langle r_n : n < \omega \rangle$ over $\mathcal{A}$ and $\mathcal{A} \prec_{dense} \mathcal{B}$, we say that $\langle \mathbf{a}_n \in \mathcal{B} : n < \omega \rangle$* realizes $\langle r_n : n < \omega \rangle$ *iff*
  (1) $\mathbf{a}_0 \vDash r_0$; *and*
  (2) $\mathbf{a}_{n+1}\mathbf{a}_n \vDash r_{n+1}$
- *Given a sequence Galois type $\langle r_n : n < \omega \rangle$ over $\mathcal{A}$ and $\mathcal{A} \prec_{dense} \mathcal{B}$, we say that $\langle \mathbf{a}_n \in \mathcal{B} : n < \omega \rangle$* weakly realizes $\langle r_n : n < \omega \rangle$ *iff there is some $\mathcal{C}$ and $\langle \mathbf{b}_n \in \mathcal{C} : n < \omega \rangle$ such that*
  (1) $\mathcal{B} \prec_{dense} \mathcal{C}$;
  (2) $\langle \mathbf{b}_n : n < \omega \rangle$ *realizes* $\langle r_n : n < \omega \rangle$; *and*
  (3) $\lim_{n<\omega} \mathbf{a}_n = \lim_{n<\omega} \mathbf{b}_n$.

Note that realizing a sequence Galois type is different than realizing each individual Galois type in the sequence separately. However, we can always realize sequence Galois types given amalgamation.

Lemma 6.7. *Suppose that K has amalgamation. Given any sequence Galois type $\langle r_n : n < \omega \rangle$ over $\mathcal{A} \in K_{dense}$, there is $\mathcal{A} \prec_{dense} \mathcal{B} \in K_{dense}$ that contains a realization of $\langle r_n : n < \omega \rangle$.*

Proof: By the definition of Galois type, we can write each r_n as $gtp_{K_{dense}}(\mathbf{a}_0^0/\mathcal{A}; \mathcal{B}_0)$ and $gtp_{K_{dense}}(\mathbf{a}_{n+1}^{n+1}\mathbf{a}_n^{n+1}/\mathcal{A}; \mathcal{B}_{n+1})$. Using amalgamation in K_{dense}, which follows from amalgamation in K, we can construct increasing $\langle \mathcal{C}_n : n < \omega \rangle$ and increasing $f_n : \mathcal{B}_n \to_{\mathcal{A}} \mathcal{C}_n$ such that f_0 is the identity and $f_n(a_n^n) = f_{n+1}(a_n^{n+1})$; this second part is due to the second clause in the definition of sequence types. Setting $\mathcal{C} = \cup_{n<\omega}\mathcal{C}_n$, we have that $\langle f_n(a_n^n) : n < \omega \rangle$ realizes $\langle r_n : n < \omega \rangle$. †

Unfortunately, we don't have the same tight connection between Galois types in K and sequence Galois types in K_{dense} as exists in Theorem 5.4. This is due to the fact that the Galois version of sequence types specifies a distance between consecutive members of the Cauchy sequence, rather than just specifying a bound on the distance. It is possible that perturbations (as in Hirvonen and Hyttinnen

[HH12]) might be used to restore this connection. Instead, we have introduced the notion of weakly realizing a sequence Galois type because this is enough to prove a variant of Theorem 5.6 in this context.

Theorem 6.8. *Let $M \in K$ and $\mathcal{A} \in K_{dense}$ such that $\overline{\mathcal{A}} = M$.*

(1) *If M is κ-Galois saturated and $\lambda^{\aleph_0} < \kappa$, then $\mathcal{A}$ is λ^+-weakly saturated for sequence Galois types (i.e. given any $\mathcal{A}_0 \prec_{dense} \mathcal{A}$ of size $< \lambda^+$, every sequence Galois type over $\mathcal{A}_0$ is weakly realized in $\mathcal{A}$).*

(2) *If $\mathcal{A}$ is κ-weakly saturated for sequence Galois types, then M is κ-Galois saturated.*

Proof: First, suppose that M is κ saturated and $\lambda^{\aleph_0} < \kappa$. Let $\mathcal{A}_0 \prec_{dense} \mathcal{A}$ be of size $\leq \lambda$ and let $\langle r_n : n < \omega \rangle$ be a sequence Galois type over $\mathcal{A}_0$. By Lemma 6.7, there is some $\mathcal{B}_{dense} \succ \mathcal{A}_0$ and $\langle \mathbf{a}_n : n < \omega \rangle$ that realizes $\langle r_n : n < \omega \rangle$. After completing the members of K_{dense}, we have $\overline{\mathcal{A}_0} \prec M$ and $\overline{\mathcal{A}_0} \prec \overline{\mathcal{B}} \in K$. Since $\langle \mathbf{a}_n \in \mathcal{B} : n < \omega \rangle$ is a Cauchy sequence, there is some $\mathbf{a} \in \mathcal{B}$ such that $\lim_{n \to \infty} \mathbf{a}_n = \mathbf{a}$. Since M is κ-saturated and $\|\overline{\mathcal{A}_0}\| \leq \lambda^{\aleph_0} < \kappa$, there is $\mathbf{b} \in M$ that realizes $gtp_K(\mathbf{a}/\overline{\mathcal{A}_0}; \overline{\mathcal{B}})$. Since $\mathcal{A}$ is dense in M, there is some Cauchy sequence $\langle \mathbf{b}_n \in \mathcal{A} : n < \omega \rangle$ that converges to $\mathbf{b}$. Then $\langle \mathbf{b}_n : n < \omega \rangle$ weakly realizes $\langle r_n : n < \omega \rangle$.

Second, suppose that $\mathcal{A}$ is κ-weakly saturated for sequence Galois types and let $M_0 \prec M$ of size $< \kappa$ and $r \in gS(M_0)$. Let $A_0 \subset A$ be nicely dense in M_0; then $\mathcal{A}_0 := (M_0)_{A_0} \prec_{dense} \mathcal{A}$. In K, we can write r as $gtp_K(\mathbf{a}/M_0; N)$. Then, in K_{dense}, $\overline{r} := \langle gtp_{K_{dense}}(\mathbf{a}/\mathcal{A}_0; N_{|N|}) : n < \omega \rangle$ is a sequence Galois type over $\mathcal{A}_0$. Since $\|\mathcal{A}_0\| < \kappa$, by $\mathcal{A}$'s weak saturation, there is some $\langle \mathbf{b}_n : n < \omega \rangle$ that weakly realizes $\overline{r}$. This means that we can find an extension $\mathcal{B}_{dense} \succ \mathcal{A}$ and $f : N_{|N|} \to_{\mathcal{A}_0} \mathcal{B}$ such that

$$\lim_{n \to \infty} f(\mathbf{a}) = \lim_{n \to \infty} \mathbf{b}_n$$

Since $\mathbf{b}_n \in \mathcal{A}$, this means that $f(\mathbf{a}) \in M$. Since $N_{|N|}$ is complete, the K_{dense}-embedding f is in fact a K-embedding from N into $\overline{\mathcal{B}}$ and fixes $\overline{\mathcal{A}_0} = M_0$. Thus, we have that $f(\mathbf{a}) \in M$ realizes $gtp_K(\mathbf{a}/M_0; N)$.   †

A crucial property in the study of MAECs is whether the natural notion of distance between Galois types defines a metric or not. This property is called the Pertubation Property by Hirvonen and Hyttinen [HH09] and the Continuity Type Property by Zambrano [Zam12]. For ease, we assume that K (equivalently, K_{dense}) has a monster model $\mathfrak{C}$.

Definition 6.9.   • *Given $M \in K$ and $p, q \in S(M)$, we define*

$$\mathbf{d}(p, q) = \inf\{d(a, b) : a \vDash p \text{ and } b \vDash q\}$$

• *K has the Pertubation Property (PP) iff, given any Cauchy sequence $\langle b_n \in \mathfrak{C} : n < \omega \rangle$ and $M \in K$, if, for all $n < m < \omega$,*

$$gtp(b_n/M) = gtp(b_m/M)$$

then, $gtp(\lim_{n\to\infty} b_n/M) = gtp(b_0/M)$.

Although these properties might not initially seem related, a little work shows that **d** is always a pseudometric and that it is a metric iff PP holds; this is due Hirvonen and Hyttinen. Then, similar to tameness from AECs, Zambrano [Zam12].2.9 defines a notion of tameness in MAECs that satisfy PP.

Definition 6.10. *K is μ-d-tame iff for every $\epsilon > 0$, there is a $\delta > 0$ such that for every $M \in K$ of density character $\geq \mu$ and $p, q \in gS(M)$, if $\mathbf{d}(p, q) \geq \epsilon$, then there is some $N \prec M$ of density character μ such that $\mathbf{d}(p \restriction N, q \restriction N) \geq \delta_\epsilon$.*

Again these properties transfer to sequence types in K_{dense}. We can define a pseudometric on sequence Galois types in K_{dense} by

$$\mathbf{d}_{dense}(\langle r_n : n < \omega \rangle, \langle s_n : n < \omega \rangle) \quad := \quad \inf\{\lim_{n\to\infty} d(a_n, b_n) : \langle a_n : n < \omega \rangle \text{ realizes}$$

$$\langle r_n : n < \omega \rangle, \langle b_n : n < \omega \rangle \text{ realizes } \langle s_n : n < \omega \rangle\}$$

Then $\mathbf{d}_{dense}$ is a metric iff **d** is, and μ-d-tameness transfers from K to K_{dense} in the obvious way. This functor has recently been used in Boney and Zambrano [BoZa] to transfer various large cardinal results from Boney [Bon14] to the MAEC setting. Additionally, it can be used to transfer stability theoretic results both via characterization (as in Section 5) and via independence relations.

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