On finite categoricity

by

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Abstract

In this work we are taking the first steps towards studying so called finitely categorical structures.

By a celebrated theorem of Morley, a structure $\mathcal{A}$ is $\aleph_1$-categorical if and only if it is κ-categorical for all uncountable κ. Our main goal is to examine finitary analogues of Morley's theorem. A model $\mathcal{A}$ is defined to be finitely categorical (or $<\omega$-categorical) if for a large enough finite set Δ of formulas $\mathcal{A}$ can have at most one n-element Δ-elementary substructure for each natural number n.

We are going to investigate some conditions on $\aleph_1$-categorical structures which imply finite categoricity. Proving finite categoricity for certain $\aleph_1$-categorical structures can be considered as an extension of Morley's theorem "all the way down".

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1 Introduction

Modern model theory partly centers around the rather general and vague *classification program* which aim is to describe models of (complete) first order theories in a 'useful' way. Intuitively, a theory T has a structure theory if there is a set of invariants which determine every model of T, up to isomorphism. Natural candidates are cardinal invariants and their generalizations (see Shelah [14]). Consider, as an example, the class of structures in the empty language (i.e. sets). These models can be characterized by their cardinality. Another, a bit more sophisticated but still obvious example, is the class of models containing a single equivalence relation; these can be classified by giving for each cardinal κ, how many equivalence classes of this power occur.

The quest of classifying models has a strong and deep connection with the spectrum function $I(T, \kappa)$ which denotes the number of non-isomorphic models of the theory T of power κ. Studying the spectrum function has a long tradition. From the structural point of view those theories whose models (of power κ) can be described with a single cardinal invariant can be regarded as the 'simplest' ones (they may be rather complex from some other point of view). T is called κ-categorical if $I(T, \kappa) = 1$.

By early results of Ryll-Nardzewski, Svevonius and others, models of $\aleph_0$-categorical theories has been completely characterized in terms of automorphism groups (cf. [1, Theorem 2.3.13]). Somewhat later it turned out by a famous theorem of Morley (see [1, Theorem

7.1.14]) that a theory is $\aleph_1$-categorical if and only if it is categorical for all uncountable cardinal κ.

In the present work we are going to extend Morley's theorem to finite cardinals. A model $\mathcal{A}$ is defined to be finitely categorical if for a large enough finite set Δ of formulas $\mathcal{A}$ can have at most one n-element Δ-elementary substructure for each natural number n. We are going to investigate some conditions on $\aleph_1$-categorical structures which imply finite categoricity.

The next paragraph gives some more detailed and technical introduction, followed by a short summary of the organization of the thesis. Our notation is standard and basically we use notation of Chang-Keisler [1], Hodges [5], Shelah [15] and Marker [6]. However, the most basic conceptions will be recalled at the end of this chapter.

The thesis is based on our paper [9].

Further introduction. There is a bunch of (first order) theories, naturally arising in mathematics, that can have at most one n-element model, up to isomorphism, for each natural number n. The most basic examples are the theory of linear orders, the theory of fields, or the theory of vector spaces: any two models of each of these theories that have the same finite cardinality are isomorphic. This property of theories motivates our two basic definitions which this work centers around:

Definition 1.0.1 (Finite categoricity in the strong sense)**.** The first order theory T is called *finitely categorical in the strong sense* (or strongly $<\omega$-categorical) if for large enough finite $T_0 \subseteq T$, up to isomorphism, T_0 can have at most one n-element model for each natural number n.

The structure $\mathcal{A}$ is defined to be finitely categorical in the strong sense (or strongly $<\omega$-categorical) if $\mathsf{Th}(\mathcal{A})$ is strongly $<\omega$-categorical.

Some further explanations are in order here. Firstly, any finite structure with a finite vocabulary can be described by a first order formula and hence finite structures or theories of such structures are obviously strongly $<\omega$-categorical. This notion becomes interesting when infinite structures are involved. If T is the theory of an infinite structure then clearly T does not have any finite model (e.g. because the description 'there are at least n elements' is contained in T for all n). So, if we have defined finite categoricity in such a way that a theory is finitely categorical if it can have at most one n-element model for each natural number n, then theories of infinite structures would have been finitely categorical for trivial reasons. This justifies why do we care for large enough fragments. Similarly, we could have said 'exactly one n-element model' instead of 'at most one' – but we did not do this in order not to exclude important examples like fields or vector spaces: these theories do not have n element models for arbitrary finite n. Observe, that by definition, strong $<\omega$-categoricity of $\mathcal{A}$ and $\mathsf{Th}(\mathcal{A})$ coincide.

We would like to emphasize that a large enough finite $T_0 \subseteq T$ in the definition cares for models of arbitrary finite size.

In a more model theoretic spirit (from the structural point of view) one defines a similar notion:

Definition 1.0.2 (Finite categoricity)**.** The structure $\mathcal{A}$ is *finitely categorical* ($<\omega$-categorical) if for a large enough finite set Δ of formulas $\mathcal{A}$ can have at most one n-element Δ-elementary substructure for each natural number n.

Similarly, a theory T is *finitely categorical* ($<\omega$-categorical) if all models of T are such.

Here, by saying $\mathcal{B}$ is a Δ-elementary substructure of $\mathcal{A}$ we mean that $\mathcal{B}$ is a substructure of $\mathcal{A}$ and for every $\phi \in \Delta$ and $\bar{b} \in B$ the statements $\mathcal{B} \vDash \phi(\bar{b})$ and $\mathcal{A} \vDash \phi(\bar{b})$ are equivalent. It is easy to see that if $\mathcal{B}$ is a Δ-elementary substructure of $\mathcal{A}$ then $\mathcal{B} \vDash \mathsf{Th}(\mathcal{A}) \cap \Delta$, that is, $\mathcal{A}$ and $\mathcal{B}$ are elementary equivalent with respect to closed formulas of Δ. What it follows is that strong $<\omega$-categoricity implies $<\omega$-categoricity. (That is why we called the first notion 'strong'). Unfortunately, the reverse implication does not hold. For a counterexample we refer to Example II below.

From the definition it may not be that clear for the first sight that $<\omega$-categoricity of a structure $\mathcal{A}$ and $\mathsf{Th}(\mathcal{A})$ coincide: it may happen, in principle, that for elementary equivalent structures $\mathcal{A}$ and $\mathcal{B}$ we have that $\mathcal{A}$ is $<\omega$-categorical while $\mathcal{B}$ is not. But as the next proposition states this is not the case.

Proposition 1.0.3. *$\mathcal{A}$ is $<\omega$-categorical if and only if $\mathsf{Th}(\mathcal{A})$ is $<\omega$-categorical.*

We omit the proof which is based on the following simple fact: If Δ is a finite set of formulas (which is closed under subformulas) and $\mathcal{X}$ is a finite structure, then there is a first order formula $\Phi^{\Delta}_{\mathcal{X}}$ such that $\mathcal{A}$ has a Δ-elementary substructure isomorphic to $\mathcal{X}$ if and only if $\mathcal{A} \models \Phi^{\Delta}_{\mathcal{X}}$.

To illustrate the nature of finite categoricity and the connection between finite and infinite categoricity we list some examples.

Example I. The theory T of linear orders. It is not infinitely categorical (and not even stable) but each pairs of finite linear orders of the same cardinality are isomorphic, hence T is finitely categorical (in the strong sense).

Example II. Let $\mathcal{A}$ be the structure consisting of $2^{\aleph_0}$ copies of an infinite path (as a graph):

$$\mathcal{A} = \bigsqcup_{2^{\aleph_0}} (\cdots - - \bullet - - \bullet - - \bullet - - \cdots).$$

If we denote by C_n the circle on n vertices, then a simple argument shows $\mathcal{A} \cong \Pi_{n\in\omega} C_{2n}/\mathcal{F}$ for any non-principal ultrafilter $\mathcal{F}$, and in a similar vein $\mathcal{A} \cong \Pi_{n\in\omega}(C_n \sqcup C_n)/\mathcal{F}$, where $C_n \sqcup C_n$ denotes the disjoint union of two circles. Now, if $T \subseteq \mathsf{Th}(\mathcal{A})$ is a finite subtheory, then by Łoś's theorem for large enough n we have that C_{2n} and $C_n \sqcup C_n$ are models of

T and clearly $C_{2n} \ncong C_n \sqcup C_n$. This shows $\mathcal{A}$ is not strongly $<\omega$-categorical. But $\mathcal{A}$ is $<\omega$-categorical for trivial reasons: $\mathcal{A}$ does not have any finite φ-elementary substructure, where φ expresses that each vertices have degree two. Note also that $\mathcal{A}$ is κ-categorical for all uncountable cardinal κ.

Example III. The theory T of algebraically closed fields of a fixed positive characteristic. It is $\aleph_1$-categorical but not $\aleph_0$-categorical and already the field axioms are finitely categorical in the strong sense.

Example IV. By a result of Peretyatkin (see [8]) there exists a finitely axiomatizable $\aleph_1$-categorical structure $\mathcal{A}$; let T be the theory of $\mathcal{A}$. Infinite structures with a finitely axiomatizable theory cannot be pseudo-finite, i.e. large enough finite subsets of T cannot have finite models. Consequently, T is finitely categorical, for trivial reasons.

At this point the most ambitious project would be to characterize those theories and those models which are finitely categorical. However, in this generality the problem seems to be quite hard and therefore it is reasonable to concentrate only on theories (models) with some special properties. One such special property is $\aleph_1$-categoricity and in fact we are going to deal with certain $\aleph_1$-categorical structures.

Why $\aleph_1$-categoricity? By Morley's categoricity theorem, a countable, first order theory T is $\aleph_1$-categorical if and only if it is κ-categorical for all uncountable κ, see [7] or Theorem 7.1.14 of [1]. In other words, $\aleph_1$-categoricity implies categoricity all the way up. Now, proving finite categoricity for such theories could be considered as an extension of Morley's theorem 'all the way down' (except for $\aleph_0$, of course).

Infinitely categorical structures are $\aleph_0$-categorical and $\aleph_0$-stable. Studying $\aleph_0$-categorical, $\aleph_0$-stable structures in their own right has a great tradition. In this direction we refer to [3], [17], [18], where, among others, it was shown that $\aleph_0$-categorical, $\aleph_0$-stable structures are smoothly approximable, particularly, they are not finitely axiomatizable. For more recent related results we refer to Cherlin-Hrushovski [2]. By a personal communication with Zilber and Cherlin, it turned out, that finite categoricity follows for $\aleph_0$-categorical, $\aleph_0$-stable theories from already known results. However, to show this, $\aleph_0$-categoricity plays a critical role. Here we do not assume $\aleph_0$-categoricity.

At that point one would temple to think that if T is $\aleph_1$-categorical then finite categoricity would follow without any additional condition but in fact, the situation is more complicated as the examples show above.

In order to provide conditions for T which makes it finitely categorical, we will deal with 'finitary analogues' of some classical notions such as elementary and Φ-elementary substructures. Here are some more 'finitary' notions we will need below.

Definition 1.0.4. If $\mathcal{A}$ is a structure $X \subseteq A$ and Δ is a set of formulas then by $\mathsf{acl}^{\mathcal{A}}_{\Delta}(X)$ we understand the smallest (w.r.t. inclusion) set Y containing X which is closed under Δ-algebraic formulas, i.e. whenever $\varphi \in \Delta$, $\bar{y} \in Y$ and $A_0 = \{a : \mathcal{A} \models \varphi(a, \bar{y})\}$ is finite then $A_0 \subseteq Y$.

It is worth noting here that if the formula $v_0 = v_1$ is in Δ then acl_{Δ} is a closure operator. In addition, $\mathsf{acl}_{\Delta}(X)$ is not the same as the set of those elements which are algebraic over X witnessed by a formula in Δ. In fact, if we denote this latter set by X^{Δ} then

$$\mathsf{acl}^{\mathcal{A}}_{\Delta}(X) = \bigcup_{n \in \omega} X_n,$$

where $X_0 = X$ and $X_{n+1} = X_n^{\Delta}$ for all $n \in \omega$.

We write CB_X for the usual Cantor-Bendixson rank over the parameter set X (the definition will be recalled in Chapter 2). Our aim is to prove the following theorem.

Theorem 5.0.10. *Suppose $\mathcal{A}$ is an $\aleph_1$-categorical structure satisfying (a)-(b) below:*

(a) For any finite *set ε of formulas there exists another finite set $\Delta \supseteq \varepsilon$ of formulas such that whenever $\Delta' \supseteq \Delta$ is finite and g is a Δ'-elementary mapping then there exists a Δ-elementary mapping h extending g such that $\mathsf{dom}(h) = \mathsf{acl}_{\Delta'}(\mathsf{dom}(g))$.*

(b) For each finite $\bar{a} \in A$ and each infinite subset E of A definable over $\bar{a}$ there exists a function $\partial_E : \mathsf{Form}_{\bar{a}} \to \mathsf{Form}_{\bar{a}}$ such that $\mathsf{CB}_{\bar{a}}(\partial_E \varphi) = 0$ for all formula φ and $\varphi(\bar{x}, \bar{d})$ defines an atom of the Boolean–algebra of E–definable relations of $\mathcal{A}$ if and only if $\mathcal{A} \models \partial_E \varphi(\bar{d})$.

Then $\mathcal{A}$ is $<\omega$-categorical, that is, up to isomorphism, every large enough $T \subseteq \mathsf{Th}(\mathcal{A})$ has at most one n-element model for each $n \in \omega$.

We note that every elementary mapping f can be extended to an elementary mapping to $\mathsf{acl}(\mathsf{dom}(f))$; clause (a) is a finitary analogue of this well known fact. We will informally refer to (b) as "E-atoms have a definition schema", for infinite, definable E (see Definition 2.1.3 below). We are going to discuss these two notions in detail in Chapter 2 (in fact, Chapter 2 is completely devoted to a brief motivation, explanation and analysis of these notions).

Before going further, let us list a couple of examples for which our theorem can be applied (i.e. structures satisfying clauses (a) and (b) above).

Example A1. Infinite dimensional vector spaces $\mathcal{V} = \langle V, +, \lambda \rangle_{\lambda \in \mathbb{F}}$ over a finite field $\mathbb{F}$. Here the language contains a binary function symbol for vector addition and a unary function symbol for each scalar in the field. Then $\mathcal{V}$, as it is $\aleph_0$-categorical, satisfies our clause (b) by Proposition 2.2.1 below. Further, it is easy to check clause (a): if a function preserves unnested atomic formulas then it is a linear map, therefore it extends to an automorphism of $\mathcal{V}$. Note that $\mathcal{V}$ is pseudo-finite and clearly any two vector spaces of the same finite dimension are isomorphic.

Example A2. Let $\mathbf{F}$ be an algebraically closed field with a given positive characteristic. Then, similarly to the case of vector spaces, $\mathbf{F}$ satisfies condition (a), and since it is strongly minimal, Proposition 4.1.4 below implies, that it is finitely categorical. Note, that $\mathbf{F}$ is not $\aleph_0$-categorical.

For completeness, we note, that if E is an infinite definable subset of $\mathbf{F}$ then E-atoms have a definition schema (this is condition (b) of Theorem 5.0.10 without the assumption $\mathsf{CB}(\partial_E\varphi) = 0$). To check this let E' be the subfield of $\mathbf{F}$ generated by E. We claim, that $E' = \mathbf{F}$. For, assume, seeking a contradiction, that $a \in \mathbf{F} - E'$. Then, for any $b \in E' - \{0\}$ we also have $a \cdot b \notin E'$, thus $\mathbf{F} - E'$ would be infinite. On the other hand, $\mathbf{F}$ is strongly minimal, hence $\mathbf{F} - E$ is finite, as well as $\mathbf{F} - E'$; this contradiction verifies our claim. It follows, that $\mathsf{dcl}(E) = E' = \mathbf{F}$, hence each E-atom consists a single element of $\mathbf{F}$. In other words, for any formula φ and parameters $\bar{d} \in E$, the relation defined by $\varphi(v, \bar{d})$ is an E-atom iff $\varphi(v, \bar{d})$ can be realized by a unique element of $\mathbf{F}$; this is of course, a first order property of $\bar{d}$.

Example B. Take any finite structure $\mathcal{X}$ (in a finite language) and let $\mathcal{A} = \bigsqcup_\omega \mathcal{X}$ be the disjoint union of $\aleph_0$ many copies of $\mathcal{X}$. If a function g preserves the diagram of $\mathcal{X}$ then it extends to an automorphism h of $\mathcal{A}$, hence clause (a) holds. Since $\mathcal{A}$ is $\aleph_0$-categorical clause (b) holds, too (see Proposition 2.2.1 below). $\mathcal{A}$ has, for any finite set Δ of formulas, a Δ-elementary substructure, and any two of them, for large enough Δ, are isomorphic.

Example C. The structure $\mathcal{A} = \langle A, U, g \rangle$ where $g : {}^nU \to A \smallsetminus U$ is a one-to-one mapping and U is a unary relation. Then $\mathcal{A}$ also satisfies the conditions of our Theorem 5.0.10.

Example D. Let $n \in \omega$ be fixed and let $A_0, \ldots, A_{n-1}$ be pairwise disjoint sets of the same infinite cardinality. Further, for all $i < n$ let $f_i : A_0 \to A_i$ be a bijection and set $A = \bigcup_{i<n} A_i$. It is not hard to check that the structure $\mathcal{A} = \langle A, A_0, \ldots, A_{n-1}, f_0, \ldots, f_{n-1} \rangle$ satisfies all of the assumptions of Theorem 5.0.10.

Example E. Let $q \in \omega$ be a prime power. Consider the group $\bigoplus_\omega \mathbb{Z}/q\mathbb{Z}$. It is totally categorical and has a finite base for elimination of quantifiers. By Proposition 2.2.2 this structure satisfies the assumptions of Theorem 5.0.10. We also note that by total categoricity, this group has finite Δ-elementary substructures for all finite Δ (which, for large enough Δ, are unique up to isomorphism, according to our Theorem 5.0.10).

Example F. Any $\aleph_1$-categorical structure having a finite elimination base. Theorem 5.0.10 applies to all of these structures, see Proposition 2.2.2.

We will see in Proposition 4.1.4, that in the case, when $\mathcal{A}$ is strongly minimal, the conditions of Theorem 5.0.10 may be simplified (in fact, we need to assume a weak version of (a) only, and do not need to assume (b)). We note, that the structures in Examples C, D, E and F above are not strongly minimal, but satisfy the conditions of Theorem 5.0.10.

The proof of Theorem 5.0.10 is divided into two parts. First we establish some basic properties of finite substructures of a structure satisfying conditions (a)-(b). Then we examine a method to find isomorphisms between ultraproducts acting "coordinatewise". This method is related to (but does not depend on) the results of [10], [4], [12]. To establish further investigations of finitary generalizations of Morley's theorem, we are trying to be rather general. We offer a variety of notions which perhaps may be used in related investigations. Some of them may seem rather technical, or complicated. However, we hope, these notions will be useful to find other (possibly more natural) finitary generalizations of Morley's Theorem.

The rest of this work is organized as follows. At the end of this chapter we summarize our system of notation. In Chapter 2 we present some basic observations about $\aleph_1$-categorical structures also satisfying some variants of the conditions of Theorem 5.0.10. Section 2.1 contains the definitions needed in later sections; Section 2.2 is devoted to establishing connections between definitions given in Section 2.1 and traditional model theoretic notions. These investigations (combining with the examples given above) may illustrate how general our results are. Section 2.2 is inserted to the thesis for completeness, we do not use its results in later sections. Readers, who would prefer to see our main results rather than the brief analysis of the notions involved, may simply skip Section 2.2.

Chapter 3 makes some preliminary observations on stable structures. In Chapter 4 we are dealing with ultraproducts of finite structures. This chapter contains the technical cornerstones of our construction. Here *decomposable* sets play a central role: a subset R of an ultraproduct $A = \Pi_{i\in I}\mathcal{A}_i/\mathcal{F}$ is decomposable iff for every $i \in I$ there are $R_i \subseteq A_i$ such that $R = \Pi_{i\in I}R_i/\mathcal{F}$, for more details see [10], [12] and [4]. As another tool, we also will use basics of stability theory. In general, our strategy is as follows: to obtain results about finite structures first we study an infinite ultraproduct of them. A similar approach may be found in [16] and in [11].

The main goal of Chapter 4 is to prove Theorem 4.3.7 which claims, that Theorem 5.0.10 (the main result of the thesis) is true, if we add to our assumptions, that there exists a $\emptyset$-definable strongly minimal set. Chapter 4 is divided into three sections.

In Section 4.1 we are dealing with strongly minimal structures. Here the goal is to establish our finite categoricity theorem for certain strongly minimal structures. This is achieved in Proposition 4.1.4.

In Section 4.2 we assume that our structures contain a $\emptyset$-definable strongly minimal set. Using Zilber's ladder theorem (which will be recalled at the beginning of Section 4.2), in Theorem 4.2.10 we show, that certain decomposable elementary mappings defined on a $\emptyset$-definable strongly minimal set can be extended to a decomposable elementary embedding.

In Section 4.3 we combine the results of the previous two sections to obtain Theorem 4.3.7; as we already mentioned, this theorem establishes finite categoricity of $\aleph_1$-categorical structures containing a $\emptyset$-definable strongly minimal set and satisfying (a) and (b) of Theorem 5.0.10.

On the basis of these results, in Chapter 5 we present the main result of the thesis: we show that the assumption of the existence of a $\emptyset$-definable strongly minimal set may be omitted. Thus, under some additional technical conditions, Morley's Categoricity Theorem may be extended to the finite. For the details, see Theorem 5.0.10. Finally, at the end of Chapter 5 we mention further related questions which remained open.

Notation

Sets.

Throughout ω denotes the set of natural numbers and for every $n \in \omega$ we have $n = \{0, 1, \ldots, n-1\}$. Let A and B be sets. Then ${}^AB$ denotes the set of functions from A to B, $|A|$ denotes the cardinality of A, $[A]^{<\omega}$ denotes the set of finite subsets of A and if κ is a cardinal then $[A]^\kappa$ denotes the set of subsets of A of cardinality κ.

Sequences of variables or elements will be denoted by overlining, that is, for example, $\bar{x}$ denotes a sequence of variables $x_0, x_1, \ldots$

Let f be a function. Then $\mathsf{dom}(f)$ and $\mathsf{ran}(f)$ denote the domain and range of f, respectively. If A is a set, $f : A \to A$ is a unary partial function and $\bar{x}$ is a sequence of elements of A then, for simplicity, by a slight abuse of notation, we will write $\bar{x} \in A$ in place of $\mathsf{ran}(\bar{x}) \subseteq A$. Particularly, $\bar{x} \in \mathsf{dom}(f)$ expresses that f is defined on every member of $\bar{x}$, that is, $\mathsf{ran}(\bar{x}) \subseteq \mathsf{dom}(f)$.

Structures.

We will use the following conventions. Models are denoted by calligraphic letters and the universe of a given model is always denoted by the same latin letter.

If $\mathcal{A}$ is a model for a language L and $R_0, \ldots, R_{n-1}$ are relations on A, then $\langle \mathcal{A}, R_0, \ldots, R_{n-1} \rangle$ denotes the expansion of $\mathcal{A}$, whose similarity type is expanded by n new relation symbols (with the appropriate arities) and the interpretation of the new symbols are $R_0, \ldots, R_{n-1}$ respectively. The set of formulas of a language L is denoted by $\mathsf{Form}(L)$. Throughout L will be fixed so we may simply write Form instead. If X is a set (of parameters), then by Form_X we understand the set of formulas in the language extended with constant symbols for $x \in X$.

Throughout, we denote the relation defined by the formula φ in $\mathcal{A}$ by $\|\varphi\|^{\mathcal{A}}$, that is, $\|\varphi\|^{\mathcal{A}} = \{\bar{a} \in A : \mathcal{A} \vDash \varphi(\bar{a})\}$. If $\mathcal{A}$ is clear from the context, we omit it.

We will rely on the following natural convention. If $\mathcal{M}$ is a structure and $X \subseteq M$ is defined by the formula φ and $\mathcal{A}$ is any structure then by $X^{\mathcal{A}}$ we understand $\|\varphi\|^{\mathcal{A}}$. In particular if $\mathcal{A} = \Pi_{i\in\omega}\mathcal{A}_i/\mathcal{F}$ then every definable subset of $\mathcal{A}$ is decomposable and hence

$$X^{\mathcal{A}} = \|\varphi\|^{\mathcal{A}} = \Pi_{i\in\omega}\|\varphi\|^{\mathcal{A}_n}/\mathcal{F} = \Pi_{i\in\omega}X^{\mathcal{A}_n}/\mathcal{F}$$

in this case. We note that $X^{\mathcal{A}}$ depends on the choice of φ as X may be defined in $\mathcal{M}$ by some other formulas, as well. If $\mathcal{A}$ is a φ-elementary substructure of $\mathcal{M}$ then $X^{\mathcal{A}} = A \cap X^{\mathcal{M}}$. Sometimes, when it is clear from the context, we omit the superscript.

2 Basic definitions and preliminary observations

This chapter is devoted to study the conditions occurring in the main result (Theorem 5.0.10) of the thesis. In Section 2.1 we present our basic definitions; in Section 2.2 we provide a brief analysis for them. As we already mentioned, later sections do not depend on Section 2.2, so it may be skipped if the reader would prefer doing so.

Recall, that we are working with a fixed finite first order language L.

2.1 Definitions and some explanations for them

Let $\mathcal{A}$ be a first order structure and let $X \subseteq A$ be arbitrary. Then $\mathsf{acl}^{\mathcal{A}}(X)$ denotes the *algebraic closure of X in $\mathcal{A}$*. When $\mathcal{A}$ is clear from the context, we omit it. Recall, that acl_Δ was defined in Definition 1.0.4.

Suppose Δ is a set of formulas and let $\mathcal{A}$, $\mathcal{B}$ be two structures. A partial function $f : A \to B$ is said to be Δ-elementary if it preserves formulas in Δ, that is, for any $\varphi \in \Delta$ and $\bar{x} \in \mathsf{dom}(f)$ we have $\mathcal{A} \models \varphi(\bar{x})$ if and only if $\mathcal{B} \models \varphi(f(\bar{x}))$.

By a *partial isomorphism* we mean a partial function $f : A \to B$ such that if $\bar{a}, b \in \mathsf{dom}(f)$ then for every relation symbol R and function symbol g we have

$\mathcal{A} \models R(\bar{a})$ if and only if $\mathcal{B} \models R(f(\bar{a}))$ and

$\mathcal{A} \vDash g(\bar{a}) = b$ if and only if $\mathcal{B} \vDash g(f(\bar{a})) = f(b)$.

We remark that f is a partial isomorphism if and only if it is elementary with respect to the set of unnested atomic formulas (for the definition of an unnested atomic formula see [5, p. 58]).

Let us recall, for completeness, the notion of Cantor-Bendixson rank CB.

Definition 2.1.1. Suppose that $\mathcal{M}$ is a structure $A \subseteq M$ and $\phi(v)$ is a formula with parameters from A. We recall the usual definition of $\mathsf{CB}_A^{\mathcal{M}}(\phi)$, the *Cantor-Bendixson rank* of ϕ in $\mathcal{M}$. First, we inductively define $\mathsf{CB}_A^{\mathcal{M}}(\phi) \geq \alpha$ for α an ordinal.

(i) $\mathsf{CB}_A^{\mathcal{M}}(\phi) \geq 0$ if and only if $\|\phi\|^{\mathcal{M}}$ is nonempty.

(ii) if α is a limit ordinal, then $\mathsf{CB}_A^{\mathcal{M}}(\phi) \geq \alpha$ if and only if $\mathsf{CB}_A^{\mathcal{M}}(\phi) \geq \beta$ for all $\beta < \alpha$.

(iii) for any ordinal α, $\mathsf{CB}_A^{\mathcal{M}}(\phi) \geq \alpha+1$ if and only if there is a sequence $\langle \psi_i(v, \bar{a}_i) : i \in \omega \rangle$ of formulas with parameters $\bar{a}_i \in A$ such that $\langle \|\psi_i(v, \bar{a}_i)\|^{\mathcal{M}} : i \in \omega \rangle$ forms an infinite family of pairwise disjoint subsets of $\|\phi(\bar{v})\|^{\mathcal{M}}$ and $\mathsf{CB}_A^{\mathcal{M}}(\psi_i) \geq \alpha$ for all i.

If $\|\phi\|^{\mathcal{M}}$ is empty, then $\mathsf{CB}_A^{\mathcal{M}}(\phi) = -1$. If $\mathsf{CB}_A^{\mathcal{M}}(\phi) \geq \alpha$ but $\mathsf{CB}_A^{\mathcal{M}}(\phi) \not\geq \alpha + 1$, then $\mathsf{CB}_A^{\mathcal{M}}(\phi) = \alpha$. If $\mathsf{CB}_A^{\mathcal{M}}(\phi) \geq \alpha$ for all ordinals α, then $\mathsf{CB}_A^{\mathcal{M}}(\phi) = \infty$.

If $\mathsf{CB}_A^{\mathcal{M}}(\phi) = \alpha$ for all finite set $A \subseteq M$ then we write $\mathsf{CB}^{\mathcal{M}}(\phi) = \alpha$. If $\mathcal{M}$ or A is clear from the context, we may omit them.

Definition 2.1.2. Let $\mathcal{M}$ be a structure and let $E \subseteq M$, $\bar{e} \in E$. Then we say that $\varphi(x, \bar{e})$ is an E-atom if $\|\varphi(x, \bar{e})\|^{\mathcal{M}}$ is an atom of the Boolean-algebra of E-definable relations of $\mathcal{M}$. Similarly if a subset A is defined by an E-atom $\varphi(x, \bar{e})$ then we may simply write A is an E-atom.

As we mentioned in the introduction, if $X \subseteq M$ then Form_X denotes the set of formulas that may contain parameters from X. Now we turn to discuss condition (b) of Theorem 5.0.10.

Definition 2.1.3. Let E be an infinite subset of M definable by parameters from $X \subseteq M$. Then a function $\partial_E : \mathsf{Form}_X \to \mathsf{Form}_X$ is defined to be an *atom defining schema for E over $\mathcal{M}$* if $\|\varphi(x, \bar{e})\|$ is an E-atom if and only if $\mathcal{M} \models \partial_E\varphi(\bar{e})$ and $\mathsf{CB}_X(\partial_E\varphi) = 0$.

We say that the structure $\mathcal{M}$ has an atom defining schema if for all infinite definable subset E there exist the corresponding function ∂_E. Further, when it is clear from the context, we may simply write ∂ instead of ∂_E.

Having an atom defining schema expresses, that for a fixed infinite, definable relation E and formula φ, the fact, that $\varphi(v, \bar{d})$ defines an atom in the Boolean-algebra of E-definable relations of $\mathcal{A}$, is a first order property of $\bar{d}$. Particularly, $\varphi(v, \bar{d})$ is an atom if and only if $\mathcal{A} \models \partial_{E\varphi}(\bar{d})$ for a first order formula $\partial_{E\varphi}$. We also require the Cantor-Bendixson rank of $\partial_{E\varphi}$ to be equal to zero. This condition expresses that whenever $\varphi(v, \bar{d})$ isolates a type in the Stone space $\mathsf{S}(E)$, the type $\mathsf{tp}(\bar{d}/\emptyset)$ is also an isolated point of $\mathsf{S}_n(\emptyset)$ (where n is the length of $\bar{d}$). In this point of view, our condition can be seen as a transfer principle stating, that utilizing φ, isolated points of $\mathsf{S}(E)$ may be obtained from isolated points of $S_n(\emptyset)$, only.

We will see in Proposition 2.2.1, that $\aleph_0$-categoricity implies the existence of an atom defining schema. We note, that in example A2 it was shown, that algebraically closed fields of a given positive characteristic also have an atom defining schema, but they are not $\aleph_0$-categorical.

Next, we analyze condition (a) of Theorem 5.0.10.

Definition 2.1.4. A structure $\mathcal{A}$ is said to have the *extension property* if the following holds. For any finite set ε of formulas there exists another finite set $\Delta \supseteq \varepsilon$ of formulas such that whenever $\Delta' \supseteq \Delta$ is finite and g is a Δ'-elementary mapping then there exists a

Δ-elementary mapping h such that $h \supseteq g$ and such that the following hold:

$$\begin{aligned} \mathsf{dom}(h) &= \mathsf{acl}_{\Delta'}(\mathsf{dom}(g)) \quad \text{and} \\ \mathsf{ran}(h) &= \mathsf{acl}_{\Delta'}(\mathsf{ran}(g)). \end{aligned}$$

As we mentioned in the Introduction, every elementary mapping f can be extended to an elementary mapping to $\mathsf{acl}(\mathsf{dom}(f))$; this fact will be called 'extension property for elementary mappings' (EPE, for short). Definition 2.1.4 above is a finitary version of EPE. Let $f : X \to Y$ be a function that we would like to extend to another function f'. To get a finitary version of EPE it is useful to isolate three hidden parameters occurring in it:

- which formulas are preserved by f;
- which formulas are preserved by f' (the extension of f);
- what is the relationship between $\mathsf{dom}(f)$ and $\mathsf{dom}(f')$.

Roughly, our extension property expresses, that if ε is a finite set of formulas, and Δ' is another large enough finite set of formulas then an ε-elementary function f can be extended to $\mathsf{acl}_{\Delta'}(\mathsf{dom}(f))$ and the extension remains elementary enough. If we do not require finiteness of ε, Δ and Δ', and letting them equal to the set of all formulas, then clause (a) reduces to the original notion of EPE. We will see shortly that if the theory of $\mathcal{A}$ has a finite elimination base for quantifiers, (particularly, if a countable elementary substructure of $\mathcal{A}$ is isomorphic to the Fraïssé limit of its age), then $\mathcal{A}$ has the extension property.

We will also deal with a special weaker form of the extension property, mainly in Section 4.1, which we call the *weak extension property*. We will see in Theorem 4.1.5, that for strongly minimal structures this weaker property already implies finite categoricity.

Definition 2.1.5. The structure $\mathcal{A}$ satisfies the *weak extension property* if and only if $(*)$ below holds for it.

> $(*)$ There exists a finite set Δ of formulas such that whenever $\Delta' \supseteq \Delta$ is a finite set of formulas and f is a Δ'-elementary mapping then there exists a partial isomorphism f' extending f so that $\mathsf{dom}(f') = \mathsf{acl}_{\Delta'}(\mathsf{dom}(f))$ and $\mathsf{ran}(f') = \mathsf{acl}_{\Delta'}(\mathsf{ran}(f))$.

We note, that this condition is somewhat weaker than the condition obtained from the extension property by letting ε in it to be the set of unnested atomic formulas.

We will see in Proposition 2.2.2, that the presence of a finite elimination base implies the extension property.

2.2 Connections with traditional notions

We start by providing sufficient conditions for the extension property and the existence of an atom defining schema.

Proposition 2.2.1. *Suppose $\mathcal{A}$ is $\aleph_0$-categorical and let E be an infinite X-definable subset of A for some finite $X \subseteq A$. Then there is an atom-defining schema ∂_E for E in $\mathcal{A}$.*

Proof. Suppose $\varphi(v, \bar{d})$ defines an E-atom. Then this is a property of $\bar{d}$, which is invariant under those elements of $\mathsf{Aut}(\mathcal{A})$ that fix X pointwise. Hence $\mathsf{tp}^{\mathcal{A}}(\bar{d}/\emptyset)$ determines it. But $\mathcal{A}$ is $\aleph_0$-categorical, thus this type can be described with one single formula. Let $\partial\varphi$ be this formula.

To see $\mathsf{CB}_X(\partial\varphi) = 0$ we need to prove that $\|\partial\varphi\|$ cannot split into infinitely many parts using a fixed finite set P of parameters. But this follows immediately from the fact that after adjoining P as constant symbols to the language of $\mathcal{A}$, the resulting structure is still

$\aleph_0$-categorical. ∎

Proposition 2.2.2. *Suppose $\mathcal{A}$ has a finite elimination base. Then $\mathcal{A}$ satisfies the extension property and has an atom defining schema.*

Proof. If $\mathcal{A}$ has a finite elimination base then it is $\aleph_0$-categorical whence, by Proposition 2.2.1 it has an atom defining schema.

To show $\mathcal{A}$ has the extension property suppose Δ is a finite set of formulas which forms an elimination base, i.e. any formula is equivalent to a Boolean combination of formulas in Δ. Then if f is Δ-elementary then it is elementary, as well, consequently it can be extended to $\mathsf{acl}(\mathsf{dom}(f))$ as an elementary function (see e.g. Hodges [5]), thus the extension property easily follows. ∎

Next, we turn to study the weak extension property.

Proposition 2.2.3. *Any $\aleph_0$-categorical structure with degenerated algebraic closure has the weak extension-property.*

For the proof we need some further preparation.

Definition 2.2.4. The algebraic closure operator acl (on the structure $\mathcal{A}$) is said to be *k-degenerated* if

$$\mathsf{acl}(X) = \bigcup\{\mathsf{acl}(Y) : Y \in [X]^k\} \text{ for all } X.$$

Similarly, we say acl is *degenerated* is it is k-degenerated for some $k \in \omega$.

The algebraic closure is *uniformly bounded* if there exists a function $\mathsf{s} : \omega \to \omega$ such that for all $\mathsf{n} \in \omega$ and $X \in [A]^n$ we have $|\mathsf{acl}^{\mathcal{A}}(X)| \leq \mathsf{s}(n)$.

Remark. If acl is k-degenerated and $|\mathsf{acl}(X)| \leq \mathsf{s}(k)$ for $X \in [A]^k$, then it is uniformly bounded since $|\mathsf{acl}(X)| \leq \binom{l}{k}\mathsf{s}(k)$ for $X \in [A]^l$.

Lemma 2.2.5. *Let $\mathcal{A}$ be a structure having degenerated, uniformly bounded algebraic closure. Then for any finite set ε of formulas there exists another finite set of formulas Δ such that for all Δ-elementary mapping $f : A \to A$ there exists an ε-elementary mapping h with $f \subseteq h$ and $\mathsf{dom}(h) = \mathsf{acl}^{\mathcal{A}}(\mathsf{dom}(f))$.*

Proof. Let k be the least constant such that for all X we have $\mathsf{acl}(X) = \bigcup\{\mathsf{acl}(Y) : Y \in [X]^k\}$. Notice, that because ε is finite there are only finitely many ε-types over any finite set. Denote by $\mathsf{def}(X)$ the set of subsets of X definable by parameters from A. Two k-element subsets X and Y of A are said to be equivalent ($X \sim Y$ for short) if the following stipulations hold:

(i) there is an ε-elementary mapping between $\mathsf{acl}(X)$ and $\mathsf{acl}(Y)$;

(ii) there exists a bijection $\vartheta_{X,Y} : \mathsf{acl}(X) \to \mathsf{acl}(Y)$ such that

$$\vartheta_{X,Y}[R] \in \mathsf{def}(\mathsf{acl}(Y)) \text{ if and only if } R \in \mathsf{def}(\mathsf{acl}(X)).$$

We are going to define Δ in such a way that if f is Δ-elementary then the following two stipulations hold:

(a) $X \sim f[X]$ for all $X \in [A]^k$;

(b) if $\mathsf{acl}(X) \cap \mathsf{acl}(X') \neq \emptyset$ then $\vartheta_{X,f[X]} \cup \vartheta_{X',f[X']}$ is a function, for any $X, X' \in [A]^k$.

By assumption if $|X| = k$ then $|\mathsf{acl}(X)| \leq \mathsf{s}(k)$, consequently $\sim$ has finitely many equivalence classes, say $X_0/{\sim}, \ldots, X_{l-1}/{\sim}$. Let χ'_i be the ε-diagram of $\mathsf{acl}(X_i)$ and let χ''_i be the diagram of $\mathsf{def}(\mathsf{acl}(X))$. Further, let $\xi'_{i,j}$ be the formula described in (b) above with

$X = X_i$ and $X' = X_j$: if $\mathsf{acl}(X_i) \cap \mathsf{acl}(X_j) \neq \emptyset$, and

$$\begin{aligned}\mathsf{acl}(X_i) &= \{s_\ell : \ell < |\mathsf{acl}(X_i)|\}, \\ \mathsf{acl}(X_j) &= \{t_\ell : \ell < |\mathsf{acl}(X_j)|\},\end{aligned}$$

and

$$\{y_\ell : \ell < |\mathsf{acl}(X_i)|\},$$
$$\{z_\ell : \ell < |\mathsf{acl}(X_j)|\}$$

are arbitrary and such that $\vartheta : t_\ell \mapsto y_\ell$ and $\vartheta' : s_\ell \mapsto z_\ell$ for $\ell < |\mathsf{acl}(X_i)|$ preserve $\mathsf{def}(\mathsf{acl}(X_i))$ and $\mathsf{def}(\mathsf{acl}(X_j))$ respectively, then $\vartheta \cup \vartheta'$ is a function.

For χ_i', χ_i'' and $\xi_{i,j}'$ denote by χ_i, χ_i^* and $\xi_{i,j}$, respectively the formulas obtained by replacing the constant symbols by variables and let Δ be the existential closure of the conjunctions of the formulas $\{\xi_{i,j}, \chi_i, \chi^* : i, j < l\}$. We claim that this Δ satisfies the statement of the Lemma.

Suppose $f : A \to A$ is Δ-elementary. Then we define its desired extension h as follows. For $a \in \mathsf{acl}(\mathsf{dom}(f))$ there exists $X \in [\mathsf{dom}(f)]^k$ such that $a \in \mathsf{acl}(X)$. Because f is Δ-elementary the set $Y = f[X]$ is equivalent to X: $X \sim Y$. Therefore, there is a function $\vartheta_{X,Y} : \mathsf{acl}(X) \to \mathsf{acl}(Y)$ with property (ii). Now define $h(a)$ to be equal to $\vartheta_{X,Y}(a)$. We claim that h is a well defined ε-elementary mapping satisfying the requirements of the present lemma.

First we shall prove that h is well defined. Suppose $a \in \mathsf{acl}(X) \cap \mathsf{acl}(X')$ for two k-element subsets X, X' of $\mathsf{dom}(f)$ and let $Y = f[X]$ and $Y' = f[X']$. We have to prove that $\vartheta_{X,Y}(a) = \vartheta_{X',Y'}(a)$. But this follows from the fact (encoded by the ξ-s in Δ), that in such cases $\vartheta_{X,Y} \cup \vartheta_{X',Y'}$ is a function.

It remains to show that h is ε-elementary. Let $\psi \in \varepsilon$ and suppose $\mathcal{A} \vDash \psi(\bar{a})$ where $\bar{a} \in \mathsf{acl}(\mathsf{dom}(f))$. Divide $\bar{a}$ into two parts $\bar{a} = a^\frown\bar{b}$. Then there exists $X \in [\mathsf{dom}(f)]^k$ such that $a \in \mathsf{acl}(X)$. Let $Y = f[X]$ and further let R be the smallest (w.r.t inclusion) definable relation in which a is contained. Suppose, seeking a contradiction, that $\mathcal{A} \vDash \neg\psi(h(\bar{a}))$. If we let $\varphi(x) = \neg\psi(x, h(\bar{b}))$ then by property (ii) of $\vartheta_{X,Y}$, the relation

$$R' = \vartheta^{-1}_{X,Y}\left(\vartheta_{X,Y}[R] \cap \|\varphi\|^{\mathcal{A}}\right)$$

is also definable and R' would be a proper subset of R containing a, which contradicts to the choice of R. ∎

Lemma 2.2.6. *Let $\mathcal{A}$ be a structure. Then*

(i) *If $\mathcal{A}$ is $\aleph_0$-categorical, then $\mathsf{acl}^{\mathcal{A}}$ is uniformly bounded.*

(ii) *If $\mathcal{A}$ is $\aleph_1$-categorical and $\mathsf{acl}^{\mathcal{A}}$ is uniformly bounded, then it is $\aleph_0$-categorical.*

We note that this statement is already known. For (ii) see e.g. Theorem 6.1.22 in [6]. A variant of (i) can be found e.g. in Section 7.4 of [5]. For completeness, we include here a proof.

Proof. First we prove (i). Suppose $\mathcal{A}$ is $\aleph_0$-categorical and let $\bar{a} \in {}^kA$ for some $k \in \omega$. Then $\mathsf{S}^{\mathcal{A}}(\bar{a})$ is finite, by $\aleph_0$-categoricity, hence there is a number $s_{\bar{a}}$ such that $|\mathsf{acl}(\bar{a})| \leq s_{\bar{a}}$. If $\bar{a}$ and $\bar{b}$ are on the same orbit according to $\mathsf{Aut}(\mathcal{A})$, then $|\mathsf{acl}(\bar{a})| = |\mathsf{acl}(\bar{b})|$ since for the automorphism α which moves $\bar{a}$ onto $\bar{b}$ we have $\alpha[\mathsf{acl}(\bar{a})] = \mathsf{acl}(\bar{b})$. But $\mathsf{Aut}(\mathcal{A})$ has only finitely many orbits on ${}^kA$. Choose a representative $\bar{a}_i$ of every orbit. Then $\mathsf{s}(k) = \max\{s_{\bar{a}_0}, s_{\bar{a}_1}, \ldots\}$ is as desired.

Next, we turn to prove (ii). Since $\mathcal{A}$ is $\aleph_1$-categorical, it is $\aleph_0$-stable as well, and hence there exists a prime model $\mathcal{P}$ of $\mathsf{Th}(\mathcal{A})$ and a strongly minimal formula $\phi(v, \bar{a})$ with parameters $\bar{a}$ from P. Let now $\mathcal{B}$ and $\mathcal{C}$ be two countable models (of $\mathsf{Th}(\mathcal{A})$). Then we may consider these two models as elementary extensions of $\mathcal{P}$. If

$$\mathsf{dim}^{\mathcal{B}}(\|\phi(v,\bar{a})\|^{\mathcal{B}}/\bar{a}) = \mathsf{dim}^{\mathcal{C}}(\|\phi(v,\bar{a})\|^{\mathcal{C}}/\bar{a}),$$

then there is an elementary mapping $f : \|\phi\|^{\mathcal{B}} \to \|\phi\|^{\mathcal{C}}$. Now, $\mathcal{B}$ is prime over $\|\phi\|^{\mathcal{B}}$ since else there would be a proper elementary submodel $\mathcal{D} \prec \mathcal{B}$ which is prime over $\|\phi\|^{\mathcal{B}}$, but then $(\mathcal{D}, \mathcal{B})$ would be a Vaughtian pair contradicting $\aleph_1$-categoricity. In the same way $\mathcal{C}$ is prime over $\|\phi\|^{\mathcal{C}}$. But then f extends to an elementary mapping $f' : \mathcal{B} \to \mathcal{C}$ which implies $\mathcal{B} \cong \mathcal{C}$.

So it remained to show that the dimension above are equal. The fact that $\mathsf{acl}^{\mathcal{A}}$ is uniformly bounded can be expressed by first order formulas. Hence $\mathsf{acl}^{\mathcal{B}}$ and $\mathsf{acl}^{\mathcal{C}}$ are uniformly bounded, too. In particular, the algebraic closure of a finite set is finite hence the dimensions above cannot be finite (because $\|\phi\|$ is infinite). Therefore both dimensions are countably infinite, hence equal. ∎

Proof of Proposition 2.2.3. By Lemma 2.2.6, every $\aleph_0$-categorical structure has uniformly bounded algebraic closure, thus Lemma 2.2.5 applies: let ε be the set of unnested atomic formulas and let Δ be the finite set of formulas obtained from Lemma 2.2.5. Finally, observe that if f is a Δ' elementary mapping for some $\Delta' \supseteq \Delta$, it is Δ-elementary, as well. So, the statement follows from Lemma 2.2.5. ∎

3 Stability and categoricity

3.1 Splitting chains

We start by recalling the definition of splitting (c.f. Definition I.2.6 of [15]).

Definition 3.1.1. Let $p \in \mathsf{S}_n^{\mathcal{A}}(X)$ and $Y \subseteq X$. Then *p splits over Y* if there exist $\bar{a}, \bar{b} \in X$ and $\varphi \in \mathsf{Form}$ such that $\mathsf{tp}^{\mathcal{A}}(\bar{a}/Y) = \mathsf{tp}^{\mathcal{A}}(\bar{b}/Y)$, but $\varphi(v, \bar{a}) \in p$ and $\neg\varphi(v, \bar{b}) \in p$.

Lemma 3.1.2. *Suppose $\mathcal{A}$ is a λ-stable structure, $D \subset A$ and $\langle \mathcal{A}, D \rangle$ is λ^+-saturated. Then there exist $A_D \subseteq D$, $p_D \in \mathsf{S}(A_D)$, and $a_D \in A \smallsetminus D$, such that $|A_D| \leq \lambda$, a_D realizes p_D, and if $c \in A \smallsetminus D$ realizes p_D then $\mathsf{tp}^{\mathcal{A}}(c/D)$ does not split over A_D.*

Proof. We apply transfinite recursion. Let $a_0 \in A \smallsetminus D$ be arbitrary, $A_0 = \emptyset$ and $p_0 = \mathsf{tp}^{\mathcal{A}}(a_0/A_0)$. Let $\beta < \lambda$ be an ordinal and suppose for all $\alpha < \beta$ that a_α, $A_\alpha \subseteq D$, and p_α are already defined, such that $p_\alpha \in \mathsf{S}(A_\alpha)$, $|A_\alpha| \leq |\alpha| + \aleph_0$, and a_α realizes p_α.

I. β is successor, say $\beta = \alpha + 1$. First, suppose there exists $c \in A \smallsetminus D$ which realizes p_α but $\mathsf{tp}^{\mathcal{A}}(c/D)$ splits over A_α (it may happen that $c = a_\alpha$). Then by definition there exist $\bar{d}_0, \bar{d}_1 \in D$ and φ such that $\mathsf{tp}^{\mathcal{A}}(\bar{d}_0/A_\alpha) = \mathsf{tp}^{\mathcal{A}}(\bar{d}_1/A_\alpha)$, but $\varphi(v, \bar{d}_0) \in \mathsf{tp}^{\mathcal{A}}(c/D)$ and $\varphi(v, \bar{d}_1) \notin \mathsf{tp}^{\mathcal{A}}(c/D)$. Let $A_\beta = A_\alpha \cup \{\bar{d}_0, \bar{d}_1\}$, $p_\beta = \mathsf{tp}^{\mathcal{A}}(c/A_\beta)$, and $a_\beta = c$. If there are no such $c \in A \smallsetminus D$ with $\mathsf{tp}^{\mathcal{A}}(c/D)$ splitting over A_α, then A_β, p_β and a_β are undefined, and the transfinite construction is complete.

II. β is a limit ordinal. Let $A_\beta = \cup_{\alpha<\beta} A_\alpha$ and $p_\beta = \cup_{\alpha<\beta} p_\alpha$. By assumption $\langle \mathcal{A}, D\rangle$ is λ^+-saturated hence there exists $a_\beta \in A \setminus D$ which realizes p_β.

III. Clearly, for each α, $p_{\alpha+1}$ splits over A_α, hence by Lemma I.2.7 of [15] this construction stops at a level $\beta < \lambda$. Let $A_D = A_\beta$, $p_D = p_\beta$, and $a_D = a_\beta$. ∎

Lemma 3.1.3. *Let $\mathcal{A}$ be λ-stable, and $D \subseteq A$ such that $\langle \mathcal{A}, D\rangle$ is a λ^+-saturated structure. Then there exist $a \in A \setminus D$ and sets $A(a) \subseteq B(a) \subseteq D$ such that*

(1) $|A(a)| \leq \lambda$ and $\mathsf{tp}^{\mathcal{A}}(a/D)$ does not split over $A(a)$;

(2) $|B(a)| \leq \lambda$ and every type over $A(a)$ can be realized in $B(a)$;

(3) for all $b \in A \setminus D$ the following holds:

$$\mathsf{tp}^{\mathcal{A}}(a/B(a)) = \mathsf{tp}^{\mathcal{A}}(b/B(a)) \Longrightarrow \mathsf{tp}^{\mathcal{A}}(a/D) = \mathsf{tp}^{\mathcal{A}}(b/D).$$

Proof. (1) Let A_D, p_D and a_D be as in Lemma 3.1.2, and let $A(a) = A_D$ and $a = a_D$. Then $\mathsf{tp}^{\mathcal{A}}(a/D)$ does not split over $A(a)$.

(2) Choose an arbitrary realization of each type over $A(a)$, and let their collection be $B(a)$. By (1) we have $|A(a)| \leq \lambda$, hence by stability

$$|B(a)| \leq \aleph_0 \cdot |\bigcup_{i\in\omega} \mathsf{S}_i^{\mathcal{A}}(A(a))| \leq \aleph_0^2 \lambda = \lambda.$$

Clearly $A(a) \subseteq B(a)$, and every type over $A(a)$ can be realized in $B(a)$.

(3) We prove that $B(a)$ fulfills (3). Suppose $\mathsf{tp}^{\mathcal{A}}(a/B(a)) = \mathsf{tp}^{\mathcal{A}}(b/B(a))$ and $\varphi(v, \bar{d}) \in \mathsf{tp}^{\mathcal{A}}(a/D)$. We have to show $\varphi(v, \bar{d}) \in \mathsf{tp}^{\mathcal{A}}(b/D)$. By (2) there exists $\bar{d}' \in B(a)$ such that $\mathsf{tp}^{\mathcal{A}}(\bar{d}/A(a)) = \mathsf{tp}^{\mathcal{A}}(\bar{d}'/A(a))$. By (1) $\mathsf{tp}^{\mathcal{A}}(a/D)$ does not split over $A(a)$ hence

$$\varphi(v, \bar{d}') \in \mathsf{tp}^{\mathcal{A}}(a/B(a)) = \mathsf{tp}^{\mathcal{A}}(b/B(a)).$$

Since b realizes p_D, Proposition 3.1.2 implies that $\mathsf{tp}^{\mathcal{A}}(b/D)$ does not split over $A(a)$ as well. Therefore $\varphi(v, \bar{d}) \in \mathsf{tp}^{\mathcal{A}}(b/D)$, as desired. ∎

3.2 Elementary extension in the $\aleph_1$-categorial case

Lemma 3.2.1. *Suppose $\mathcal{A}$ and $\mathcal{B}$ are elementarily equivalent, their common theory is uncountably categorical, $f : A \to B$ is an elementary mapping such that $D = \mathsf{dom}(f) \neq A$, $R = \mathsf{ran}(f) \neq B$ and $\langle \mathcal{A}, D \rangle$, $\langle \mathcal{B}, R \rangle$ are $\aleph_1$-saturated. Then there exists an elementary mapping f' strictly extending f.*

It is well known that every saturated structure $\mathcal{A}$ is strongly homogeneous: every elementary mapping f of $\mathcal{A}$ with $|f| < |A|$ can be extended to an automorphism of $\mathcal{A}$; for more details, we refer to Proposition 5.1.9 of [1]. The basic idea of the proof of this theorem is that by saturatedness, if $f : A \to A$ is a "small" elementary mapping, and $a \notin \mathsf{dom}(f)$, then the type $f[\mathsf{tp}^{\mathcal{A}}(a/\mathsf{dom}(f))]$ can be realized outside of $\mathsf{ran}(f)$. In our case the problem is that it is not only the "small" mappings which we would like to extend. For instance if $\mathcal{A}$ is an ultraproduct and f is decomposable then $|f|$ might be as big as $|A|$, and since $\mathcal{A}$ can not be $|A|^+$-saturated we can not hope anything like above. The point here is, that our statement may also apply to cases when $|\mathsf{dom}(f)| = |A|$, so ordinary saturation cannot be used.

Proof. We distinguish two cases.

Case 1: $D = \mathsf{dom}(f)$ is not an elementary substructure of $\mathcal{A}$. Then by the Łoś-Vaught test, there is a formula ψ, and constants $\bar{d} \in D$, such that $\mathcal{A} \vDash \exists v \psi(v, \bar{d})$, but there is no such $v \in D$. Since $\mathcal{A}$ is uncountably categorical, it is $\aleph_0$-stable. Hence, the isolated types over D are dense in $\mathsf{S}_1^{\mathcal{A}}(D)$. Consequently, there is an isolated type $p \in \mathsf{S}_1^{\mathcal{A}}(D)$ containing

$\psi(v, \bar{d})$. Let $a \in A$ be a realization of p (such a realization exists since p is isolated). Then $\mathcal{A} \vDash \psi(a, \bar{d})$, so $a \notin D$. Let $b \in B$ be a realization of $f[p]$ in $\mathcal{B}$. Again, since $f[p]$ is isolated, b exists. Finally let $f' = f \cup \{\langle a, b\rangle\}$. Clearly, f' is an elementary mapping strictly extending f.

Case 2: $\mathcal{D} \prec \mathcal{A}$ is an elementary substructure. Let $a \in A \smallsetminus D$, $A(a) \subseteq B(a) \subseteq D$ as in Lemma 3.1.3. It is enough to show that $p = f[\mathsf{tp}^{\mathcal{A}}(a/B(a))]$ can be realized in $B \smallsetminus \mathsf{ran}(f)$ because if b realizes p in $B \smallsetminus \mathsf{ran}(f)$ then $f' = f \cup \langle\{a, b\}\rangle$ is the required elementary mapping strictly extending f. Note, that $\mathcal{A}$ and $\mathcal{B}$ are $\aleph_1$-categorical, hence they are $\aleph_0$-stable. Consequently, Lemma 3.1.3 (2) ensures $|B(a)| \leq \aleph_0$.

Adjoin a new relation symbol R to the language of $\mathcal{B}$ and interpret it in $\mathcal{B}$ as $\mathsf{ran}(f)$. By saturatedness it is enough to show that each $\phi \in p$ can be realized in $B \smallsetminus R$. Let $\phi \in p$ be arbitrary, but fixed. By assumption, $\mathcal{D}$ is an elementary substructure of $\mathcal{A}$, so it follows that a is not algebraic over D. Hence, because of f is elementary, the relation defined by ϕ in $\mathcal{B}$ is infinite as well. In addition, $\mathcal{B}$ is uncountably categorical, consequently $\langle \mathcal{B}, f[\mathcal{D}]\rangle$ is not a Vaughtian pair (see, for example, Theorem 6.1.18 of [6]). Thus the relation defined by ϕ in $\mathcal{B}$ can be realized in $B \smallsetminus R$, therefore $\neg R(v) \wedge \phi(v)$ can be satisfied in $\mathcal{B}$, for all $\phi \in p$. ∎

4 Extending decomposable mappings

In this section we present a method for constructing so called *decomposable* isomorphisms between certain ultraproducts. As introduced in [10], and further studied in [4] and [12], a relation R in an ultraproduct $\Pi_{i\in I}\mathcal{A}_i/\mathcal{F}$ is defined to be decomposable iff for all $i \in I$ there are relations R_i on A_i such that $R = \Pi_{i\in I}R_i/\mathcal{F}$. Similarly, a function $f : \Pi_{i\in I}\mathcal{A}_i/\mathcal{F} \to \Pi_{i\in I}\mathcal{B}_i/\mathcal{F}$ is called decomposable iff "f acts coordinatewise", that is, iff for all $i \in I$ there are functions $f_i : A_i \to B_i$ such that $f = \Pi_{i\in I}f_i/\mathcal{F}$.

Our method is similar in spirit to [16]: to prove certain properties of finite structures, we deal with infinite ultraproducts of them. As we already mentioned, to establish further applications, we are trying to present our construction in a rather general way.

Definition 4.0.2. A sequence $\langle \Delta_n \in [\mathsf{Form}]^{<\omega} : n \in \omega \rangle$ is defined to be a *covering sequence of formulas* if the following properties hold for it.

1. The sequence is increasing: $\Delta_i \subseteq \Delta_j$ whenever $i \leq j \in \omega$;
2. For all $n \in \omega$ the finite set of formulas Δ_n is closed under subformulas;
3. $\bigcup\{\Delta_n : n \in \omega\} = \mathsf{Form}$, i.e. the sequence covers Form.

If $\mathcal{M}$ is a structure and $\mathcal{A}_n \leq \mathcal{M}$ is a Δ_n-elementary substructure then $\Pi_{n\in\omega}\mathcal{A}_n/\mathcal{F}$ is elementarily equivalent to $\mathcal{M}$.

Our aim in this section is to prove the following Theorem.

Theorem 4.3.7. *Let $\mathcal{M}$ be an $\aleph_1$-categorical structure with an atom–defining schema, having the extension property. Suppose that there is a $\emptyset$-definable strongly minimal subset M_0 of M and suppose for each $n \in \omega$ the finite structures $\mathcal{A}_n$ and $\mathcal{B}_n$ are equinumerous, Δ_n–elementary substructures of $\mathcal{M}$. Then there is a decomposable isomorphism*

$$f = \langle f_n : \ n \in \omega \rangle / \mathcal{F} : \Pi_{n\in\omega}\mathcal{A}_n/\mathcal{F} \to \Pi_{n\in\omega}\mathcal{B}_n/\mathcal{F}.$$

We split the proof into three parts: each part is contained in a different section. We sketch here the main line of the proof. If $\mathcal{M}$ is an $\aleph_1$-categorical structure with $M_0 \subseteq M$ being a $\emptyset$-definable strongly minimal subset then by Zilber's Ladder Theorem (Theorem 0.1 of Chapter V of [18]) there exists a finite increasing sequence

$$M_0 \subseteq M_1 \subseteq \ldots \subseteq M_{z-1} = M$$

of subsets of M such that M_ℓ is $\emptyset$-definable for all $\ell \in z$ (and certain other remarkable properties which will be recalled later).

First, in Section 4.1 we extend certain decomposable elementary mappings to the whole of M_0 (see Proposition 4.1.6). Then, in Section 4.2 we continue to extend the mapping along Zilber's ladder to M (see Theorem 4.2.10). Finally, in Section 4.3, we combine our results obtained so far to get Theorem 4.3.7.

From now on, throughout this section $\mathcal{M}$ is a fixed $\aleph_1$-categorical structure satisfying the extension property and having an atom-defining schema. Further, we assume that $M_0 \subseteq M$ is a $\emptyset$-definable strongly minimal subset of M.

For completeness, we note that, we do not need all these properties in all of our steps. To be more concrete, in Section 4.1 we need $\mathcal{M}$ to be $\aleph_1$-categorical satisfying the extension property, and in Section 4.2 we need $\mathcal{M}$ to be $\aleph_1$-categorical having an atom-defining schema for $\emptyset$-definable infinite relations.

4.1 The strongly minimal case

We will deal first with strongly minimal structures $\mathcal{N}$ and we provide a method to extend certain decomposable mapping in this case (Proposition 4.1.4). Then we move on to the case when the whole structure is not strongly minimal (Proposition 4.1.6). We will need several Lemmas.

Lemma 4.1.1. *Let $\mathcal{A}$ be a structure and let $M \subseteq A$ be $\emptyset$-definable and strongly minimal. Then there exists a function $\varepsilon : [\mathsf{Form}]^{<\omega} \to \omega$ such that for all $\Delta \in [\mathsf{Form}]^{<\omega}$ if $\mathcal{B} \leq \mathcal{A}$ is a Δ-algebraically closed substructure with $B \subseteq M$ and $|B| \geq \varepsilon(\Delta)$ then $\mathcal{B}$ is a Δ-elementary substructure of $\mathcal{A}$.*

Proof. By strong minimality, for any formula φ either $\|\varphi\| \cap M$ or $(A \smallsetminus \|\varphi\|) \cap M$ is finite, i.e. φ is algebraic or transcendental, respectively. Let Δ be a finite set of formulas and let $\mathcal{B}$ be a Δ-algebraically closed substructure of $\mathcal{A}$ with $B \subseteq M$. Let Δ' be the smallest set of formulas containing Δ and closed under subformulas. We shall define the number $\varepsilon(\Delta)$ so that if $|B| \geq \varepsilon(\Delta)$ then $\mathcal{B}$ is a Δ-elementary substructure. Pick $\varphi \in \Delta$ and $\bar{b} \in B$.

Case 1. Suppose $\varphi(x, \bar{b})$ is algebraic and suppose $\mathcal{A} \vDash \varphi(a, \bar{b})$ for some $a \in A$. Then $a \in B$ because $\mathcal{B}$ is Δ-algebraically closed. In this case let $\mathsf{n}(\varphi) = 0$.

Case 2. Suppose $\varphi(x, \bar{b})$ is transcendental. By compactness, there exists $\mathsf{n}(\varphi)$, depending on φ only, such that $\left|M \smallsetminus \|\varphi(x, \bar{b})\|\right| \leq \mathsf{n}(\varphi)$. Thus if $|B| > \mathsf{n}(\varphi)$ then there must exists $c \in B$ such that $\mathcal{B} \vDash \varphi(c, \bar{b})$.

Setting $\varepsilon(\Delta) = \max\{\mathsf{n}(\varphi)+1 : \varphi \in \Delta'\}$, a straightforward induction on the complexity of elements of Δ' completes the proof. ∎

The next lemma is a kind of converse of Lemma 4.1.1.

Lemma 4.1.2. *Let $\mathcal{A}$ be strongly minimal and let $\mathcal{B}$ be a substructure of $\mathcal{A}$. Then for all finite set ε of formulas there exists a finite set δ of formulas such that if $\mathcal{B}$ is a δ-elementary substructure then $\mathcal{B}$ is $\mathsf{acl}^{\mathcal{A}}_{\varepsilon}$-closed.*

Proof. For all $\varphi \in \varepsilon$, by compactness, there is a natural number $\mathsf{n}(\varphi)$ (depending only on φ) such that if $\varphi(v, \bar{b})$ is algebraic for some $\bar{b} \in B$, then $\varphi(v, \bar{b})$ can have at most $\mathsf{n}(\varphi)$ pairwise distinct realizations in A (else, there would exists an infinite–co-infinite definable subset in some elementary extension, contradicting strong minimality). Let $\varphi_n(\bar{y})$ denote the next formula:

$$\varphi_n(\bar{y}) = \exists_n x \varphi(x, \bar{y}) = \text{“}\varphi(x, \bar{y}) \text{ has exactly } n \text{ realizations''}.$$

Clearly φ_n can be made a strict first order formula, for all fixed $n \in \omega$. Put

$$\delta = \{\varphi_n : n \leq \mathsf{n}(\varphi), \varphi \in \varepsilon\} \cup \varepsilon.$$

Clearly, if $\mathcal{B}$ is δ-elementary then it is $\mathsf{acl}^{\mathcal{A}}_{\varepsilon}$-closed. ∎

Lemma 4.1.3. *Let $\Delta \in [\mathsf{Form}]^{<\omega}$ be closed under subformulas. Let $\mathcal{B}, \mathcal{C}$ be Δ-elementary substructures of $\mathcal{A}$. If $f : \mathcal{B} \to \mathcal{C}$ is an isomorphism then f is a Δ-elementary mapping of $\mathcal{A}$.*

Proof. A straightforward induction on the complexity of the formulas in Δ; the details are left to the Reader. ∎

Let $\mathcal{N}$ be a fixed strongly minimal (hence $\aleph_1$-categorical) structure with the weak extension property (see Definition 2.1.5). Recall that by the weak extension property there exists a finite set Δ of formulas satisfying $(*)$ of Definition 2.1.5. Let Φ be a set of formulas such that if $X = \mathsf{acl}_\Phi(X)$ then X is a substructure. Such Φ exists and can be chosen to be finite because our language is finite. Fix a covering sequence of formulas $\langle \Delta_n \in [\mathsf{Form}]^{<\omega} : \ n \in \omega \rangle$ in a way that $\Phi, \Delta \subseteq \Delta_n$ for all $n \in \omega$. By Lemma 4.1.2, after a possibly rescaling, we may assume that

$(**)$ $\mathcal{A}_n$ and $\mathcal{B}_n$ are $\mathsf{acl}^{\mathcal{N}}_{\Delta_n}$-closed substructures of $\mathcal{N}$.

Proposition 4.1.4 can be considered as the strongly minimal case of Theorem 4.3.7.

Proposition 4.1.4. *Let $\mathcal{N}$ be a strongly minimal structure with the weak extension property. Suppose for each $n \in \omega$ the finite structures $\mathcal{A}_n$ and $\mathcal{B}_n$ are Δ_n-elementary (hence, by $(**)$, acl_{Δ_n}-closed) substructures of $\mathcal{N}$ with $|A_n| \leq |B_n|$. Let*

$$g = \langle g_n : \ n \in \omega \rangle / \mathcal{F} : \Pi_{n\in\omega} \mathcal{A}_n / \mathcal{F} \to \Pi_{n\in\omega} \mathcal{B}_n / \mathcal{F}$$

be a decomposable elementary mapping with

$$\left\{ n \in \omega : g_n \textit{ is } \Delta_n - \textit{elementary and } |\mathsf{dom}(g_n)| \geq \varepsilon(\Delta_n) \right\} \in \mathcal{F},$$

where ε comes from Lemma 4.1.1. Then g can be extended to a decomposable elementary embedding.

We remark, that if $|A_n| = |B_n|$ for all (in fact, almost all) n, then the resulting extension is a decomposable isomorphism.

Proof. Let $\mathcal{A} = \Pi_{n\in\omega}\mathcal{A}_n/\mathcal{F}$ and $\mathcal{B} = \Pi_{n\in\omega}\mathcal{B}_n/\mathcal{F}$. Note that $\mathcal{A}$ and $\mathcal{B}$ are elementarily equivalent with $\mathcal{N}$ because the increasing sequence Δ_n covers Form. By transfinite recursion we construct a sequence $\langle f^\alpha : \ \alpha \leq \kappa\rangle$ such that for $\alpha \leq \kappa$ the following properties hold:

(P1) $f^\alpha = \langle f^\alpha_n : n \in \omega\rangle/\mathcal{F} : A \to B$ is a decomposable elementary mapping;

(P2) $f^\gamma_n \subseteq f^\nu_n$ for $\gamma < \nu \leq \kappa$ and all $n \in \omega$;

(P3) $\mathsf{dom}(f^\alpha_n)$ is an $\mathsf{acl}^{\mathcal{N}}_{\Delta_n}$-closed substructure of $\mathcal{A}_n$ for all $n \in \omega$;

(P4) $\mathsf{ran}(f^\alpha_n)$ is an $\mathsf{acl}^{\mathcal{N}}_{\Delta_n}$-closed substructure of $\mathcal{B}_n$ for all $n \in \omega$;

(P5) f^α_n is Δ_n-elementary for all $n \in \omega$.

If $\mathsf{dom}(f^\kappa) = A$ then we are done, because since each A_i and B_i are finite, it follows that f^κ is a decomposable elementary embedding.

Now we construct the first element f^0 of the sequence. By assumption

$$J = \big\{n \in \omega : g_n \text{ is } \Delta_n - \text{elementary and } |\mathsf{dom}(g_n)| \geq \varepsilon(\Delta_n)\big\} \in \mathcal{F}.$$

Because Δ in the weak extension property is contained in each Δ_n, it follows that for all $n \in J$ there exists a partial isomorphism h_n extending g_n, with $\mathsf{dom}(h_n) = \mathsf{acl}^{\mathcal{N}}_{\Delta_n}(\mathsf{dom}(g_n))$ and $\mathsf{ran}(h_n) = \mathsf{acl}^{\mathcal{N}}_{\Delta_n}(\mathsf{ran}(g_n))$. Note that because $\mathcal{A}_n$ is Δ_n-algebraically closed, it follows that $\mathsf{dom}(h_n) \subseteq A_n$. Therefore $\mathsf{dom}(h_n)$ is a substructure of $\mathcal{N}$ (hence of $\mathcal{A}_n$, too). By $|\mathsf{dom}(h_n)| \geq \varepsilon(\Delta_n)$ and by Lemma 4.1.1 we get $\mathsf{dom}(h_n)$ is a Δ_n-elementary substructure of ($\mathcal{N}$ and hence of) $\mathcal{A}_n$. Similarly $\mathsf{ran}(h_n)$ is a Δ_n-elementary substructure of $\mathcal{B}_n$. But then Lemma 4.1.3 applies: h_n is also a Δ_n-elementary mapping. Let

$$f^0_n = \begin{cases} h_n & \text{if } n \in J \\ \emptyset & \text{otherwise,} \end{cases}$$

and $f^0 = \langle f_n^0 :\ n \in \omega\rangle/\mathcal{F}$. Then properties (P1)-(P5) hold.

Now suppose $\langle f^\alpha : \alpha < \beta\rangle$ has already been defined for some $\beta \leq \kappa$. Then we define f^β as follows.

I. Successor case

Suppose $\beta = \alpha + 1$. We may assume $A \setminus \mathsf{dom}(f^\alpha) \neq \emptyset$, since otherwise the construction would stop. Because f^α is decomposable we have

$$\langle \mathcal{A}, \mathsf{dom}(f^\alpha)\rangle = \Pi_{n\in\omega}\langle \mathcal{A}_n, \mathsf{dom}(f_n^\alpha)\rangle/\mathcal{F}$$

and thus $\langle \mathcal{A}, \mathsf{dom}(f^\alpha)\rangle$ is $\aleph_1$-saturated (and similarly with $\langle \mathcal{B}, \mathsf{ran}(f^\alpha)\rangle$). Consequently Lemma 3.2.1 applies: there exist $a \in A \setminus \mathsf{dom}(f^\alpha)$, $b \in B \setminus \mathsf{ran}(f^\alpha)$ such that $f = f^\alpha \cup \{\langle a, b\rangle\}$ is an elementary mapping. If $a = \langle a_n : n \in \omega\rangle/\mathcal{F}$ and $b = \langle b_n : n \in \omega\rangle/\mathcal{F}$ then

$$I = \{n \in \omega : a_n \notin \mathsf{dom}(f_n^\alpha),\ b_n \notin \mathsf{ran}(f_n^\alpha)\} \in \mathcal{F}.$$

Thus if

$$f_n = \begin{cases} f_n^\alpha \cup \{\langle a_n, b_n\rangle\} & \text{if } n \in I \\ f_n^\alpha & \text{otherwise,} \end{cases}$$

then $f = \langle f_n : n \in \omega\rangle/\mathcal{F}$. By Łoś's Lemma

$$J = \{n \in \omega : f_n \text{ is } \Delta\text{-elementary }\} \in \mathcal{F}.$$

We claim that for each $n \in J$, f_n is not only Δ-elementary but Δ_n-elementary. To see this, let $\varphi \in \Delta_n$, $\bar{d} \in \mathsf{dom}(f_n)$ and suppose $\mathcal{A}_n \vDash \varphi(\bar{d})$. We have to show that $\mathcal{B}_n \vDash \varphi(f_n(\bar{d}))$. Let us replace all the occurrences of a_n in $\bar{d}$ with a variable v and denote this sequence by $v^\frown\bar{d}'$. Then $\bar{d}' \in \mathsf{dom}(f_n^\alpha)$ and $a_n \in \|\varphi(v, \bar{d}')\|^{\mathcal{A}_n}$. Since $\mathsf{dom}(f_n^\alpha)$ is $\mathsf{acl}_{\Delta_n}^{\mathcal{N}}$-closed (by (P3)), it follows that $\varphi(v,\bar{d}')$ is not a Δ_n-algebraic formula since else it would imply $a_n \in \mathsf{dom}(f_n^\alpha)$. Since $\mathcal{N}$ is strongly minimal, exactly one of $\varphi(v,\bar{d}')$ or $\neg\varphi(v,\bar{d}')$ is algebraic, thus if $\varphi(v,\bar{d}')$ is not algebraic then $\varphi(v, f_n^\alpha(\bar{d}'))$ is not algebraic, too. The same is the situation in $\mathcal{B}_n$, hence $b_n \notin \|\neg\varphi(v, f_n^\alpha(\bar{d}'))\|^{\mathcal{B}_n}$, and thus $b_n \in \|\varphi(v, f_n^\alpha(\bar{d}'))\|^{\mathcal{B}_n}$, as needed.

So, f_n is Δ_n-elementary and $\Delta \subseteq \Delta_n$ hence by the weak extension property, for all $n \in J$ there exists a partial isomorphism h_n extending f_n with $\mathsf{dom}(h_n) = \mathsf{acl}^{\mathcal{N}}_{\Delta_n}(\mathsf{dom}(f_n))$. Then by Lemma 4.1.1, $\mathsf{dom}(h_n)$ is a Δ_n-elementary substructure of $\mathcal{A}_n$ (similarly $\mathsf{ran}(h_n)$ is a Δ_n-elementary substructure of $\mathcal{B}_n$) and hence by Lemma 4.1.3, h_n is a Δ_n-elementary mapping. Let us define f_n^β as follows:

$$f_n^\beta = \begin{cases} h_n & \text{if } n \in J \\ f_n^\alpha & \text{otherwise.} \end{cases}$$

Set $f^\beta = \langle f_n^\beta : n \in \omega \rangle / \mathcal{F}$. Then clearly, stipulations (P1)-(P5) hold for f^β.

II. Limit case

Suppose β is a limit ordinal. Set $f_n^\beta = \bigcup_{\alpha<\beta} f_n^\alpha$ for all $n \in \omega$, and let $f^\beta = \langle f_n^\beta : n \in \omega \rangle / \mathcal{F}$. Then (P2)-(P4) are true for f^β and for (P1) we only have to show that f^β is still elementary. For this it is enough to prove that f_n^β preserves Δ_n for all $n \in \omega$, i.e. f_n^β is a Δ_n-elementary mapping. But this is exactly (P5) which property is preserved under chains of Δ_n-elementary mappings. ∎

As an immediate corollary of the results established so far, in Theorem 4.1.5 below, we prove, that a strongly minimal structure with the weak extension property can be obtained, in an essentially unique way, as an ultraproduct of its certain finite substructures.

Theorem 4.1.5 (First Unique Factorization Theorem). *Let $\mathcal{N}$ be a strongly minimal structure having the weak extension property (see Definition 2.1.5). Suppose $\mathcal{A}_n$, $\mathcal{B}_n$ are equinumerous finite, acl_{Δ_n}-closed substructures of $\mathcal{N}$ for all $n \in \omega$ such that $\sup\{|A_n| : n \in \omega\}$ is infinite. Then*

$$\{n \in \omega : \mathcal{A}_n \cong \mathcal{B}_n\} \text{ is cofinite.}$$

Proof. We will prove that $\{n \in \omega : \mathcal{A}_n \cong \mathcal{B}_n\} \in \mathcal{F}$ for any non-principal ultrafilter $\mathcal{F}$. From this the statement follows.

Since $\sup\{|A_n| : n \in \omega\}$ is infinite by assumption, it follows that for all $n \in \omega$ there exists $\gamma(n) \in \omega$ such that $|A_{\gamma(n)}| \geq \varepsilon(\Delta_n)$, where ε comes from Lemma 4.1.1. Hence the structure $\mathcal{A}_{\gamma(n)}$ is a Δ_n-elementary substructure of $\mathcal{N}$. For simplicity, to avoid ugly notation, by replacing $\mathcal{A}_n$ with $\mathcal{A}_{\gamma(n)}$ we may suppose $\mathcal{A}_n$ and $\mathcal{B}_n$ are equinumerous Δ_n-elementary finite substructures of $\mathcal{N}$. Let $\mathcal{A} = \Pi_{n\in\omega}\mathcal{A}_n/\mathcal{F}$ and let $\mathcal{B} = \Pi_{n\in\omega}\mathcal{B}_n/\mathcal{F}$. The increasing sequence Δ_n covers Form hence $\mathcal{A}$ and $\mathcal{B}$ are both elementarily equivalent with $\mathcal{N}$. By universality, taking a large enough ultrapower $\mathcal{A}'$ of $\mathcal{A}$, $\mathcal{N}$ can be elementarily embedded into $\mathcal{A}'$. Hence $\mathcal{A}_n$ is a Δ_n-elementary substructure of $\mathcal{A}'$ as well. Now taking an elementary substructure of $\mathcal{A}'$ of power $|A|$ containing (the image of) $\mathcal{A}_n$ it is isomorphic to $\mathcal{A}$ by categoricity. Hence we may assume that $\mathcal{A}_n$ is a Δ_n-elementary substructure of $\mathcal{A}$ for all $n \in \omega$. By a similar argument we may also assume that $\mathcal{B}_n$ is a Δ_n-elementary substructure of $\mathcal{B}$.

For all $n \in \omega$ because $\mathcal{A}_n$ is finite, by Łoś's Lemma, there exists $n \leq \beta(n) \in \omega$ such that $\mathcal{A}_{\beta(n)}$ and $\mathcal{B}_{\beta(n)}$ contains an isomorphic copy of $\mathcal{A}_n$. By $\Delta_n \subseteq \Delta_{\beta(n)}$ we get $\mathcal{A}_{\beta(n)}$ and $\mathcal{B}_{\beta(n)}$ are also Δ_n-elementary substructures. Consequently there exist partial isomorphisms $g_{\beta(n)} : \mathcal{A}_{\beta(n)} \to \mathcal{B}_{\beta(n)}$ whose domains are the $\mathcal{A}_n$-s. By Lemma 4.1.3 these partial isomorphisms are Δ_n-elementary mappings.

Let $\mathcal{A}^* = \Pi_{n\in\omega}\mathcal{A}_{\beta(n)}/\mathcal{F}$ and $\mathcal{B}^* = \Pi_{n\in\omega}\mathcal{B}_{\beta(n)}/\mathcal{F}$. Then $g = \langle g_{\beta(n)} : n \in \omega\rangle/\mathcal{F} : \mathcal{A}^* \to \mathcal{B}^*$ is a decomposable elementary mapping which, by Proposition 4.1.4, extends to a decomposable isomorphism $f = \langle f_n : n \in \omega \rangle / \mathcal{F} : \mathcal{A}^* \to \mathcal{B}^*$. Then the statement follows from Łoś's Lemma (applied to the structure $\langle \mathcal{A}^*, \mathcal{B}^*, f \rangle$). ∎

Now we turn to the case when the whole structure is not strongly minimal. As we mentioned, $\mathcal{M}$ is a fixed $\aleph_1$-categorical structure satisfying the extension property and M_0 is a $\emptyset$-definable strongly minimal subset of M.

Proposition 4.1.6. *Suppose for each $n \in \omega$ the finite structures $\mathcal{A}_n, \mathcal{B}_n$ are Δ_n-elementary substructures of $\mathcal{M}$ such that*

$$\left\{ n \in \omega : |M_0^{\mathcal{A}_n}| \leq |M_0^{\mathcal{B}_n}| \right\} \in \mathcal{F}.$$

Let $g = \langle g_n : n \in \omega \rangle / \mathcal{F} : \Pi_{n\in\omega} \mathcal{A}_n / \mathcal{F} \to \Pi_{n\in\omega} \mathcal{B}_n / \mathcal{F}$ be a decomposable elementary mapping with $\mathsf{dom}(g_n) \subseteq M_0^{\mathcal{A}_n}$ and $\mathsf{ran}(g_n) \subseteq M_0^{\mathcal{B}_n}$ for all $n \in \omega$. Assume that

$$\left\{ n \in \omega : g_n \textit{ is } \Delta_n\textit{-elementary and } |\mathsf{dom}(g_n)| \geq \varepsilon(\Delta_n) \right\} \in \mathcal{F}$$

where ε comes from Lemma 4.1.1. Then g can be extended to a decomposable elementary mapping $g^+ = \langle g_n^+ : n \in \omega \rangle / \mathcal{F}$ such that $\mathsf{dom}(g_n^+) = M_0^{\mathcal{A}_n}$ and $\mathsf{ran}(g_n^+) \subseteq M_0^{\mathcal{B}_n}$ (almost everywhere).

We note, that if $|M_0^{\mathcal{A}_n}| = |M_0^{\mathcal{B}_n}|$ almost everywhere, then we get $\mathsf{dom}(g_n^+) = M_0^{\mathcal{A}_n}$ and $\mathsf{ran}(g_n^+) = M_0^{\mathcal{B}_n}$ for almost all n.

Proof. We intend to use Proposition 4.1.4. To do so we have to ensure that M_0 is not just a strongly minimal set but a structure. In general this cannot be guaranteed in the original language of $\mathcal{M}$. Our plan is to apply Proposition 4.1.4 for a sequence of strongly minimal structures defined in terms of relations of M_0.

Since we will use different first order languages in this proof, let us denote by $L(\mathcal{M})$ the language of $\mathcal{M}$. For each $L(\mathcal{M})$-formula φ let us associate a relation symbol R_φ whose arity equals to the number of free variables in φ. Let $L(R)$ be the language consists of these new relation symbols:

$$L(R) = \big\{R_\varphi : \varphi \in \mathsf{Form}(L(\mathcal{M}))\big\}.$$

Next, we turn $\mathcal{M}$ into an $L(R)$-structure as follows: if $\varphi(\bar{x})$ is an $L(\mathcal{M})$-formula then interpret R_φ in $\mathcal{M}$ as follows:

$$R_\varphi^{\mathcal{M}} = \|\varphi\|^{\mathcal{M}} \cap {}^{|\bar{x}|}M_0.$$

It is easy to see that relations definable with $L(R)$-formulas (in $\mathcal{M}$) are also definable with $L(\mathcal{M})$-formulas. In fact by an obvious induction on the complexity of formulas of $L(R)$ one can easily check that there is a function $\iota : \mathsf{Form}(L(R)) \to \mathsf{Form}(L(\mathcal{M}))$ such that for any formula $\psi \in \mathsf{Form}(L(R))$ we have

$$\|\psi\|^{\mathcal{M}} = R_{\iota(\psi)}^{\mathcal{M}}.$$

For a set Δ of $L(\mathcal{M})$-formulas we write

$$R(\Delta) = \{R_\varphi : \varphi \in \Delta\}.$$

Let us enumerate $\mathsf{Form}(L(\mathcal{M}))$ as

$$\mathsf{Form}(L(\mathcal{M})) = \langle \varphi_n : n \in \omega \rangle.$$

For $\ell \in \omega$ let us define a structure $\mathcal{N}_\ell$ as follows.

By the extension property of $\mathcal{M}$, for $\varepsilon_\ell = \{\varphi_0, \ldots, \varphi_{\ell-1}\}$ there exists a corresponding finite set of formulas Δ_ℓ. Let

$$\mathcal{N}_\ell = \langle M_0, R_\varphi^{\mathcal{M}} \rangle_{\varphi \in \Delta_\ell}.$$

Thus the language $L(\mathcal{N}_\ell)$ consists of the relation symbols $\{R_\varphi : \varphi \in \Delta_\ell\}$. We have the next few auxiliary claims.

(1) $\mathcal{N}_\ell$ is strongly minimal: To see this, let $\psi \in \mathsf{Form}(L(\mathcal{N}_\ell))$ be any formula. Then $\|\psi\|^{\mathcal{M}} = R_{\iota(\psi)}^{\mathcal{M}} = \|\iota(\psi)\|^{\mathcal{M}} \cap M_0$ which is either finite or cofinite (because $\iota(\psi) \in \mathsf{Form}(L(\mathcal{M}))$).

(2) $\mathcal{N}_\ell$ has the weak extension property described in Definition 2.1.5: We have to find a set Δ (a finite set of $L(\mathcal{N}_\ell)$-formulas) such that whenever $\Delta' \supseteq \Delta$ and f is a Δ'-elementary mapping then it can be extended to a partial isomorphism to $\mathsf{acl}_{\Delta'}(\mathsf{dom}(f))$. Now we claim that $\Delta = R(\Delta_\ell)$ works. To see this, suppose $\Delta' \supseteq \Delta$ and f is a Δ'-elementary mapping. We have to extend f in a way that the extension preserves all the formulas in $R(\Delta_\ell)$ (this would mean that the extension is a partial isomorphism in the language $L(\mathcal{N}_\ell)$).
(i) Observe first, that we may assume that $\iota[R(\Delta_\ell)] = \Delta_\ell$, because the formulas in the two sides of the equation define the same relations in M_0.
(ii) Clearly, we have $\iota[\Delta'] \supseteq \Delta_\ell$.
(iii) If f preserves an $L(R)$-formula ψ then it preserves $\iota(\psi)$ as well. Therefore f is $\iota[\Delta']$-elementary.
Consequently, by the extension property of $\mathcal{M}$, there is a Δ_ℓ-elementary (in the language $L(\mathcal{M})$) extension f' of f whose domain and range are respectively $\mathsf{acl}_{\iota[\Delta']}(\mathsf{dom}(f))$ and $\mathsf{acl}_{\iota[\Delta']}(\mathsf{ran}(f))$. Clearly, if f' preserves Δ_ℓ then it also preserves $R(\Delta_\ell)$. Thus f' is a partial isomorphism in the language $L(\mathcal{N}_\ell)$, as desired.

(3) Let $i \in \omega$ be arbitrary. Then there exists ℓ such that $\Delta_i \subseteq \{\varphi_k : k \in \ell\}$. Since $\mathcal{A}_i$ is a

Δ_i-elementary substructure of $\mathcal{M}$, it follows that $M_0^{\mathcal{A}_i}$ (which equals $A_i \cap M_0$ if i is large enough) is the underlying set of an $R(\Delta_i)$-elementary substructure of $\mathcal{N}_\ell$. If $\langle \Delta_i : i \in \omega \rangle$ is a covering sequence of $\mathsf{Form}(L(\mathcal{M}))$ then $\langle R(\Delta_i) : i \in \omega \rangle$ can be considered as a covering sequence of $\mathsf{Form}(L(R))$: note, that for each $\psi \in \mathsf{Form}(L(R))$ we have $\|\psi\|^{\mathcal{M}} = R^{\mathcal{M}}_{\iota(\psi)}$ and $\iota(\psi) \in \Delta_i$ for large enough i. By (2) above, $\mathcal{N}_\ell$ has the weak extension property and g_n is $R(\Delta_n)$-elementary for almost all $n \in \omega$. Observe, that $R(\Delta_i)$ and Δ_i define the same relations in M_0, hence $\varepsilon(R(\Delta_i))$ and $\varepsilon(\Delta_i)$ in Lemma 4.1.1 are equal. Consequently, conditions of Proposition 4.1.4 are satisfied.

By Proposition 4.1.4 for all $\ell \in \omega$ there exists a decomposable elementary embedding $g^\ell = \langle g_n^\ell : n \in \omega \rangle / \mathcal{F}$ (it is elementary in the language $L(\mathcal{N}_\ell)$) extending g, with $\mathsf{dom}(g_n^\ell) = M_0^{\mathcal{A}_n}$ and $\mathsf{ran}(g_n^\ell) \subseteq M_0^{\mathcal{B}_n}$.

Let $\langle I_n : n \in \omega \rangle$ be a decreasing sequence with $I_n \in \mathcal{F}$, $I_0 = \omega$ and $\cap_{n\in\omega} I_n = \emptyset$. Write

$$J_n = \{ i \in I_n : g_i^n \text{ is } \Delta_n - \text{elementary and } \mathsf{dom}(g_i^n) = M_0^{\mathcal{A}_i}, \mathsf{ran}(g_i^n) \subseteq M_0^{\mathcal{B}_i} \}.$$

Then $J_n \in \mathcal{F}$ for all $n \in \omega$ and for a fixed i the set $\{n : i \in J_n\}$ is finite. Let

$$\nu(i) = \max\{ n \in \omega : i \in J_n \}$$

and put

$$g^+ = \langle g_i^{\nu(i)} : i \in \omega \rangle / \mathcal{F}.$$

Then g^+ is the desired extension. ∎

4.2 Climbing Zilber's ladder

Recall, that $\mathcal{M}$ is a fixed $\aleph_1$-categorical structure with an atom–defining schema ∂ for $\emptyset$-definable infinite relations (see Definition 2.1.3). By Zilber's Ladder Theorem (Theorem 0.1 of Chapter V of [18]) if $\mathcal{M}$ is $\aleph_1$-categorical and $M_0 \subseteq M$ is $\emptyset$-definable and strongly minimal then there exists a finite increasing sequence

$$M_0 \subseteq M_1 \subseteq \ldots \subseteq M_{z-1} = M$$

of subsets of M such that for all $\ell \in z$ we have

1. $M_{\ell+1}$ is $\emptyset$-definable;
2. $\mathsf{Gal}(A, M_\ell)$ is $\emptyset$-definable together with its action on A for all M_ℓ-atom $A \subseteq M_{\ell+1}$. Moreover $\mathsf{Gal}(A, M_\ell) \subseteq \mathsf{dcl}(M_\ell)$.

Here by $\mathsf{Gal}(A, M_\ell)$ we understand the group of all M_ℓ-elementary automorphisms of the set A. We note that $\mathsf{Gal}(A, M_\ell)$ acts transitively on A because A is an atom. We fix this ladder and z will denote its length.

The main proposition in this section is Theorem 4.2.10. In order to prove it we make use of the following Lemmas.

Lemma 4.2.1. *Suppose $\mathcal{M}$ has an atom-defining schema. Then for all infinite, definable E and formula ϕ there exists a* finite *set $T_\phi \subseteq \mathsf{S}^{\mathcal{M}}(\emptyset)$ of types such that if $\phi(v, \bar{e})$ defines an E-atom, then $\mathsf{tp}^{\mathcal{M}}(\bar{e}) \in T_\phi$.*

Informally we will refer to this fact as "the formula φ has finitely many atom-types over E".

Proof. Suppose, seeking a contradiction, that $\{e_i \in \|\partial_E \varphi\| : i \in \omega\}$ is such that

$$H = \{\mathsf{tp}^{\mathcal{M}}(e_i) : i \in \omega\}$$

is infinite. Then $H \subseteq \mathsf{S}^{\mathcal{M}}(\emptyset)$ is an infinite topological subspace of $\mathsf{S}^{\mathcal{M}}(\emptyset)$, hence it has an infinite strongly discrete subspace: there is an injective function $s : \omega \to \omega$ and there are pairwise disjoint basic open sets $U_i \subseteq \mathsf{S}^{\mathcal{M}}(\emptyset)$ such that $\mathsf{tp}^{\mathcal{M}}(e_{s(i)}) \in U_j$ if and only if $i = j$. Thus there are pairwise contradictory formulas $\{\gamma_i : i \in \omega\}$ (γ_i corresponds to U_i) such that $\|\gamma_i\| \subseteq \|\partial_E \varphi\|$ and $\gamma_i \in \mathsf{tp}^{\mathcal{M}}(e_{s(i)})$. Then $\mathsf{CB}(\partial_E \varphi) > 0$ which is a contradiction.

Note, that here the γ_i-s are parameter-free formulas. ∎

Lemma 4.2.2. *M_ℓ-atoms cover $M_{\ell+1} \smallsetminus M_\ell$ for all $\ell \in z$, that is, every element $m \in M_{\ell+1} \smallsetminus M_\ell$ is contained in a (unique) M_ℓ-atom.*

Proof. Since $\mathcal{M}$ is $\aleph_1$-categorical it is prime, hence atomic over M_ℓ. Consequently, only isolated types are realized. Therefore for all $m \in M_{\ell+1}$ the type $\mathsf{tp}^{\mathcal{M}}(m/M_\ell)$ is isolated by some formula φ_m. Clearly φ_m defines an M_ℓ-atom in which m is contained. ∎

Lemma 4.2.3. *Let E be a definable subset of $\mathcal{M}$. Then there exists a finite set Γ of formulas such that any E-atom can be defined by a formula $\psi \in \Gamma$. In more detail, if $\varphi(x, \bar{e})$ defines an E-atom in $\mathcal{M}$, then $\|\varphi(x, \bar{e})\|^{\mathcal{M}} = \|\psi(x, \bar{e}')\|^{\mathcal{M}}$ for some formula $\psi(x, \bar{y}) \in \Gamma$ and parameters $\bar{e}' \in E$.*

Proof. Suppose the contrary. Then for all finite Γ there is an E-atom which cannot be defined by a formula from Γ, in particular, there is an element a_Γ such that whenever $\psi(v, \bar{e})$ defines an E-atom, where $\psi \in \Gamma$ and $\bar{e} \in E$ then $a_\Gamma \notin \|\psi(v, \bar{e})\|^{\mathcal{M}}$.

Since E is definable and $\mathcal{M}$ has an atom defining schema, this fact can be expressed by a first order formula. In fact, the formula

$$\theta_\Gamma(v) = \bigwedge_{\psi \in \Gamma} \forall \bar{e}\big(E(\bar{e}) \wedge \partial_E \psi(\bar{e}) \to \neg\psi(v, \bar{e})\big)$$

is realized by a_Γ.

Therefore the set $H = \{\theta_\Gamma : \Gamma \in [\mathsf{Form}]^{<\omega}\}$ is finitely satisfiable and since $\mathcal{M}$ is $\aleph_1$-categorical it is saturated so H is realized by some $a \in M$. But then a cannot be contained in any atom which contradicts to Lemma 4.2.2. ∎

Lemma 4.2.4. *The action of the group* $\mathsf{Gal}(A, M_\ell)$ *is regular (in other words,* $\mathsf{Gal}(A, M_\ell)$ *is sharply transitive) for each* $\ell \in z$*, that is, if* A *is an* M_ℓ*-atom and* $a, b \in A$ *then there is a unique* $g \in \mathsf{Gal}(A, M_\ell)$ *such that* $g(a) = b$*.*

Proof. The group $G = \mathsf{Gal}(A, M_\ell)$ acts transitively on A because A is an E-atom. Suppose $g(a) = h(a) = b$ for some elements $g, h \in G$. We shall prove $g = h$. Consider the set

$$H = \{x \in A : g^{-1}h(x) = x\}.$$

Then $a \in H$, so $H \neq \emptyset$. But A is an E-atom and H is definable over E. It follows, that $H = A$, whence $g^{-1}h = \mathsf{id}$, consequently $g = h$. ∎

If $A \subseteq M$ is a subset and $\bar{d} \in M \smallsetminus A$ is a *finite* set of parameters then by $\Theta(\bar{d})$ we denote the equivalence relation on A where

$$(a, b) \in \Theta(\bar{d}) \text{ if and only if } \mathsf{tp}^{\mathcal{M}}(a/\bar{d}) = \mathsf{tp}^{\mathcal{M}}(b/\bar{d}).$$

$\Theta(\bar{d})$ is called a *cut* with parameters $\bar{d}$. By a *partition* of $\Theta(\bar{d})$ we understand an equivalence class of it. $\Theta(\bar{d}')$ is defined to be a *refinement* of $\Theta(\bar{d})$ iff each partition of the prior is contained in a partition of the latter; we denote this fact by

$$\Theta(\bar{d}') \leq \Theta(\bar{d}).$$

Clearly, if $\bar{d} \subseteq \bar{d}'$ then $\Theta(\bar{d}')$ is a refinement of $\Theta(\bar{d})$. We say $\Theta(\bar{d})$ is *minimal* if no further refinement can be made by increasing $\bar{d}$, i.e. for all $\bar{d}' \supseteq \bar{d}$ we have $\Theta(\bar{d}') = \Theta(\bar{d})$.

Lemma 4.2.5. *Every M_ℓ-atom has minimal cuts, in more detail, if A is an M_ℓ-atom, then there exists a finite $\bar{d} \in M \setminus A$ such that $\Theta(\bar{d})$ is minimal.*

Proof. Let A be an M_ℓ-atom defined by the formula ψ with parameters $\bar{e} \in M_\ell$. Starting from $\bar{d}_0 = \bar{e}$ we build a chain of refinements

$$\Theta(\bar{d}_0) \gneqq \Theta(\bar{d}_1) \gneqq \ldots \gneqq \Theta(\bar{d}_i) \gneqq \ldots,$$

in such a way that $\bar{d}_i \subsetneq \bar{d}_j$ for all $i \leq j$. For each cut $\Theta(\bar{d})$ define $G(\bar{d})$ to be the subgroup of $\mathsf{Gal}(A, M_\ell)$ containing those permutations of $\mathsf{Gal}(A, M_\ell)$ which preserve each partitions of $\Theta(\bar{d})$.

Auxiliary Claim: For any finite $\bar{d}$ containing $\bar{e}$, partitions of $\Theta(\bar{d})$ and orbits of $G(\bar{d})$ coincide. In other words, the following are equivalent:

(i) $\mathsf{tp}^{\mathcal{M}}(a/\bar{d}) = \mathsf{tp}^{\mathcal{M}}(b/\bar{d})$;

(ii) a and b are in the same orbit according to the action of $G(\bar{d})$.

Proof: Direction (ii)⇒(i) is easy, so we prove (i)⇒(ii). Assume (i) holds. By saturatedness of $\mathcal{M}$ there exists an automorphism $\alpha \in \mathsf{Aut}(\mathcal{M})$ which fixes $\bar{d}$ and maps a onto b. Then $\alpha \restriction A$ is M_ℓ-elementary because of the following. Let $x \in A$ and observe, that $\alpha(A) = A$ because $\bar{e} = \bar{d}_0 \subseteq \bar{d}$ is fixed by α. Therefore, since A is an M_ℓ-atom, $\mathsf{tp}(x/M_\ell) = \mathsf{tp}(\alpha(x)/M_\ell)$. Hence $\alpha \restriction A \in G(\bar{d})$. ∎

We recall that by Theorem 7.1.2 of [6] any descending chain of definable subgroups of an $\aleph_0$-stable group is of finite length. We claim that $G(\bar{d})$ is a definable subgroup of $\mathsf{Gal}(A, M_\ell)$ (which is $\aleph_0$-stable since it is definable in $\mathcal{M}$). For a formula ψ let $C_\psi(\bar{d})$ be the subgroup defined as

$$C_\psi(\bar{d}) = \{g \in \mathsf{Gal}(A, M_\ell) : \forall a \in A\ (\mathcal{M} \vDash \psi(a, \bar{d}) \longleftrightarrow \psi(g(a), \bar{d}))\}.$$

Then

$$G(\bar{d}) = \bigcap_\psi C_\psi(\bar{d}).$$

This intersection gives rise to a chain of definable subgroups which must stop after finitely many steps. Consequently, $G(\bar{d})$ can be defined using those finitely many formulas appeared in the chain.

It is easy to see that if $\Theta(\bar{d}_i) \gneqq \Theta(\bar{d}_j)$ is a proper refinement, then $G(\bar{d}_i) \gneqq G(\bar{d}_j)$, and we just have seen, that each group $G(\bar{d})$ is a definable subgroup of $\mathsf{Gal}(A, M_\ell)$. Thus for our chain of refinements $\Theta(\bar{d}_0) \gneqq \Theta(\bar{d}_1) \gneqq \ldots$ there exist a corresponding (proper) descending chain of subgroups

$$\mathsf{Gal}(A, M_\ell) = G(\bar{d}_0) \gneqq G(\bar{d}_1) \gneqq \ldots \gneqq G(\bar{d}_i) \gneqq \ldots.$$

Again, by Theorem 7.1.2 of [6] any descending chain of definable subgroups of an $\aleph_0$-stable group is of finite length, hence, our chain of cuts above stops in finitely many steps. The last member of the chain is minimal. ∎

Lemma 4.2.6. *Let A be an M_ℓ-atom and let $\Theta(\bar{d})$ be a minimal cut with the corresponding subgroup $G = G(\bar{d})$. Then G has finitely many orbits, or equivalently, the cut is finite: it has finitely many partitions.*

Proof. Since $\bar{d}$ is finite, by $\aleph_0$-stability there are at most $\aleph_0$ many types over $\bar{d}$, hence G has at most $\aleph_0$ many orbits. Suppose, seeking a contradiction, that G has infinitely many orbits, say $\langle O_i : i \in \omega \rangle$. For each i fix $o_i \in O_i$ and let $\varphi_i(v)$ be the formula expressing

$$v \in A \text{ but } v \notin O_i.$$

Then $\{\varphi_n : n \in \omega\}$ is finitely satisfiable, hence by $\aleph_1$-saturatedness of $\mathcal{M}$ it can be realized. But this is a contradiction, therefore G has finitely many orbits. ∎

We introduce the finitary analogue dcl_Γ of dcl, much as we defined acl_Γ. In our investigations below the parameter Γ will be a finite set of formulas – this is the reason why we refer to it as a finitary analogue.

Definition 4.2.7. If $\mathcal{M}$ is a structure $X \subseteq M$ and Γ is a set of formulas then by $\mathsf{dcl}_\Gamma^{\mathcal{M}}(X)$ we understand those points of $\mathsf{dcl}^{\mathcal{M}}(X)$ which are witnessed by a formula in Γ, i.e.

$$\mathsf{dcl}_\Gamma^{\mathcal{M}}(X) = \big\{a \in M : \mathcal{M} \models \exists! v\varphi(v, \bar{x}) \wedge \varphi(a, \bar{x}) \text{ for some } \bar{x} \in X \text{ and } \varphi \in \Gamma\big\}.$$

We stress the difference between the definitions of dcl_Γ and acl_Γ. On the one hand for $a \in \mathsf{dcl}_\Gamma(X)$ we require a unique witness and in acl_Γ only that the set of witnesses be finite. On the other hand $\mathsf{dcl}_\Gamma(X)$ is not necessary closed under Δ-definable formulas. While $\mathsf{acl}_\Gamma(X)$ can be thought as a result of an iteration (see comments after Definition 1.0.4), there is no iteration in the definition of $\mathsf{dcl}_\Gamma(X)$.

Lemma 4.2.8. *Suppose $g = \langle g_n : n \in \omega \rangle/\mathcal{F} : \Pi_{n\in\omega}\mathcal{A}_n/\mathcal{F} \to \Pi_{n\in\omega}\mathcal{B}_n/\mathcal{F}$ is a decomposable elementary mapping. Then there exists a decomposable elementary mapping $g^+ = \langle g_n^+ : n \in \omega \rangle$ extending g such that $\mathsf{dom}(g^+) \supseteq \mathsf{dcl}(\mathsf{dom}(g))$.*

We note, that $\mathsf{dcl}(\mathsf{dom}(g))$ is not necessarily decomposable.

Proof. Our plan is to find two covering sequences Γ_n and Φ_n of formulas in such a manner that we can extend g_n to g_n^+ defined on $\mathsf{dcl}_{\Gamma_n}(\mathsf{dom}(g_n))$ so that this extension is

Φ_n-elementary. Then because

$$\Pi_{n\in\omega}\mathsf{dcl}_{\Gamma_n}\mathsf{dom}(g_n)/\mathcal{F} \;\supseteq\; \mathsf{dcl}(\mathsf{dom}(g)),$$

we get the desired decomposable elementary mapping extending g by setting

$$g^+ = \langle g_n^+ : n \in \omega\rangle/\mathcal{F}.$$

Let $\rho(x_0, \ldots, x_n)$ be any formula and let Φ be a finite set of formulas. We write

$$\rho^\Phi = \big\{\forall x_0 \ldots \forall x_n(\varphi_0(x_0, \bar{y}_0) \wedge \ldots \wedge \varphi_n(x_n, \bar{y}_n) \to \rho(x_0, \ldots, x_n)) : \varphi_i \in \Phi\big\}.$$

Then ρ^Φ is a finite set.

We define now the sets Γ_n and Φ_n as follows.

$$\begin{aligned}\Gamma_n &= \big\{\varphi(x,\bar{y}) : g_n \text{ preserves } \exists! x\varphi(x,\bar{y})\big\}, \text{ and}\\ \Phi_n &= \big\{\rho : g_n \text{ preserves } \rho^{\Gamma_n}\big\}.\end{aligned}$$

Then it is easy to see that for any formulas φ and ρ we have

$$\{n : \varphi \in \Gamma_n\} \in \mathcal{F} \text{ and } \{n : \rho \in \Phi_n\} \in \mathcal{F}.$$

Now we claim that g_n can be extended to g_n^+, defined on $\mathsf{dcl}_{\Gamma_n}(\mathsf{dom}(g_n))$ in such a way that g_n^+ is Φ_n-elementary. First we give the extension. If $a \in \mathsf{dcl}_{\Gamma_n}(\mathsf{dom}(g_n))$ then there is a formula $\varphi \in \Gamma_n$ witnessing this: there are parameters $\bar{y} \in \mathsf{dom}(g_n)$ such that

$$\mathcal{A}_n \vDash \exists! x\varphi(x,\bar{y}) \wedge \varphi(a,\bar{y}).$$

Since $\varphi \in \Gamma_n$, we have $\mathcal{B}_n \vDash \exists! x \varphi(x, g_n(\bar{y}))$. Let $b_a \in B_n$ be this unique element and put

$$g_n^+ = g_n \cup \big\{ \langle a, b_a \rangle : a \in \mathsf{dcl}_{\Gamma_n}(\mathsf{dom}(g_n)) \big\}.$$

We claim that g_n^+ is Φ_n-elementary: if g_n preserves ρ^{Γ_n} then g_n^+ preserves ρ. For, suppose $\mathcal{A}_n \vDash \rho(\bar{a})$ for $\bar{a} \in \mathsf{dcl}_{\Gamma_n}(\mathsf{dom}(g_n))$. Then there are formulas $\varphi_i \in \Gamma_n$ and parameters $\bar{y}_i \in \mathsf{dom}(g_n)$ such that

$$\mathcal{A}_n \vDash \exists! x_0 \varphi_0(x_0, \bar{y}_0) \wedge \ldots \wedge \exists! x_k \varphi(x_k, \bar{y}_k),$$

hence

$$\mathcal{A}_n \vDash \forall x_0 \ldots \forall x_k \big(\varphi_0(x_0, \bar{y}_0) \wedge \ldots \wedge \varphi_k(x_k, \bar{y}_k) \to \rho(\bar{x}) \big).$$

But this formula is an element if Φ_n, therefore it is preserved by g_n. ∎

Lemma 4.2.9. *Suppose $g = \langle g_n : n \in \omega \rangle / \mathcal{F} : \Pi_{n\in\omega} \mathcal{A}_n / \mathcal{F} \to \Pi_{n\in\omega} \mathcal{B}_n / \mathcal{F}$ is a decomposable elementary mapping with $\mathsf{dom}(g_n) = M_\ell^{\mathcal{A}_n}$ and $\mathsf{ran}(g_n) \subseteq M_\ell^{\mathcal{B}_n}$ for a fixed $0 \leq \ell < z - 1$, where $\mathcal{A}_n$ and $\mathcal{B}_n$ are finite, Δ_n–elementary substructures of $\mathcal{M}$. Then g can be extended to a decomposable elementary mapping $h = \langle h_n : n \in \omega \rangle / \mathcal{F}$ with $\mathsf{dom}(h_n) = M_{\ell+1}^{\mathcal{A}_n}$ and $\mathsf{ran}(h_n) \subseteq M_{\ell+1}^{\mathcal{B}_n}$. Particularly, $|M_{\ell+1}^{\mathcal{A}_n}| \leq M_{\ell+1}^{\mathcal{B}_n}$.*

Similarly as in Propositions 4.1.4 and 4.1.6, we note that if $|M_{\ell+1}^{\mathcal{A}_n}| = |M_{\ell+1}^{\mathcal{B}_n}|$ then $\mathsf{ran}(h_n) = M_{\ell+1}^{\mathcal{B}_n}$.

Proof. Let us denote by $\mathcal{A}$ and $\mathcal{B}$ the structures $\Pi_{n\in\omega} \mathcal{A}_n / \mathcal{F}$ and $\Pi_{n\in\omega} \mathcal{B}_n / \mathcal{F}$, respectively. By a slight abuse of notation (or rather for the sake of keeping superscripts at a bearable level) we will have $\mathcal{A} = \mathcal{M}$ in mind. Since $\mathcal{A} \equiv \mathcal{M}$ everything which was said about $\mathcal{M}$ is true for $\mathcal{A}$. So from now on definable notions like M_ℓ, $\mathsf{Gal}(A, M_\ell)$ and atom are meant to be in $\mathcal{A}$. E.g. from now on $\mathsf{Gal}(A, M_\ell)$ denotes $\mathsf{Gal}^{\mathcal{A}}(A^{\mathcal{A}}, M_\ell^{\mathcal{A}})$, etc. Note that here A is an M_ℓ-atom and *not* the universe of $\mathcal{A}$.

Using Lemma 4.2.8 there is an elementary extension $g^+ = \langle g_n^+ : n \in \omega \rangle$ of g such that $\mathsf{dom}(g^+) \supseteq \mathsf{dcl}(\mathsf{dom}(g))$. Since $\mathsf{Gal}(A, M_\ell) \in \mathsf{dcl}(M_\ell)$ for all atom A, these groups are also contained in $\mathsf{dom}(g^+)$. In order to keep notation simpler, from now on denote g^+ by g.

We show first that there is an isomorphism $f : \mathcal{A} \to \mathcal{B}$ which is an extension of g (but f is not necessarily decomposable). By $\aleph_0$-stability, there are elementary substructures $\mathcal{A}^*$ and $\mathcal{B}^*$ of $\mathcal{A}$ and $\mathcal{B}$, respectively which are constructible over $\mathsf{dom}(g)$ and $\mathsf{ran}(g)$. As $M_\ell^{\mathcal{A}}$ is infinite, definable and contained in $\mathsf{dom}(g)$, by a standard two cardinals theorem (see e.g. Theorem 3.2.9 of [1]) $\mathcal{A}^* = \mathcal{A}$ and similarly, $\mathcal{B}^* = \mathcal{B}$. Since they are constructible, they are atomic over $M_\ell^{\mathcal{A}}$ and hence there is an isomorphism $f : \mathcal{A} \to \mathcal{B}$ extending g.

By Lemma 4.2.2, M_ℓ-atoms cover $M_{\ell+1} \smallsetminus M_\ell$, so fix an enumeration of M_ℓ-atoms $\langle A^\lambda : \lambda < \kappa \rangle$. By Lemma 4.2.5 for all atom A^λ there is a minimal cut Θ^λ and by Lemma 4.2.6 this cut has finitely many partitions, say $\mathsf{n}(\lambda)$ many. For each $\lambda < \kappa$ and $i < \mathsf{n}(\lambda)$ let us adjoin a new relation symbol $R_{\lambda,i}$ to our language and interpret it in $\mathcal{A}$ as the corresponding partition of A_λ. So $R_{\lambda,i}^{\mathcal{M}}$ is the i^{th} partition of the λ^{th} atom. We denote this extended language by L^+ and let us denote the set of new relation symbols by $\mathcal{R}$:

$$\mathcal{R} = \big\{ R_{\lambda,i} : \lambda < \kappa, i < \mathsf{n}(\lambda) \big\}.$$

Each $R \in \mathcal{R}$ is a partition of a minimal cut of an atom, hence R is definable by a formula with parameters. It follows that each $R \in \mathcal{R}$ is decomposable (by Łoś's Lemma) and so it is meaningful to speak about $R^{\mathcal{A}_n}$ for $R \in \mathcal{R}$ and $n \in \omega$.

Define the interpretation of these relations in $\mathcal{B}$ as

$$R_{\lambda,i}^{\mathcal{B}} = f[R_{\lambda,i}^{\mathcal{A}}],$$

for all λ and i. Observe that f is an elementary mapping in the extended language L^+ because it is an isomorphism. In addition, a restriction of an elementary mapping is still elementary, therefore g is also elementary in the language L^+.

For a formula $\varphi(v, \bar{y})$ let

$$\begin{aligned} \varphi' &= \Big\{ \forall v \big(R(v) \to \varphi(v, \bar{y}) \big) : R \in \mathcal{R} \Big\} \text{ and let} \\ \varphi^+ &= \Big\{ \forall \bar{y} \big(\exists x (R(x) \wedge \varphi(x, \bar{y})) \to \forall x (R(x) \to \varphi(x, \bar{y})) \big) : R \in \mathcal{R} \Big\}. \end{aligned}$$

We emphasize, that φ' and φ^+ are possibly infinite sets of formulas. Observe first that $\mathcal{A}, \mathcal{B} \vDash \varphi^+$ for all formula φ and thus by Łoś's Lemma for any $\vartheta \in \varphi^+$ we have

$$\{ n \in \omega : \mathcal{A}_n, \mathcal{B}_n \vDash \vartheta \} \in \mathcal{F}.$$

What is more, we claim that formulas in φ^+ are "simultaneously" decomposable, i.e. we claim that for any formula φ the following hold:

$$\{ n \in \omega : \mathcal{A}_n \vDash \varphi^+ \} \in \mathcal{F}.$$

For if not, for almost all $n \in \omega$ there is some $R_n \in \mathcal{R}$ and $\bar{y}_n$ such that

$$R_n^{\mathcal{A}_n} \cap \|\varphi(v, \bar{y}_n)\|^{\mathcal{A}_n} \neq \emptyset \text{ and } R_n^{\mathcal{A}_n} \smallsetminus \|\varphi(v, \bar{y}_n)\|^{\mathcal{A}_n} \neq \emptyset.$$

According to Lemmas 4.2.3 and 4.2.1, there is a finite set $S \subseteq \mathsf{S}(\mathcal{M})$ of types such that if a sequence $\bar{e}$ defines an atom (say, with a formula $\psi \in \Gamma$, where Γ comes from Lemma 4.2.3), then $\mathsf{tp}(\bar{e}) \in S$. Consequently there is a big set of indices such that R_n-s are partitions of a minimal cut of the same type of atom, and since every minimal cut has finitely many partitions, R_n-s are defined with the same formula ϑ in a big set of indices (of course with potentially different parameters). So for some sequences $\bar{c}_n$ in a big set of indices we have

$$\|\vartheta(v,\bar{c}_n)\|^{\mathcal{A}_n} \cap \|\varphi(v,\bar{y}_n)\|^{\mathcal{A}_n} \neq \emptyset \text{ and } \|\vartheta(v,\bar{c}_n)\|^{\mathcal{A}_n} \smallsetminus \|\varphi(v,\bar{y}_n)\|^{\mathcal{A}_n} \neq \emptyset.$$

Considering the ultraproduct we get

$$\|\vartheta(v,\bar{c})\|^{\mathcal{A}} \cap \|\varphi(v,\bar{y})\|^{\mathcal{A}} \neq \emptyset \text{ and } \|\vartheta(v,\bar{c})\|^{\mathcal{A}} \smallsetminus \|\varphi(v,\bar{y})\|^{\mathcal{A}} \neq \emptyset,$$

which is impossible, because by construction $\|\vartheta(v,\bar{c})\|$ defines a partition of a minimal cut.

Recall that by "g preserves φ" we mean that for all $\bar{d} \in \mathsf{dom}(g)$ the following is true:

$$\text{if } \mathcal{A} \vDash \varphi(\bar{d}) \text{ then } \mathcal{B} \vDash \varphi(g(\bar{d})).$$

Similarly, by "g preserves φ'" we mean that all the formulas in φ' are preserved by g. For $\varphi(v,\bar{y}) \in \mathsf{Form}$ we define $I(\varphi) \in \mathcal{F}$ follows.

$$I(\varphi) = \big\{n \in \omega : g_n \text{ preserves } \{\varphi\} \cup \varphi' \text{ and } \mathcal{A}_n, \mathcal{B}_n \vDash \varphi^+\big\}$$

We claim that $I(\varphi) \in \mathcal{F}$. Similarly as we showed that formulas of φ^+ are simultaneously decomposable, it is also true that

$$(\star) \qquad \{n \in \omega : g_n \text{ preserves } \vartheta \text{ for all } \vartheta \in \varphi'\} \in \mathcal{F}.$$

To see this, suppose, seeking a contradiction, that for almost all n there is $\vartheta_n \in \varphi'$ which is not preserved by g_n. In more detail, this means that g_n doesn't preserve a formula of the form

$$\vartheta_n = \forall v(R_n(v) \to \varphi(v,\bar{y}_n)).$$

In a similar manner as above, by Lemmas 4.2.3 and 4.2.1 there is a big set of indices such that R_n-s are defined with the same parametric formula ϑ. Then considering the ultraproduct we get that f, which is an extension of g, does not preserve the formula

$$\forall v(\vartheta(v) \to \varphi(v, \bar{y})).$$

But this is impossible because f is an isomorphism. So ($\star$) above has been established.

Next we define sets Δ_n of formulas for $n \in \omega$ as follows:

$$\Delta_n = \{\varphi : n \in I(\varphi)\}.$$

Then as we saw $I(\varphi) \in \mathcal{F}$ and for all formula φ we have

$$\{n \in \omega : \varphi \in \Delta_n\} \in \mathcal{F}.$$

We divide the rest of the proof into two steps. In the first step, we extend g so that it will meet every atom in at least one point, then in the second step we continue the extension to the remaining parts of the atoms.

Step 1.

We proceed by transfinite recursion. Let $g_n^0 = g_n$ for all $n \in \omega$. We construct a sequence of mappings $\langle g_n^\lambda : n \in \omega, \lambda \leq \kappa \rangle$ in such a way that the following stipulations hold.

(S1) $g^\lambda = \langle g_n^\lambda : n \in \omega \rangle / \mathcal{F}$ is elementary;

(S2) $g_n^\varepsilon \subseteq g_n^\delta$ for all $\varepsilon \leq \delta \leq \kappa$ and $n \in \omega$;

(S3) $A^\varepsilon \cap \mathsf{dom}(g^\lambda) \neq \emptyset$ for all $\varepsilon < \lambda$;

(S4) g_n^λ is Δ_n-elementary for $\lambda \leq \kappa$ and $n \in \omega$.

Note that (S1) is a consequence of (S4). Suppose that g_n^ε has already been defined for $n \in \omega$ and $\varepsilon < \delta \leq \kappa$.

If δ is limit then, similarly as in the proof of Proposition 4.1.6, we take the coordinate-wise union, i.e. $g_n^\delta = \bigcup_{\varepsilon<\delta} g_n^\varepsilon$ for $n \in \omega$.

Suppose δ is successor, say $\delta = \varepsilon + 1$, and $A^\delta \cap \mathsf{dom}(g^\varepsilon) = \emptyset$. First, observe that A^δ is definable by parameters from M_ℓ and g^ε is elementary, hence $(A^\delta)^{\mathcal{B}} \cap \mathsf{ran}(g^\varepsilon) = \emptyset$ as well. Pick an arbitrary $a \in A^\delta$. There is a unique $R \in \mathcal{R}$ such that $a \in R^{\mathcal{A}}$. Since $R^{\mathcal{A}}$ is non-empty and f is an isomorphism, $R^{\mathcal{B}}$ is also non-empty. So pick any $b \in R^{\mathcal{B}}$. Note that $R^{\mathcal{A}} \subseteq A^\delta$ and hence $\mathcal{A} \vDash \forall v(R(v) \to A^\delta(v))$ (and similarly with $\mathcal{B}$). If

$$\begin{aligned} I_{\notin} &= \{n \in \omega : a_n \notin \mathsf{dom}(g_n^\varepsilon) \text{ and } b_n \notin \mathsf{ran}(g_n^\varepsilon)\}, \\ I_{\mathcal{R}} &= \{n \in \omega : a_n \in R^{\mathcal{A}_n}, b_n \in R^{\mathcal{B}_n} \text{ and } R^{\mathcal{A}_n} \subseteq (A^\delta)^{\mathcal{A}_n}, R^{\mathcal{B}_n} \subseteq (A^\delta)^{\mathcal{B}_n}\} \end{aligned}$$

then clearly $I_{\notin} \cap I_{\mathcal{R}} \in \mathcal{F}$. Set $g^\delta = \langle g_n^\delta : n \in \omega \rangle / \mathcal{F}$ where

$$g_n^\delta = \begin{cases} g_n^\varepsilon \cup \{\langle a_n, b_n \rangle\} & \text{if } n \in I_{\notin} \cap I_{\mathcal{R}} \\ g_n^\varepsilon & \text{otherwise.} \end{cases}$$

We claim that g^δ satisfies properties (S1)–(S4). Here (S2) and (S3) are obvious. Moreover, as we already mentioned, (S1) is a consequence of (S4), therefore it is enough to deal with the latter one.

Let $n \in I_{\notin} \cap I_{\mathcal{R}}$ be arbitrary but fixed, and suppose $\varphi(v, \bar{y}) \in \Delta_n$. We have to prove that g_n^δ preserves φ.

Since $\varphi \in \Delta_n$ we have $n \in I(\varphi)$ hence, g_n preserves φ', in particular, g_n preserves $\forall v(R(v) \to \varphi(v, \bar{y}))$. By construction $\mathcal{A}_n, \mathcal{B}_n \vDash \varphi^+$. Suppose $a_n \in \|\varphi(v, \bar{d})\|^{\mathcal{A}_n}$ for some

$\bar{d} \in \mathsf{dom}(g_n)$. Then because $\mathcal{A}_n \vDash \varphi^+$ and $a_n \in R^{\mathcal{A}_n}$ we get

$$\mathcal{A}_n \vDash \forall v(R(v) \to \varphi(v, \bar{d})).$$

This last formula belongs to φ', hence it is preserved by g_n, therefore

$$\mathcal{B}_n \vDash \forall v(R(v) \to \varphi(v, g_n(\bar{d}))).$$

Since $b_n \in R^{\mathcal{B}_n}$, we get $b_n \in \|\varphi(v, g_n(\bar{d}))\|^{\mathcal{B}_n}$, consequently g_n preserves φ, as desired.

Step 2.

What we get so far from the transfinite recursion is a function g^κ satisfying (S1)–(S4) above. We claim that every atom A_λ is contained in $\mathsf{dcl}(\mathsf{dom}(g^\kappa))$. To prove this let A be an M_ℓ-atom and let $a \in A \cap \mathsf{dom}(g^\kappa)$. Such an element a exists by (S3). Notice that $\mathsf{Gal}(A, M_\ell) \subseteq \mathsf{dom}(g^\kappa)$. Now, by Lemma 4.2.4 (sharp transitivity of $\mathsf{Gal}(A, M_\ell)$) for any $x \in A$ there is a unique group element $g_x \in \mathsf{Gal}(A, M_\ell)$ with $g_x(a) = x$. Hence every element of the atom A can be defined from $\mathsf{dom}(g^\kappa)$. Applying Lemma 4.2.8 to g^κ one can finish the proof.

For completeness we note, that $\mathsf{dcl}(\mathsf{dom}(g^\kappa)) = M_\ell$ which is definable, hence decomposable, cf. the remark before the proof of Lemma 4.2.8. The last sentence of the statement of Lemma 4.2.9 follows, because h is a decomposable elementary mapping. ∎

Theorem 4.2.10. *Suppose $\mathcal{A}_n$, $\mathcal{B}_n$ are finite Δ_n-elementary substructures of $\mathcal{M}$. Let $g = \langle g_n : n \in \omega \rangle / \mathcal{F} : \Pi_{n\in\omega}\mathcal{A}_n/\mathcal{F} \to \Pi_{n\in\omega}\mathcal{B}_n/\mathcal{F}$ be a decomposable elementary mapping with $\mathsf{dom}(g_n) = M_0^{\mathcal{A}_n}$, $\mathsf{ran}(g_n) \subseteq M_0^{\mathcal{B}_n}$. Then g can be extended to a decomposable elementary embedding.*

We have the usual remark: if we assume $|M_\ell^{\mathcal{A}_n}| = |M_\ell^{\mathcal{B}_n}|$ for all $0 \leq \ell < z-1$ and $n \in \omega$, and $\mathsf{ran}(g_n) = M_0^{\mathcal{B}_n}$, then the resulting extension is a decomposable isomorphism.

Proof. Straightforward iteration of Lemma 4.2.9. ∎

4.3 The general case

We put the result of Sections 4.1 and 4.2 together. Recall, that $\mathcal{M}$ is an $\aleph_1$-categorical structure with an atom–defining schema for $\emptyset$-definable infinite relations, having the extension property. Also, we assume that there is a $\emptyset$-definable strongly minimal subset $M_0 \subseteq M$.

Lemma 4.3.1. *For each $n \in \omega$ let $\mathcal{A}_n$, $\mathcal{B}_n$ be finite, Δ_n-elementary substructures of $\mathcal{M}$. Then for any $k, m \in \omega$ there exists $N \in \omega$ such that $m \leq N$ and whenever $n \geq N$ then there is a Δ_m-elementary mapping $g_n : \mathcal{A}_n \to \mathcal{B}_n$ such that $\mathsf{dom}(g_n) \subseteq M_0^{\mathcal{A}_n}$, $\mathsf{ran}(g_n) \subseteq M_0^{\mathcal{B}_n}$ and $|\mathsf{dom}(g_n)| \geq k$.*

Proof. Let $k, m \in \omega$ be fixed and for each $n \in \omega$ let $\bar{a}_n \in M_0^{\mathcal{A}_n}$ and $\bar{b}_n \in M_0^{\mathcal{B}_n}$ be bases in $\mathcal{A}_n$ and $\mathcal{B}_n$, respectively. We emphasize that acl and algebraic dependence is always computed in the infinite structure $\mathcal{M}$. We distinguish three cases.

Case 1: Suppose $I = \{n \in \omega : |\bar{a}_n| < k\}$ is infinite. Observe that $A_n \cap M_0 = M_0^{\mathcal{A}_n}$ for large enough n, because M_0 is definable by an element of Δ_n. Since $\sup\{|A_n \cap M_0| : n \in \omega\}$ is infinite, it follows, that $\sup\{|\mathsf{acl}(\bar{a}_n) \cap M_0| : n \in \omega\}$ is infinite, as well. Hence, for all $n \in I$ there exists $\gamma(n) \in \omega$ with

$$|\mathsf{acl}_{\Delta_{\gamma(n)}}(\bar{a}_n) \cap M_0| \geq k.$$

Let $N_0 \in I$ and let $N \geq \max\{\gamma(N_0), m\}$ be such that M_0 is definable by a formula in Δ_N

and the existential closure of the type

$$p = \mathsf{tp}_{\Delta_m}\big(\mathsf{acl}_{\Delta_{\gamma(N_0)}}(\bar{a}_{N_0}) \cap M_0\big)$$

is in Δ_N. Now, p can be realized in $\mathcal{A}_n$ and $\mathcal{B}_n$ for any $n \geq N$. A bijection g_n between these realizations is a Δ_m-elementary mapping, so g_n satisfies the conclusion of the lemma.

Case 2: Suppose $I = \{n \in \omega : |\bar{b}_n| < k\}$ is infinite. Swapping $\mathcal{A}_n$ and $\mathcal{B}_n$, one can apply case one above.

Case 3: Suppose, there is an $N_0 \in \omega$ such that $n \geq N_0$ implies $|\bar{a}_n|, |\bar{b}_n| \geq k$. Then choose N so that $N \geq \max\{N_0, m\}$. If $n \geq N$ then let g_n be a bijection mapping the first k elements of $\bar{a}_n$ onto the first k elements of $\bar{b}_n$. Since $\bar{a}_n$ and $\bar{b}_n$ are bases, $g_n : M \to M$ is an elementary mapping, hence $g_n : A_n \to B_n$ is Δ_m-elementary, as desired. ∎

Lemma 4.3.2. *Suppose $\mathcal{A}_n$ and $\mathcal{B}_n$ are finite, Δ_n-elementary substructures of $\mathcal{M}$ such that $|M_0^{\mathcal{A}_n}| = |M_0^{\mathcal{B}_n}|$ for almost all $n \in \omega$. Then $|A_n| = |B_n|$ almost everywhere.*

A converse of this statement is presented in Lemma 4.3.6.

Proof. Suppose, seeking a contradiction, that

$$(*) \qquad I = \{n \in \omega : |A_n| < |B_n|\} \in \mathcal{F}.$$

Let m be arbitrary. Applying Lemma 4.3.1 with $k = \varepsilon(\Delta_n)$ we get a Δ_m-elementary function

$$g_m : M_0^{\mathcal{A}_{n(m)}} \to M_0^{\mathcal{B}_{n(m)}},$$

where $m \leq n(m) \in I$ such that $|\mathsf{dom}(g_m)| \geq \varepsilon(\Delta_m)$. Applying Proposition 4.1.6 to $\mathcal{A}_{n(m)}$ and $\mathcal{B}_{n(m)}$, we obtain a decomposable elementary mapping

$$g^+ = \langle g_m^+ : m \in \omega \rangle / \mathcal{F} : \Pi_{m\in\omega}\mathcal{A}_{n(m)}/\mathcal{F} \to \Pi_{m\in\omega}\mathcal{B}_{n(m)}/\mathcal{F}$$

with $\mathsf{dom}(g_m^+) = M_0^{\mathcal{A}_{n(m)}}$ and $\mathsf{ran}(g_m^+) = M_0^{\mathcal{B}_{n(m)}}$ (here equality holds because we assumed $|M_0^{\mathcal{A}}| = |M_0^{\mathcal{B}}|$). By Theorem 4.2.10, g^+ can be extended to a decomposable elementary embedding

$$g^{++} : \Pi_{m\in\omega}\mathcal{A}_{n(m)}/\mathcal{F} \to \Pi_{m\in\omega}\mathcal{B}_{n(m)}/\mathcal{F}.$$

On the one hand $g^{++}[M_0^{\mathcal{A}}] = M_0^{\mathcal{B}}$, on the other hand, g^{++} is not surjective (this is because g^{++} is decomposable and by the indirect assumption $(*)$). Thus,

$$g^{++}\left[\Pi_{m\in\omega}\mathcal{A}_{n(m)}/\mathcal{F}\right] \quad \text{and} \quad \Pi_{m\in\omega}\mathcal{B}_{n(m)}/\mathcal{F}$$

forms a Vaughtian pair for the $\aleph_1$-categorical theory of $\mathcal{M}$ – which is a contradiction. ∎

Remark 4.3.3. If M_0 is strongly minimal, then, by compactness, for all formula φ there is a natural number $\mathsf{n}(\varphi)$ (not depending on parameters in φ) such that if $M_0 \cap \|\varphi(v,\bar{c})\|$ is infinite then $\left|M_0 \smallsetminus \|\varphi(v,\bar{c})\|\right| \leq \mathsf{n}(\varphi)$. This we used once in the proof of Lemma 4.1.2. Next, we utilize another variant of this idea.

Lemma 4.3.4. *Let $\mathcal{M}$ be $\aleph_1$-categorical and let $M_0 \subseteq M$ be a $\emptyset$-definable, strongly minimal subset. Then for all finite set ε of formulas there exists another finite set δ of formulas such that if $\mathcal{A}$ is a δ-elementary substructure of $\mathcal{M}$ and $\varphi \in \varepsilon$, $\bar{c} \in A$ and $M_0 \cap \|\varphi(v,\bar{c})\|^{\mathcal{M}}$ is finite, then $M_0 \cap \|\varphi(v,\bar{c})\|^{\mathcal{M}} \subseteq M_0^{\mathcal{A}}$.*

Proof. For all $\varphi \in \varepsilon$ let $\varphi_n(\bar{y})$ denote the next formula:

$$\varphi_n(\bar{y}) = \text{“}\varphi(x, \bar{y}) \text{ has exactly } n \text{ realizations”}.$$

For all fixed $n \in \omega$, φ_n can be made a strict first order formula and it is sometimes denoted as $\exists_n x \varphi(x, \bar{y})$. Put

$$\delta = \{\varepsilon\} \cup \{\text{a formula defining } M_0\} \cup \{\varphi_n : n \leq \mathsf{n}(\neg\varphi), \varphi \in \varepsilon\}.$$

A simple argument shows that δ fulfills our purposes. ∎

Lemma 4.3.5. *For a formula φ, let $n(\varphi)$ be as in Remark 4.3.3. For all (large enough) finite set ε of formulas there is another finite set $\delta \supset \varepsilon$ of formulas such that if $\mathcal{A}$ is a δ-elementary substructure of $\mathcal{M}$ with*

$$|M_0^{\mathcal{A}}| > \max\{\mathsf{n}(\varphi) : \varphi \in \delta\}$$

and $\bar{b} \in M_0$ is arbitrary then $A \cup \{\bar{b}\}$ is a universe of an ε-elementary substructure $\mathcal{A}'$ of $\mathcal{M}$ and $\mathcal{A}$ is an ε-elementary substructure of $\mathcal{A}'$.

Proof. For a formula $\varphi(v, \bar{y})$ let $\hat{\varphi}$ be the formula expressing

$$\hat{\varphi}(\bar{y}) = \text{”there are at most } \mathsf{n}(\varphi) \text{ many elements } x \text{ of } M_0 \text{ such that } \neg\varphi(x, \bar{y})\text{”}.$$

Since M_0 is definable and $\mathsf{n}(\varphi)$ is finite, this can be made a first order formula for each φ.

For ε let δ be the smallest set of formulas closed under subformulas and containing the union of ε, $\{\hat{\varphi} : \varphi \in \varepsilon\}$ and the set of formulas δ in Lemma 4.3.4 (corresponding to ε). We prove this choice is suitable. We apply the Łoś-Vaught test. Let $\varphi \in \varepsilon$, $\bar{c} \in A$ and suppose

$\varphi(v, \bar{c})$ is realized by $a \in A'$. If $a \in A$ then there is nothing to prove, so assume $a \notin A$. Then by construction $a \in M_0 \setminus A$.

If $M_0 \cap \|\varphi(v, \bar{c})\|^{\mathcal{M}}$ is finite then by Lemma 4.3.4, $a \in M_0^{\mathcal{A}} \subseteq A$ would follow, which contradicts to $a \in M_0 \setminus A$. So we have $M_0 \cap \|\varphi(v, \bar{c})\|^{\mathcal{M}}$ is infinite. Then, since M_0 is strongly minimal, each but finitely many elements of M_0 realizes $\varphi(v, \bar{c})$. But $|M_0^{\mathcal{A}}| > \mathsf{n}(\varphi)$ is large enough, consequently there is an $a' \in A$ realizing $\varphi(v, \bar{c})$. This proves that $\mathcal{A}$ is a φ-elementary substructure of $\mathcal{A}'$.

Next, we prove that $\mathcal{A}'$ is an ε-elementary substructure of $\mathcal{M}$. Let $\varphi \in \varepsilon$, $\bar{c} \in A'$ and assume $\mathcal{M} \vDash \varphi(\bar{c})$. We proceed by induction on $|\bar{c} \setminus A|$.

If $|\bar{c} \setminus A| = 0$ then $\bar{c} \in A$ and since $\mathcal{A}$ is a δ-elementary substructure, it follows that $\mathcal{A} \vDash \varphi(\bar{c})$. We have already proved that $\mathcal{A}$ is an ε-elementary substructure of $\mathcal{A}'$, hence $\mathcal{A}' \vDash \varphi(\bar{c})$.

If $|\bar{c} \setminus A| > 0$ then $\bar{c} = d^\frown \bar{c}_0$ for some $d \in \bar{c} \setminus A$, $d \in \bar{b} \subseteq M_0$. By Lemma 4.3.4 we get

$$\mathcal{M} \vDash \hat{\varphi}(\bar{c}_0).$$

Because $\mathcal{A}$ is δ-elementary it follows that

$$\mathcal{A} \vDash \hat{\varphi}(\bar{c}_0),$$

and by the inductive hypothesis ($|\bar{c}_0| < |\bar{c}|$) we get

$$\mathcal{A}' \vDash \hat{\varphi}(\bar{c}_0).$$

By Lemma 4.3.4, if $x \in M_0$ is such that $\mathcal{M} \vDash \neg\varphi(x, c_0)$, then $x \in A \cap A'$. Therefore $\mathcal{A}' \vDash \varphi(d, c_0)$, as desired.

∎

Lemma 4.3.6. *Suppose for each $n \in \omega$ the finite $\mathcal{A}_n$ and $\mathcal{B}_n$ are equinumerous, Δ_n-elementary substructures of $\mathcal{M}$. Then for all but finitely many $n \in \omega$ we have*

$$|M_0^{\mathcal{A}_n}| = |M_0^{\mathcal{B}_n}|.$$

Proof. Let δ_n be the finite set of formulas guaranteed by Lemma 4.3.5 for $\varepsilon_n = \Delta_n$. Since the sequence Δ_n is monotone increasing, we may assume, by a possible re-scaling of this sequence, that $\mathcal{A}_n$ and $\mathcal{B}_n$ are also δ_n-elementary substructures of $\mathcal{M}$.

We may suppose, towards a contradiction, that $|M_0^{\mathcal{A}_n}| < |M_0^{\mathcal{B}_n}|$ for all n. For each n choose $\bar{b}_n \in M_0$ such that

$$|M_0^{\mathcal{A}_n} \cup \{\bar{b}_n\}| = |M_0^{\mathcal{B}_n}|.$$

Let $\mathcal{A}'_n$ be the substructure in Lemma 4.3.5 whose underlying set is $M_0^{\mathcal{A}_n} \cup \{\bar{b}_n\}$. Then $\mathcal{A}_n$ is a Δ_n-elementary substructure of $\mathcal{A}'_n$, hence $\mathcal{A}'_n$ is a Δ_n-elementary substructure of $\mathcal{M}$. Further, $|M_0^{\mathcal{A}'_n}| = |M_0^{\mathcal{B}_n}|$ and $|A'_n| > |B_n|$. But this contradicts Lemma 4.3.2. ∎

Theorem 4.3.7. *Let $\mathcal{M}$ be an $\aleph_1$-categorical structure with an atom–defining schema, having the extension property. Suppose that there is a $\emptyset$-definable strongly minimal subset M_0 of M and suppose for each $n \in \omega$ the finite structures $\mathcal{A}_n$ and $\mathcal{B}_n$ are equinumerous, Δ_n-elementary substructures of $\mathcal{M}$. Let $\mathcal{F}$ be a non-principal ultrafilter on ω. Then there is a decomposable isomorphism*

$$f = \langle f_n : \ n \in \omega \rangle / \mathcal{F} : \Pi_{n \in \omega} \mathcal{A}_n / \mathcal{F} \to \Pi_{n \in \omega} \mathcal{B}_n / \mathcal{F}.$$

Proof. By Lemma 4.3.6 we have $|M_0^{\mathcal{A}_n}| = |M_0^{\mathcal{B}_n}|$. Since $\Delta_n \subseteq \Delta_{n+1}$ is an increasing sequence, by Lemma 4.3.1 there is a decomposable elementary mapping

$$g = \langle g_n : \ n \in \omega \rangle / \mathcal{F} : \Pi_{n\in\omega}\mathcal{A}_n/\mathcal{F} \to \Pi_{n\in\omega}\mathcal{B}_n/\mathcal{F},$$

such that (after a suitable rescaling) the following stipulations hold for almost all $n \in \omega$:

- $\mathsf{dom}(g_n) \subseteq M_0^{\mathcal{A}_n}$ and $\mathsf{ran}(g_n) \subseteq M_0^{\mathcal{B}_n}$,
- g_n is Δ_n-elementary,
- $|\mathsf{dom}(g_n)| \geq \varepsilon(\Delta_n)$.

This function may be constructed similarly as in the proof of Lemma 4.3.2. Then Proposition 4.1.6 applies: g can be extended to a decomposable elementary mapping $g^+ = \langle g_n^+ : n \in \omega \rangle / \mathcal{F}$ such that $\mathsf{dom}(g_n^+) = M_0^{\mathcal{A}_n}$ and $\mathsf{ran}(g_n^+) = M_0^{\mathcal{B}_n}$.

Finally, applying Theorem 4.2.10, one can obtain the desired decomposable isomorphism. ∎

We close this section with the following observation. The extension property is only needed in order to be able to take the first step of the extension, namely to extend $\emptyset$ to the trace of M_0 in the A_i-s. Without the extension property one can prove the following theorem.

Theorem 4.3.8. *Let $\mathcal{M}$ be an $\aleph_1$-categorical structure with an atom–defining schema. Suppose that there is a $\emptyset$-definable strongly minimal subset M_0 of M and suppose for each $n \in \omega$ the finite structures $\mathcal{A}_n$ and $\mathcal{B}_n$ are equinumerous, Δ_n–elementary substructures of $\mathcal{M}$ such that*

$$\mathsf{tp}^{\mathcal{M}}(M_0 \cap A_n/\emptyset) = \mathsf{tp}^{\mathcal{M}}(M_0 \cap B_n/\emptyset)$$

hold for almost all $n \in \omega$. Then there is a decomposable isomorphism

$$f = \langle f_n : \ n \in \omega \rangle / \mathcal{F} : \Pi_{n \in \omega} \mathcal{A}_n / \mathcal{F} \to \Pi_{n \in \omega} \mathcal{B}_n / \mathcal{F}.$$

Proof. Observe first, that by assumption there is an elementary bijection $f_n : M_0^{\mathcal{A}_n} \to M_0^{\mathcal{B}_n}$. Combining Lemma 4.3.2 and Theorem 4.2.10 one can complete the proof. ∎

5 Categoricity in finite cardinals

In this section we show that finite fragments of certain $\aleph_1$-categorical theories T are also categorical in the following sense: for all finite subsets Σ of T there exists a finite extension Σ' of Σ, such that up to isomorphism, Σ' can have at most one n-element model Σ'-elementarily embeddable into models of T, for all $n \in \omega$. For details, see Theorem 5.0.10, which is the main theorem of the thesis.

We start by two theorems stating that (under some additional technical conditions) an $\aleph_1$-categorical structure can be uniquely decomposed to ultraproducts of its finite substructures.

Theorem 5.0.9 (Second Unique Factorization Theorem)**.** *Let $\mathcal{M}$ be an $\aleph_1$-categorical structure satisfying the extension–property and having an atom-defining schema. Suppose $\mathcal{A}_n$, $\mathcal{B}_n$ are equinumerous finite, Δ_n-elementary substructures of $\mathcal{M}$. Then the set*

$$\{n \in \omega : \mathcal{A}_n \cong \mathcal{B}_n\} \text{ is cofinite.}$$

Proof. Clearly it is enough to prove that $\{n \in \omega : \mathcal{A}_n \cong \mathcal{B}_n\} \in \mathcal{F}$ for all non-principal ultrafilter $\mathcal{F}$.

We would like to apply Theorem 4.3.7. Recall that by Lemma 6.1.13 of [6] there is a strongly minimal subset $M_0 \subseteq M$ which is definable in $\mathcal{M}$ with parameters $\bar{c} \in M$. Consider the structure $\mathcal{M}' = \langle \mathcal{M}, \bar{c} \rangle$. Then there is a $\emptyset$-definable strongly minimal subset of

$\mathcal{M}'$. Furthermore, $\mathcal{M}'$ inherits the extension property and the atom-defining schema from $\mathcal{M}$. Particularly, in $\mathcal{M}'$ every $\emptyset$-definable infinite relation has an atom-defining schema. Also, the appropriate extensions of $\mathcal{A}_n$ and $\mathcal{B}_n$ are Δ_n-elementary substructures of $\mathcal{M}'$, as well (possibly, after a rescaleing of the sequence Δ_n).

It follows that all the conditions of Theorem 4.3.7 are satisfied in $\mathcal{M}'$, whence there is a decomposable isomorphism

$$f = \langle f_n : \ n \in \omega \rangle / \mathcal{F} : \Pi_{n \in \omega} \mathcal{A}_n / \mathcal{F} \to \Pi_{n \in \omega} \mathcal{B}_n / \mathcal{F}.$$

Then the statement follows from Łoś's Lemma applied to the structure $\langle \mathcal{A}^*, \mathcal{B}^*, f \rangle$. ∎

Theorem 5.0.10 (Finite Morley Theorem)**.** *Let $\mathcal{M}$ be an $\aleph_1$-categorical structure satisfying the extension property and having an atom-defining schema. Then there exists $N \in \omega$ such that for any $n \geq N$ and $k \in \omega$ (counting up to isomorphisms) $\mathcal{M}$ has at most one Δ_n-elementary substructure of size k.*

Proof. By way of contradiction, suppose for all $N \in \omega$ there exist $l \geq N$, $k \in \omega$ and (at least) two non-isomorphic finite models $\mathcal{A}_N, \mathcal{B}_N$ of cardinality k which are Δ_l-elementary substructures of $\mathcal{M}$. Then Theorem 5.0.9 implies that $\{n \in \omega : \mathcal{A}_n \cong \mathcal{B}_n\}$ is infinite, which contradicts to the choices of $\mathcal{A}_N, \mathcal{B}_N$. ∎

Finally, we present a theorem, in which we do not assume the extension–property and still obtain uniqueness of Δ-elementary substructures having a fixed finite cardinality. This result may be a basis for further investigations, when instead of proving their uniqueness, one would like to estimate the number of pairwise non-isomorphic Δ-elementary substructures of $\mathcal{M}$ having a given finite cardinality. In this respect, we refer to Problem 5.0.16 below.

Theorem 5.0.11. *Let $\mathcal{M}$ be an $\aleph_1$-categorical structure with an atom-defining schema. Let M_0 be a strongly minimal subset of $\mathcal{M}$ definable by parameters. Then there exists $N \in \omega$ such that for any $n \geq N$ and $k \in \omega$, if $\mathcal{A}$ and $\mathcal{B}$ are Δ_n-elementary substructures of $\mathcal{M}$ of cardinality k, and $\mathsf{tp}(M_0 \cap A/\emptyset) = \mathsf{tp}(M_0 \cap B/\emptyset)$ then $\mathcal{A}$ and $\mathcal{B}$ are isomorphic.*

Proof. Similarly to Theorem 5.0.9, assume M_0 is definable by parameters $\bar{c}$. Adjoining $\bar{c}$ to the language, it still has an atom defining schema. Then the proof can be completed similarly to the proof of Theorem 5.0.10: assume, seeking a contradiction, that for all $N \in \omega$ there exists $n > N$ and non-isomorphic, equinumerous Δ_n-elementary substructures $\mathcal{A}_n$ and $\mathcal{B}_n$ of $\mathcal{M}$ with

$$\mathsf{tp}(M_0 \cap A_n/\emptyset) = \mathsf{tp}(M_0 \cap B_n/\emptyset)$$

and apply Theorem 4.3.8. ∎

We finish this work by offering some interesting open problems.

Open Problems

Conjecture 5.0.12. If the language L contains only unary or binary relation symbols, T is an L-theory and $\mathsf{S}_2(T)$ (the two dimensional Stone space of T) is finite, then T has the extension property.

We have an idea to prove this conjecture but it seems that providing a proof needs a certain amount of further work. Hence we defer examining the details.

The most ambitious question is:

Open problem 5.0.13. Give a full classification of (strongly) $<\omega$-categorical structures.

Some other ones related to our techniques:

Open problem 5.0.14. Does the conditions of Lemma 2.2.5 imply the extension property?

Open problem 5.0.15. We assumed that the Cantor-Bendixson rank of each $\partial\varphi$ in an atom-defining schema is zero. Can Theorem 5.0.10 be proved without this assumption, or from the weaker assumption that this rank is finite?

Let k be a natural number. As we mentioned before Theorem 5.0.11, instead of proving uniqueness of k-sized Δ-elementary substructures of an $\aleph_1$-categorical structure, one can try to estimate the number of pairwise non isomorphic such structures, or one can try to describe all of them. To be more specific, in this direction we offer the following problem.

Open problem 5.0.16. Let $\mathcal{M}$ be an $\aleph_1$-categorical structure with an atom-defining schema. Continuing investigations initiated in Theorem 5.0.11, characterize (or give upper estimates for the number of) equinumerous Δ_n-elementary, pairwise non-isomorphic finite substructures of $\mathcal{M}$, by using their trace on a strongly minimal subset. Perhaps, such a characterization or estimate may be obtained in terms of pre-geometries induced by the algebraic closure operation.

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