

Model Theory II

Winter Semester 2024

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November 30, 2024

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1 Why Model Theory II?

A major theme of model theory is that certain combinatorial properties of definable sets in a first order theory yield a lot of structural information about it. They can imply that a theory has a good notion of independence, or dimension, like in vector spaces, or help us understand the behaviour of groups or geometries interpretable in it. Sometimes, these properties can determine important algebraic features. This course will focus mainly on some of the strongest model theoretic properties: stability, and its strengthenings ω -stability and superstability.

Modern model theory begins with the work of Morley [14], and subsequently Shelah [17] on the spectrum problem: what are the possible behaviours of the function $I(\aleph_\alpha, T)$, counting the number of non-isomorphic models of T of cardinality \aleph_α ? Morley showed that, for countable T , if $I(\aleph_\alpha, T) = 1$ for some uncountable cardinal, then this is the case for all uncountable cardinals. Shelah studied for which theories we can define a system of

invariants under which sufficiently large models of T can be classified. In this process he defined various properties that shaped the development of model theory. Two of the major results of [17] are that $I(\aleph_\alpha, T)$ is non-decreasing for uncountable cardinals and the Main Gap Theorem: for $\alpha > 0$, either T has the maximum number of models in each uncountable cardinality, $I(\aleph_\alpha, T) = 2^{\aleph_\alpha}$, or it satisfies few model theoretic properties, including super-stability, and it is bounded above by $\beth_{\omega_1}(|\alpha|)$.

Over the years, a very sophisticated theory of stability [16] was developed, with fruitful generalisations to NIP [18], simple [9], and NSOP₁ theories [7]. A map of the universe with more model theoretic properties and many examples is given on the website forkinganddividing.com. Model theory has fruitful applications and interactions in algebraic geometry [3], differential algebra [13], group theory [5, 1], number theory [11], and combinatorics [12]. Some classical notions from model theory have been independently discovered many times, such as VC-dimension in probability and combinatorics [10], and PAC learning and Littlestone dimension in machine learning [6]. My own research at TU Wien focuses on the computational complexity of problems in model theoretic structures [2], and on interactions between model theory and probability [4]. Overall, model theory is a highly versatile subject with many beautiful results, some of which we will cover in this course. I hope you will enjoy it!

2 The monster model

This first lecture will require some additional knowledge of set theory and cardinal arithmetics. If you are not familiar with set theory, Appendix A in [19] should contain most relevant facts. One of the advantages of the construction of the monster model in this lecture is preventing us from keeping track of issues of cardinal arithmetics later in the course.

Almost every article or book in model theory begins with the convention that we are working in a monster model \mathcal{M} . These are very large models of T distinguished by being highly saturated, strongly homogeneous, and universal in the following sense:

Definition 2.1. Let κ be an infinite cardinal. We say that $\mathcal{M} \models T$ is:

- **κ -saturated** if it realises types (in finitely many variables) over sets of parameters of cardinality $< \kappa$;
- **κ -universal** if every model of T of cardinality $< \kappa$ elementarily embeds into \mathcal{M} ;
- **κ -homogeneous** if for all $A \subseteq M$ of size $< \kappa$ and $a \in M$, every elementary map $f : A \rightarrow \mathcal{M}$ can be extended to an elementary map $A \cup \{a\} \rightarrow M$;
- **strongly κ -homogeneous** if for all $A \subseteq M$ of size $< \kappa$, any elementary map $f : A \rightarrow M$ can be extended to an automorphism of \mathcal{M} .

We say that \mathcal{M} is **saturated** if it is $|M|$ -saturated.

Remark 2.2. Recall that \mathcal{M} is κ -saturated if and only if it is κ -saturated over 1-types, i.e. if it realises 1-types over sets of parameters of cardinality $< \kappa$;

In the following exercises we work with $|\mathcal{L}| \leq \kappa$:

Exercise 2.3. Prove that if \mathcal{M} is κ -saturated then it is κ -homogeneous.

Exercise 2.4. Show that if \mathcal{M} is κ -saturated, then it is κ^+ -universal.

Exercise 2.5. (a) Show that if \mathcal{M} is $|M|$ -homogeneous, then it is strongly $|M|$ -homogeneous. (b) For each cardinal κ , give an example of a κ -saturated structure \mathcal{M} which is not strongly ω -homogeneous.

Exercise 2.6. Show that \mathcal{M} is κ -saturated if and only if it is κ -homogeneous and κ^+ -universal.

Ideally, we would like to work with a large saturated model since these models are universal, homogeneous and strongly homogeneous. We will see that for this we will need additional set theoretic assumptions.

Remark 2.7. Let (X, \leq) be a linear order. We say that $Y \subseteq X$ is **cofinal** with X if for each $x \in X$ there is some $y \in Y$ with $x \leq y$. The **cofinality** of X , $\text{cf}(X)$ is the smallest cardinality of a cofinal subset of X . We say that an infinite cardinal is **regular** if $\text{cf}(\kappa) = \kappa$. Any successor cardinal κ^+ is a regular cardinal, and so is ω .

Theorem 2.8. Let $|\mathcal{L}| \leq \kappa$ and \mathcal{M} be a model of cardinality $\leq 2^\kappa$. Then, \mathcal{M} has an elementary extension \mathcal{N} which is κ^+ -saturated and of size $\leq 2^\kappa$.

Proof. We build an elementary chain $(\mathcal{M}_\lambda)_{\lambda < \kappa^+}$ such that

- $|\mathcal{M}_\lambda| \leq 2^\kappa$ for each $\lambda < \kappa$;
- \mathcal{M}_{λ^+} realises all types over subsets of \mathcal{M}_λ of cardinality $\leq \kappa$;

Firstly, we show such chain exists and then we will show that its union, \mathcal{N} satisfies the requirements of the theorem. We show how to perform the successor step. Since by inductive hypothesis $|\mathcal{M}_\lambda| \leq 2^\kappa$, \mathcal{M}_λ has 2^κ subsets of size $\leq \kappa$. Since $|\mathcal{L}| \leq \kappa$, over each $B \subseteq \mathcal{M}_\lambda$ with $|B| \leq \kappa$, there are at most 2^κ -many 1-types. In particular, there are at most 2^κ -many 1-types over sets of size $\leq \kappa$. All of these can be realised in a model \mathcal{M}_{λ^+} of cardinality $\leq 2^\kappa$.

We show that $\mathcal{N} := \bigcup_{\lambda < \kappa^+} \mathcal{M}_\lambda$ is κ^+ -saturated and of size $\leq 2^\kappa$. For κ^+ -saturation, consider $B \subseteq \mathcal{N}$ of size $< \kappa^+$. Since κ^+ is regular there must be some $\lambda \leq \kappa^+$ such that $B \subseteq \mathcal{M}_\lambda$ (otherwise, there would be a cofinal subset with κ^+ of cardinality $\leq |B| < \kappa^+$). Hence, all 1-types over B are realised in \mathcal{M}_{λ^+} . Finally, for the cardinality,

$$|\mathcal{N}| \leq \bigcup_{\lambda < \kappa^+} 2^\kappa \leq 2^\kappa,$$

where the last inequality holds since we are taking a union of sets of size $\leq \alpha$ over ordinals $< \alpha$, where α is an infinite cardinal. \square

Definition 2.9. Let κ be an infinite cardinal. A cardinal α is called a **strong limit cardinal** if for all cardinals $\beta < \alpha$, we have $2^\beta < \alpha$. A regular strong limit cardinal is called a **strongly inaccessible cardinal**.

Remark 2.10. It is easy to construct strong limit cardinals within ZFC. Moreover, the **global continuum hypothesis**, (GCH) implies that every limit cardinal is a strong limit cardinal. However, ZFC is consistent with there being no strongly inaccessible cardinals apart from ω .

Corollary 2.11. Let $|\mathcal{L}| \leq \kappa$ and T be an \mathcal{L} -theory (with infinite models).

- (a) Assuming (GCH), T has a saturated model in each regular cardinal $\nu > \kappa$;
- (b) T has a saturated model in each strongly inaccessible cardinal $\nu > \kappa$.

Proof. (Omitted from lecture) The ideas are essentially the same of the previous proof. (a) If ν is a successor cardinal the argument is immediate. For a limit cardinal, one can use an analogue of the argument below. (b) Starting from a model \mathcal{M}_0 of cardinality κ , using Theorem 2.8, we build an elementary chain $(\mathcal{M}_\lambda)_{\lambda < \nu}$, where \mathcal{M}_{λ^+} is λ^+ -saturated and of cardinality $\leq 2^\lambda$, and take \mathcal{N} to be the union of this chain. Since ν is a strong limit cardinal,

$$|\mathcal{N}| \leq \bigcup_{\lambda < \nu} 2^\lambda \leq \nu.$$

Note that a β -saturated model must be of cardinality $\geq \beta$. Hence, $|\mathcal{N}| \geq \lambda^+$ for each $\lambda < \nu$, meaning that $|\mathcal{N}| = \nu$. Finally, we need to show saturation. Take $A \subseteq \mathcal{N}$ of cardinality $< \nu$. Since ν is regular, a set of cardinality $|A|$ cannot be cofinal with it, meaning that there is some $|A| \leq \lambda < \nu$ such that \mathcal{M}_λ entirely contains A . Since \mathcal{M}_λ is λ^+ saturated, it realised all types over A , and so does \mathcal{N} . \square

Example 2.12. • $(\mathbb{C}; 0, 1; +, \cdot)$ is a saturated model of the theory of algebraically closed fields;

- In general, one can prove that stable theories have saturated models of arbitrarily large cardinalities;
- If the continuum hypothesis is false, the theory of $(\mathbb{N}; 0, 1; +, \cdot)$ has no saturated models of cardinality κ for each $\aleph_0 < \kappa < 2^{\aleph_0}$.

Convention 2.13. From now on we will work with a **monster model** \mathbb{M} . which is κ -saturated, κ -universal and strongly κ -homogeneous for κ a cardinal larger than all of the cardinalities of models and sets of parameters that we want to consider. Thus, all models $\mathcal{M}, \mathcal{N}, \dots$ we will consider will be elementarily embedded into this monster model, all sets of parameters A, B, \dots will be subsets of the monster model of cardinality $< \kappa$, and a set of formulas will be consistent if it is realised in \mathbb{M} . Finally, for a formula ϕ or a type p , we write $\models \phi$ (or $\models p$) if $\mathbb{M} \models \phi$ (respectively, $\mathbb{M} \models p$).

Remark 2.14. There are several ways to achieve the above:

- Assume that strongly inaccessible cardinals exist and work in a sufficiently large one. *We will adopt this approach* since it allows us to move quickly to do more model theory;
- Work in BGC (Bernays-Gödel+Global Choice) set theory. This is a conservative extension of ZFC which allows working with classes. In this framework we can build the monster model as a class-size union of chains.
- Work with a special model (see Definition 2.16) of cardinality $\nu = \beth_\kappa(\aleph_0)$. This will be ν^+ -universal and strongly κ -homogeneous (add so κ -saturated by Exercise 2.6). This framework has the advantage of allowing us to work entirely within ZFC. If you are not comfortable with strongly inaccessible cardinals, you are welcome to read Subsection 2.1 and work with a large enough special model instead.

Lemma 2.15. *Let X be a definable subset of \mathbb{M} and A a set of parameters (i.e. a set of size $< \kappa$ inside of \mathbb{M}). Then, the following are equivalent:*

- (a) X is definable over A ;
- (b) X is $\text{Aut}(\mathbb{M}/A)$ -invariant (i.e. invariant under automorphisms of \mathbb{M} fixing A pointwise).

Proof. (\Rightarrow) This direction works in every model \mathcal{M} . Suppose that $X := \phi(\mathcal{M}, b)$ for some $b \in A$. Then, for every $a \in \mathcal{M}$ and $\sigma \in \text{Aut}(\mathcal{M}/A)$, we have that

$$a \in X \Leftrightarrow \models \phi(a, b) \Leftrightarrow \models \phi(\sigma(a), \sigma(b)) \Leftrightarrow \models \phi(\sigma(a), b) \Leftrightarrow \sigma(a) \in X,$$

where the second last equivalence holds since $b \in A$ and σ fixes A pointwise.

(\Leftarrow) Let $X = \phi(\mathbb{M}, b)$ and let $p(y) := \text{tp}(b/A)$.

Claim 1: $p(y) \vdash \forall x(\phi(x, y) \leftrightarrow \phi(x, b))$.

Proof of Claim. Take $b' \vdash p(y)$. By strong homogeneity there is some $\sigma \in \text{Aut}(\mathbb{M}/A)$ with $\sigma(b) = b'$. By assumption, $X = \sigma(X) = \phi(\mathbb{M}, b')$, yielding the desired formula is implied by $p(y)$. \square

By compactness, there is some $\psi(y) \in p(y)$ such that

$$\psi(y) \models \forall x(\phi(x, y) \leftrightarrow \phi(x, b)) \tag{1}$$

Take $\theta(x) := \exists y(\psi(y) \wedge \phi(x, y))$. This is an \mathcal{L}_A -formula. We claim $X = \theta(\mathbb{M})$. For (\subseteq) take $a \in X$. So $\vdash \phi(a, b)$. Since $\psi(y) \in \text{tp}(b/A)$, $\models \theta(a)$. For (\supseteq) , if $\models \theta(a)$ there is some b' such that $\models \psi(b') \wedge \phi(a, b')$. By $\models \psi(b')$ (1), we have $\models \phi(a, b)$, as desired. \square

2.1 Aside: special models

An issue with our definition of monster model being a saturated model of size a strongly inaccessible cardinal is that it makes it less transparent that our results are provable in ZFC. A more cautious reader might want to work with special models. An even more set theoretically oriented reader, might be interested in the approach of [8], which partially justifies the standard model theoretic practice of assuming we are working with a saturated model of large enough cardinality.

Definition 2.16. An infinite structure \mathcal{M} of cardinality κ is **special** if it is the union of an elementary chain $(\mathcal{M}_\lambda)_{\lambda < \kappa}$, where the λ are cardinals of size $< \kappa$ and each \mathcal{M}_λ is κ^+ -saturated.

★★ **Exercise 2.17.** Let $|\mathcal{L}| \leq \kappa$. Show that the following hold:

- (a) If \mathcal{M} is saturated then it is special;
- (b) A special structure of regular cardinality is saturated;
- (c) Suppose that $\lambda < \nu$ implies $2^\lambda \leq \nu$. Then, T has a special model of cardinality ν ;
- (d) A special structure of cardinality κ is κ^+ -universal and strongly $\text{cf}(\kappa)$ -homogeneous.

Definition 2.18. For every cardinal μ , the **beth function** is defined as

$$\beth_\alpha(\mu) = \begin{cases} \mu & \text{if } \alpha = 0, \\ 2^{\beth_\beta(\mu)}, & \text{if } \alpha = \beta + 1, \\ \sup_{\beta < \alpha} \beth_\beta(\mu) & \text{if } \alpha \text{ is a limit ordinal.} \end{cases}$$

Remark 2.19. We have that $\text{cf}(\beth_\kappa(\aleph_0)) = \kappa$, meaning that a special model of cardinality $\nu = \beth_\kappa(\aleph_0)$ is strongly κ -homogeneous, ν^+ -universal, and κ -saturated. There is no harm in working with a special model of such cardinality as the monster model (except from having to prove exercise 2.17).

3 Strong minimality and algebraicity

From now on it will be important to keep in mind the conventions that we set in the previous lecture (Convention 2.13). In particular, models are always taken to be elementary substructures of the monster model \mathbb{M} and parameter sets A, B, \dots are always taken to be small enough and live in the monster model (which is why I don't specify every time where they come from).

Definition 3.1. We say that a formula $\phi(x) \in \mathcal{L}(A)$ is **algebraic** (over A) if $\phi(\mathbb{M})$ is finite. $a \in \mathbb{M}$ is **algebraic** over A if it realises an algebraic formula over A .

We denote by $\text{acl}(A)$ the set of elements algebraic over A . For π a partial type over A (closed under conjunctions), we say that it is **algebraic** if it contains an algebraic formula.

👁 *Observation 3.2.* Note if a formula $\phi(x) \in \mathcal{L}(A)$ is **algebraic**, then it has the same set of realisations in every model containing A .

Exercise 3.3. Prove Neumann's Lemma: Let $A, B \subseteq \mathbb{M}$ and (c_1, \dots, c_n) a sequence of elements not algebraic over A . Show that $\text{tp}(c_1, \dots, c_n / A)$ has a realisation which is disjoint from B .

Exercise 3.4. Show that $\text{acl}(A)$ is the intersection of all models containing A .

Definition 3.5. Let \mathcal{M} be a model. Let $\phi(x) \in \mathcal{L}(M)$ be a non-algebraic formula. We say that ϕ is **minimal** in \mathcal{M} if for all $\mathcal{L}(M)$ -formulas $\psi(x)$,

$$\phi(M) \wedge \psi(M) \text{ is finite or cofinite in } \phi(M).$$

We say that $\phi(x) \in \mathcal{L}(M)$ is **strongly minimal** if it is minimal in the monster model \mathbb{M} . A theory T is **strongly minimal** if $x = x$ is strongly minimal. A type $p \in S(A)$ is **strongly minimal** if it contains a strongly minimal formula.

Examples 3.6 (Strongly minimal theories). It is easy to prove strong minimality of the following theories by quantifier eliminations:

- The theory T_∞ of an infinite set with equality;
- The theory of infinite vector spaces over a field K , $(V; 0; +; (\lambda_k)_{k \in K})$;
- ACF_p , the theory of algebraically closed fields in characteristic p .

Example 3.7 (A minimal set which is not strongly minimal). Consider the structure \mathcal{M} with an equivalence relation E that has countably many equivalence classes, one of each finite size and no infinite classes. Note that each equivalence class is a definable subsets of \mathcal{M} (using quantifiers). One can then show that adding predicates P_n for each equivalence class to the language, the (new) theory of \mathcal{M} has quantifier elimination (for example, by [19, Theorem 3.2.5]). From this it is easy to see that every definable subset of \mathcal{M} is either finite or cofinite. However, $\mathbb{M} \succ \mathcal{M}$ has an infinite class (by ω -saturation). So for a in this class, $E(x, a)$ is infinite and coinfinite. Note that the fact \mathcal{M} is not ω -saturated plays an important role here (see Exercise 3.9 below).

Non-examples 3.8. • The theory of two infinite predicates partitioning the domain is not strongly minimal. However, each predicate is;

- The theory of the random graph has no strongly minimal formula.

Exercise 3.9. Prove the following: let \mathcal{M} be ω -saturated. Suppose that $\phi \in \mathcal{L}(\mathcal{M})$ is minimal in \mathcal{M} . Then ϕ is strongly minimal.

Exercise 3.10. (a) Consider the theory of (\mathbb{Z}, s) , the integers with the successor operation $s(x) = x + 1$. This theory has quantifier elimination. What is algebraic closure in this theory? Is this $x = x$ in (\mathbb{Z}, s) minimal? is it strongly minimal?

- (b) Consider the theory of $(\mathbb{N}, <)$. This theory has quantifier elimination if we add a function symbol for the successor and a constant symbol for 0 (both of which are definable in the original theory). Is $x = x$ in $(\mathbb{N}, <)$ minimal? is it strongly minimal?

The idea of the following lemma is that algebraic sets are very small (being finite), so it is possible to extend non-algebraic types to larger parameter sets whilst avoiding algebraic sets (over those parameters):

Lemma 3.11 (Extension). *Let $\pi(x)$ be a partial type (closed under conjunctions) non-algebraic over A . Let $A \subseteq B$. Then, π has a non-algebraic extension $a \in S(B)$.*

Proof. Consider

$$q_0(x) := \pi(x) \cup \{ \neg \psi(x) \mid \psi(x) \in \mathcal{L}(B) \text{ is algebraic} \}.$$

We prove this is finitely satisfiable. Take $\phi(x) \in \pi(x)$ (note π is closed under conjunctions) and $\psi_1(x), \dots, \psi_n(x)$ algebraic. Then, since $\phi(\mathbb{M})$ is infinite and for each i $\neg \psi_i(\mathbb{M})$ is cofinite,

$$\phi(x) \wedge \bigwedge_{i \leq n} \neg \psi_i(x)$$

has infinitely many realisations. This proves finite satisfiability, and by compactness satisfiability of q_0 . Finally, take any completion $q \in S(B)$ of q_0 . This will still be non-algebraic by construction of q_0 , completing the proof. \square

One can actually prove a more general statement, where the "small" sets one is avoiding are characterised from belonging to an ideal in the Boolean algebra of definable sets. This will be very important later.

Definition 3.12. A set of definable subsets of \mathbb{M} in the variable x , $I \subseteq \text{Def}_x(\mathbb{M})$ is an **ideal** if it contains \emptyset , and it is closed under (definable) subsets and finite unions.

Exercise 3.13. Prove the following:

Let $I \subseteq \text{Def}_x(\mathbb{M})$ be an ideal. Let $\pi(x)$ be a partial type over A (closed under conjunctions) such that $p(\mathbb{M})$ is not contained in any set in I . Then, for every $B \supseteq A$, there is a type $q \in S(B)$ extending p and such that $q(\mathbb{M})$ is not contained in any set in I .

Lemma 3.14. The $\mathcal{L}(M)$ -formula $\phi(x)$ is minimal in \mathcal{M} if and only if there is a unique non-algebraic type $p \in S(M)$ containing $\phi(x)$.

Proof. (\Rightarrow) Assume ϕ is minimal in \mathcal{M} . Being non-algebraic, by extension (Lemma 3.11), it has a non-algebraic extension $p \in S(M)$. Note that if $\psi(x) \in p$, then $\phi(x) \wedge \psi(x)$ is infinite, and so by minimality of ϕ , $\phi(x) \wedge \neg\psi(x)$ is finite. So any type containing ϕ and $\neg\psi$ is algebraic. This implies that p is the unique non-algebraic type containing ϕ .

(\Leftarrow) By contrapositive. Suppose $\phi(x)$ is not minimal. If it is algebraic, then it cannot be contained in a non-algebraic type. So it is non-algebraic and by non-minimality there is some $\mathcal{L}(M)$ -formula ψ with both $\phi \wedge \psi$ and $\phi \wedge \neg\psi$ non-algebraic. Hence, by extension (Lemma 3.11), each formula extends to a non-algebraic type in $S(M)$ containing ϕ . Since the two types are clearly distinct (as one contains ψ and the other $\neg\psi$), this completes the proof of the contrapositive. \square

Corollary 3.15 (Stationarity). Let $p \in S(A)$ be strongly minimal. Then

- (a) p has a unique non-algebraic extension to all $B \supseteq A$;
- (b) If a_1^0, \dots, a_m^0 and a_1^1, \dots, a_m^1 are two sequences of realisations of p of length m which are algebraically independent in the sense that

$$a_i^j \notin \text{acl}(Aa_1^j, \dots, a_{i-1}^j)$$

for each $i \leq m$ and $j \in \{0, 1\}$. Then,

$$a_1^0, \dots, a_m^0 \equiv_A a_1^1, \dots, a_m^1.$$

So, the type over A of an algebraically independent tuple of realisations of p is entirely determined.

Proof. (a) From Lemma 3.14, p has a unique non-algebraic extension to \mathbb{M} , and so also to any set of parameters containing A .

(b) By induction. The base case is trivial. Suppose that $\bar{a}^0 \equiv_A \bar{a}^1$ for algebraically independent m -tuples of realisations of p . Let $a_{m+1}^0 \notin \text{acl}(A\bar{a}^0)$ and $a_{m+1}^1 \notin \text{acl}(A\bar{a}^1)$ be realisations of p . Take $\sigma \in \text{Aut}(\mathbb{M}/A)$ such that $\sigma(\bar{a}^0) = \bar{a}^1$. Since automorphisms preserve algebraicity, $\sigma(a_{m+1}^0)$ is non-algebraic over $A\bar{a}^1$. By Lemma 3.14, $\sigma(a_{m+1}^0) \equiv_{A\bar{a}^1} a_{m+1}^1$. So there is $\tau \in \text{Aut}(\mathbb{M}/A\bar{a}^1)$ such that $\tau\sigma(a_{m+1}^0) = a_{m+1}^1$. Since the composition of the two automorphisms fixes A , $\bar{a}^0 a_{m+1}^0 \equiv_A \bar{a}^1 a_{m+1}^1$, as desired. \square

4 Pregeometries

In this lecture we are going to use the results from the previous lecture to prove that algebraic independence behaves particularly well in strongly minimal sets (and theories). In particular, we will see that algebraic closure inside a strongly minimal set gives rise to a pregeometry: a structure whose behaviour of algebraic independence satisfies the axioms of linear independence, allowing us to talk about bases and dimensions.

The notion of a pregeometry (also known as matroid) originates from the work of Whitney [21] and Van de Waerden [20], both of whom gave axioms for linear independence in vector spaces. In particular, Whitney's work stemmed from applying notions from linear algebra to combinatorics after noticing various similarities between certain ideas of independence

and ranks in graph theory and the behaviour of linear independence. Nowadays matroid theory is a branch of mathematics with several applications in combinatorics [15]. Our interests differ from standard matroid theory because we study infinite pregeometries, but we will make use of some basic facts about pregeometries in this section.

Definition 4.1. A **pregeometry** (X, cl) consists of a set X with a closure operator

$$\text{cl} : \mathcal{P}(X) \rightarrow \mathcal{P}(X)$$

such that for all $A \subseteq X$ and $a, b \in X$:

- (REFLEXIVITY) $A \subseteq \text{cl}(A)$;
- (FINITE CHARACTER) $\text{cl}(A) = \bigcup \{\text{cl}(A') \mid A' \subseteq A \text{ finite}\}$;
- (TRANSITIVITY) $\text{cl}(\text{cl}(A)) = \text{cl}(A)$;
- (EXCHANGE) if $a \in \text{cl}(Ab) \setminus \text{cl}(A)$, then $b \in \text{cl}(Aa)$.

Remark 4.2. For any structure \mathcal{M} , $(\mathcal{M}, \text{acl})$ satisfies reflexivity, finite character, and transitivity.

Theorem 4.3. Let ϕ be a strongly minimal \mathcal{L} -formula. Let $\text{cl} : \mathcal{P}(\mathbb{M}) \rightarrow \mathcal{P}(\mathbb{M})$ be defined by, for $A \subseteq \phi(\mathbb{M})$, $\text{cl}(A) := \text{acl}(A) \cap \phi(\mathbb{M})$. Then, $(\phi(\mathbb{M}), \text{cl})$ is a pregeometry.

Proof. Reflexivity, finite character and transitivity are trivial. We only need to verify exchange. Without loss of generality (and to simplify notation), we assume that $A = \emptyset$. All elements we work with are inside of $\phi(\mathbb{M})$. Let $a \notin \text{acl}(\emptyset)$ and $b \notin \text{acl}(a)$. We need to prove $a \notin \text{acl}(b)$.

Firstly, note that $\phi(x)$ extends to a unique non-algebraic type $q(x)$ over \emptyset (Lemma 3.14). By stationarity (Corollary 3.15 (b)), all pairs $a'b'$ satisfying $a' \notin \text{acl}(\emptyset)$ and $b' \notin \text{acl}(a')$ have the same type $p(x, y)$.

Now, take $(a_i \mid i < \omega)$ an infinite sequence of realisations of $q(x)$ such that

$$a_i \notin \text{acl}(a_0 \dots a_{i-1}).$$

This can be done by induction iterating non-algebraic extensions (by Lemma 3.11). Using extension again, pick $b' \notin \text{acl}((a_i \mid i < \omega))$ realising $q(x)$. Since $a_i \notin \text{acl}(\emptyset)$ and $b' \notin \text{acl}(a_i)$ for each $i < \omega$, we have $a_i b' \equiv a b$ for all $i < \omega$. So, $a_i \notin \text{acl}(b')$, since $\text{tp}(a_i / b') = p(x, b')$ has infinitely many realisations. But then, since $b \equiv b'$, $p(x, b)$ also has infinitely many realisations. So $a \notin \text{acl}(b)$ as desired. \square

👁 *Observation 4.4.* The above proof actually works in any model: we may need to move outside of a given model M to realise the a_i . However, the conclusion that $p(x, b)$ is non-algebraic, does tell us that $a \notin \text{acl}(b)$ also in M .

Definition 4.5. Let (X, cl) be a pregeometry. For $A \subseteq X$, we say that:

- A is **independent** if $a \notin \text{cl}(A \setminus \{a\})$ for each $a \in A$;
- A is a **generating set** if $\text{cl}(A) = X$;
- A is a **basis** if it is an independent generating set for X .

Fact 4.6. (a) Every pregeometry has a basis [to prove this you need the axiom of choice];

(b) Any two bases for a pregeometry have the same cardinality.

Definition 4.7. For a pregeometry (X, cl) , we say that the **dimension** of X , $\dim(X)$ is the cardinality of a basis for X .

Definition 4.8. Given a pregeometry (X, cl) , for $S \subseteq X$, let

- (S, cl) given by $\text{cl}(A) = \text{cl}(A) \cap S$ for all $A \subseteq S$ be the **restriction** of (X, cl) to S ;

- (X, cl_S) given by $\text{cl}_S(A) = \text{cl}(A \cup S)$ for all $A \subseteq S$ be the **relativisation** of (X, cl) by S ;

We write $\dim(S)$ for $\dim((S, \text{cl}))$, and $\dim(X/S)$ for $\dim((X, \text{cl}_S))$. It is easy to show both of these are also pregeometries.

Note that thinking with the restriction and relativisation allows us to speak of bases for subspaces of X , or of independence over some subset of $S \subseteq X$.

👁 *Observation 4.9.* Note that for strongly minimal ϕ , the restriction $(\phi(M), \text{cl})$ is well defined since $\phi(M) \subseteq \phi(\mathbb{M})$. Meanwhile, its relativisation by $A \subseteq M$, $(\phi(M), \text{cl}_A)$ corresponds to the natural pregeometry on $(\phi(M_A), \text{cl})$, where M_A is the expansion of M by constants naming the elements of A . We write $\dim_\phi(M)$ for the dimension $(\phi(M), \text{cl})$, and $\dim_\phi(M/A)$ for the dimension of $(\phi(M_A), \text{cl})$.

Remark 4.10. For a pregeometry (X, cl) and $S \subseteq X$, we have

$$\dim(X) = \dim(S) + \dim(X/S).$$

Exercise 4.11. Let $f : A \rightarrow B$ be an elementary bijection between sets of parameters. Then, f extends to an elementary bijection $f' : \text{acl}(A) \rightarrow \text{acl}(B)$.

Lemma 4.12. Let $\phi \in \mathcal{L}(A)$ be strongly minimal. Let $A \subseteq \mathcal{M}, \mathcal{N} \models T$. Then, the following are equivalent:

1. there is an A -elementary bijection $f : \phi(M) \rightarrow \phi(N)$;
2. $\dim_\phi(M/A) = \dim_\phi(N/A)$.

Proof. Without loss of generality we work over \emptyset (we can always just work in $\text{Th}(\mathbb{M}_A)$). (\Rightarrow) We know there is an elementary bijection $f : \phi(M) \rightarrow \phi(N)$. Note that elementary bijections map bases to bases (since they preserve algebraic relations). Hence, $\dim_\phi(M) = \dim_\phi(N)$.

(\Leftarrow) Take bases U and V for $\phi(M)$ and $\phi(N)$. Let $f : U \rightarrow V$ be a bijection. By independence of the bases and stationarity (Corollary 3.15 (b)), there is an elementary bijection between U and V . Elementary bijection extend to algebraic closures (as noted in Exercise 4.11). So there is an elementary bijection $f' : \text{acl}(U) \rightarrow \text{acl}(V)$. Now $f'|_{\phi(M)}$ is an elementary bijection from $\phi(M)$ to $\phi(N)$. \square

👁 *Observation 4.13.* For any set of parameters A ,

$$|\text{acl}(A)| \leq \max(|\mathcal{L}|, |A|),$$

where $|\mathcal{L}|$ is the size of the set of \mathcal{L} -formulas.

Corollary 4.14. Let T be a countable and strongly minimal theory. Then, it is categorical in all uncountable cardinals.

Proof. Let $\mathcal{M}_1, \mathcal{M}_2 \models T$ have cardinality $\kappa > \aleph_0$. Choose bases B_1, B_2 respectively. By Observation 4.13, for each $i \in \{1, 2\}$:

$$\kappa = |M_i| = |\text{acl}(B_i)| \leq \max(|\mathcal{L}|, |B_i|) = \max(\aleph_0, |B_i|) = |B_i|.$$

So $\dim(M_1) = \dim(M_2)$. So there is an elementary bijection $f : M_1 \rightarrow M_2$ by Lemma 4.12. \square

Exercise 4.15. Let T be a strongly minimal theory (not necessarily countable). Show the following:

- (a) Every infinite algebraically closed set of parameters S is the universe of a model of T ;
- (b) A model \mathcal{M} is ω -saturated if and only if $\dim(M) \geq \aleph_0$;
- (c) All models are ω -homogeneous.

5 ω -stability and the downwards Morley theorem

Definition 5.1. We say that T is ω -stable if for any $n \in \mathbb{N}$ and any set of parameters A such that $|A| \leq \aleph_0$, $|S_n(A)| \leq \aleph_0$.

Remark 5.2. It is easy to prove that T is ω -stable if and only if for set of parameters A such that $|A| \leq \aleph_0$, $|S_1(A)| \leq \aleph_0$. We will generally use this characterisation of ω -stability.

Examples 5.3. • if T is strongly minimal, then it is ω -stable. To see this note that if $|A| \leq \aleph_0$, there are only $\leq \aleph_0$ many algebraic types over A (since \mathcal{L} is countable) and there is a unique non-algebraic type over A , meaning that $|S_1(A)| \leq \aleph_0$;

- if T is κ -categorical for $\kappa > \aleph_0$, then it is ω -stable. This was proven in the previous model theory course and it is a strictly more general fact than the previous one;
- the theory of an infinitely branching infinite tree is ω -stable (but not κ -categorical in any infinite κ).

Definition 5.4. We say that T is **totally transcendental** if there is no binary tree of (consistent) $\mathcal{L}(\mathbb{M})$ -formulas $(\phi_s(x) \mid s \in {}^{<\omega} 2)$ such that

- $\vdash \forall x \neg (\phi_{s0}(x) \wedge \phi_{s1}(x))$;
- $\vdash \forall x ((\phi_{s0}(x) \vee \phi_{s1}(x)) \rightarrow \phi_s(x))$.

That is, we ask that any two children of a common node are mutually inconsistent, but their union as a pair of definable sets is contained in the set defined by their parent.

Lemma 5.5. A theory T is ω -stable if and only if it is totally transcendental.

Definition 5.6. Let A be a set of parameters and x a tuple of variables. For an $\mathcal{L}(A)$ -formula $\phi(x)$, we define

$$[\phi(x)] := \{p \in S_x(A) \mid \phi(x) \in p\}.$$

Sets of the form $[\phi(x)]$ form a basis of clopen sets for a topology on $S_x(A)$, which we call the **Stone topology**.

We say that a type $p \in S_x(A)$ is **isolated** if there is some $\mathcal{L}(A)$ -formula $\psi(x)$ such that $[\psi(x)] = \{p\}$.

Fact 5.7. The type space $S_x(A)$ with the Stone topology is compact, Hausdorff, and totally disconnected (i.e. for all $p, q \in S_x(A)$ there is a clopen set X such that $p \in X$ and $q \notin X$).

Exercise 5.8. Let T be a countable complete theory. Let A be a countable set of parameters and x a finite tuple of variables. Suppose that $|S_x(A)| < 2^{\aleph_0}$. Prove the following:

- the isolated types in $S_n(A)$ are dense, i.e. for any $\mathcal{L}(A)$ -formula $\phi(x)$, $[\phi]$ contains an isolated type;
- $|S_x(A)| \leq \aleph_0$.

[Hint: in both contexts, you need to build an adequate binary tree of $\mathcal{L}(A)$ -formulas $(\phi_\sigma \mid \sigma \in 2^{<\omega})$ such that any finite branch is consistent but any two children of a common node are mutually inconsistent. Then, each infinite branch of the binary tree can be used to construct a type, giving 2^{\aleph_0} -many.]

Definition 5.9. Let $A \subseteq \mathcal{M} \models T$. We say that \mathcal{M} is **prime over** A if for all $\mathcal{N} \models T$ and $f : A \rightarrow \mathcal{N}$ a partial elementary map, f extends to an elementary $f' : \mathcal{M} \rightarrow \mathcal{N}$.

We say that \mathcal{M} is **prime**, if it is prime over \emptyset .

Example 5.10. The theory of algebraically closed fields of characteristic zero ACF_0 has $\overline{\mathbb{Q}}^{\text{alg}}$, the algebraic closure of $(\mathbb{Q}; 0, 1; +, -, \times)$ as a prime model. In fact, $\overline{\mathbb{Q}}^{\text{alg}}$ is a model of ACF_0 and it embeds in every model of the theory. By model completeness of ACF_0 , such an embedding is elementary, yielding that $\overline{\mathbb{Q}}^{\text{alg}}$ is prime. Indeed, we can prove that countable ω -stable theories always have a prime model.

Exercise 5.11. Show the following: Let T be a countable ω -stable theory, $\mathcal{M} \models T$ and $A \subseteq M$. Then, there is $\mathcal{M}_0 \preceq \mathcal{M}$ which is a prime model over A and such that every $a \in M$ realises an isolated type over A .

Theorem 5.12 (Lachlan). *Let T be ω -stable, $\mathcal{M} \models T$, $|M| \geq \aleph_1$. Then, for each $\kappa > |M|$ there is $\mathcal{N} \succeq \mathcal{M}$ of cardinality κ such that for any countable set of $\mathcal{L}(M)$ -formulas $\Gamma(x)$ in a finite variable x , if \mathcal{N} realises $\Gamma(x)$, then so does \mathcal{M} .*

Exercise 5.13. We shall prove Theorem 5.12 following the steps below. Consider an ω -stable theory T and $\mathcal{M} \models T$, such that $|M| \geq \aleph_1$. Say that an $\mathcal{L}(M)$ -formula is **large** if $\phi(M)$ is uncountable.

- Prove that there is a large $\mathcal{L}(M)$ -formula $\phi_0(x)$ such that for any other $\mathcal{L}(M)$ -formula ψ , either $\phi_0(x) \wedge \psi(x)$ or $\phi_0(x) \wedge \neg\psi(x)$ has a countable set of realisations.
- Consider

$$p(x) := \{\psi(x) \mid \psi(x) \in \mathcal{L}(M) \text{ and } \phi_0(x) \wedge \psi(x) \text{ is large}\}.$$

Show that p is a complete type over M which is not realised in M but such that all of its countable subsets are realised in M . Take $\mathcal{N}' \succeq \mathcal{M}$ with a point a realising p .

- By Exercise 5.11, take $\mathcal{N} \preceq \mathcal{N}'$ prime over Ma and such that every $b \in \mathcal{N}$ realises an isolated type over Ma . Show that for every $b \in N$, every countable subset $\Gamma(x)$ of $\text{tp}(b/M)$ is realised in M .
- Deduce Theorem 5.12.

Remark 5.14. Recall the two following facts from the model theory I course:

- any two saturated models of the same cardinality are isomorphic;
- if T is κ -categorical, then all of its models of cardinality κ are saturated.

Theorem 5.15 (Downwards Morley Theorem). *Let T be countable and κ -categorical in some uncountable κ . Then T is \aleph_1 -categorical.*

Proof. Suppose by contradiction that T is κ -categorical (so ω -stable) and not \aleph_1 -categorical. Then, it has a non-saturated model \mathcal{M} of cardinality \aleph_1 . So there is some $p \in S_1(A)$ for $A \subseteq M$ countable which is not realised in M . By Theorem 5.12 and ω -stability, there is $\mathcal{N} \succeq \mathcal{M}$ of cardinality κ and not realising p . But if T is κ -categorical, all models of cardinality κ are saturated and \mathcal{N} is not saturated. Contradiction. \square

6 Vaughtian pairs

Definition 6.1. We say that T has a **Vaughtian pair** if there are $\mathcal{M} \preceq \mathcal{N} \models T$ such that $M \subsetneq N$ and $\phi \in \mathcal{L}(M)$ non-algebraic such that $\phi(M) = \phi(N)$.

We will often write a Vaughtian pair as $(\mathcal{N}, \mathcal{M})$ since it is convenient to think about this as the expansion of \mathcal{N} by a predicate P naming the smaller model \mathcal{M} .

Exercise 6.2. Show that the theory of the random graph has a Vaughtian pair.

★★ **Exercise 6.3.** Show that there is no Vaughtian pair of real closed fields.

Lemma 6.4. *Suppose that T has a Vaughtian pair. Then, T has a Vaughtian pair $(\mathcal{N}, \mathcal{M})$ with \mathcal{N} and \mathcal{M} countable.*

Proof. This proof is essentially an application of the downwards Lowenheim-Skolem theorem. Let $(\mathcal{N}^*, \mathcal{M}^*)$ be a Vaughtian pair for T as witnessed by the formula $\phi(x) \in \mathcal{L}(A)$ for $A \subseteq M^*$ finite. Consider $(\mathcal{N}^*, \mathcal{M}^*)$ as \mathcal{N}^* expanded by a predicate P naming \mathcal{M}^* . Then,

by the downwards Lowenheim-Skolem theorem, there is $(\mathcal{N}, P(N)) \preceq (\mathcal{N}^*, \mathcal{M}^*)$ countable and containing A , and so, in particular, $A \subseteq P(N)$.

It is easy to verify that $P(N) \preceq \mathcal{N}$ by the Tarski-Vaught test. Moreover, $\phi(P(N))$ is infinite and such that $\phi(P(N)) = \phi(N)$, $P(N) \subsetneq N$, since all of this is coded by the theory of $(\mathcal{N}^*, \mathcal{M}^*)$. Hence, $(\mathcal{N}, P(N))$ is a Vaughtian pair. \square

Lemma 6.5 (Basic facts about ω -homogeneous models). *Let T be a countable theory.*

1. *Every countable model of T has a countable ω -homogeneous elementary extension;*
2. *the union of an elementary chain of ω -homogeneous models is ω -homogeneous;*
3. *two ω -homogeneous countable models of T realising the same n -types over \emptyset for all $n \in \mathbb{N}$ are isomorphic.*

Proof. For (1), start with $\mathcal{M}_0 \models T$ countable. Build a countable elementary extension $\mathcal{M}_1 \succeq \mathcal{M}_0$ such that for all $a \in M_0$, $A \subseteq M_0$ finite, $p(x, A) := \text{tp}(a/A)$ and $f : A \rightarrow \mathcal{M}_0$ elementary, \mathcal{M}_1 realises $p(x, f(A))$. This can be done since it requires realising only countably many types. Iterate this for a countable elementary chain $\mathcal{M}_0 \preceq \mathcal{M}_1 \preceq \mathcal{M}_2 \preceq \dots$, and consider $\mathcal{M} := \bigcup_{i < \omega} \mathcal{M}_i$. By construction this is ω -homogeneous (the argument is essentially the same as the one below).

For (2), Consider $\mathcal{N} := \bigcup_{\beta < \lambda} \mathcal{N}_\beta$, the union of an elementary chain of ω -homogeneous models. Take $a \in N$, $A \subseteq N$ finite, and $f : A \rightarrow \mathcal{N}$ elementary. Since A is finite, $f : A \rightarrow \mathcal{N}_\beta$ containing both A and a for some $\beta < \lambda$. Since \mathcal{N}_β is ω -homogeneous f can be extended to $f' : Aa \rightarrow \mathcal{N}_\beta \preceq \mathcal{N}$, yielding that \mathcal{N} itself is ω -homogeneous.

The proof of (3) is a trivial back & forth argument. \square

Example 6.6 (Thanks to R. Feller during the class). Usually, we work with ω -homogeneous models. For an example of a non ω -homogeneous countable structure consider the model of $\text{Th}(\mathbb{Z}, <)$ consisting of three disjoint copies of $(\mathbb{Z}, <)$ ordered one after the other $\mathcal{M} := \mathbb{Z}_{a1} \sqcup \mathbb{Z}_{a2} \sqcup \mathbb{Z}_{a3}$. Take $a \in \mathbb{Z}_{a1}$, $b \in \mathbb{Z}_{a3}$ and consider an elementary embedding $f : ab \rightarrow \mathcal{M}$ such that $a \mapsto a$ and $b \mapsto b'$ for $b' \in \mathbb{Z}_{a2}$. Take $c \in \mathbb{Z}_{a2}$. f cannot be extended to c : we know that c has infinite distance from both a and b and is between then in the order $<$. But every element between a and b' is in either \mathbb{Z}_{a1} or \mathbb{Z}_{a2} and so cannot have infinite distance from both of them.

Corollary 6.7. *Suppose $\mathcal{M}_0 \preceq \mathcal{N}_0$ are countable models of T . Then, there are $(\mathcal{N}, \mathcal{M}) \succeq (\mathcal{N}_0, \mathcal{M}_0)$ such that \mathcal{M} and \mathcal{N} are countable, ω -homogeneous and satisfy the same n -types over \emptyset . In particular, $\mathcal{M} \cong \mathcal{N}$.*

Proof. We construct a countable elementary chain

$$(\mathcal{N}_0, \mathcal{M}_0) \preceq (\mathcal{N}_1, \mathcal{M}_1) \preceq \dots$$

as follows: for $(\mathcal{N}_i, \mathcal{M}_i)$ take $(\mathcal{N}', \mathcal{M}') \succeq (\mathcal{N}_i, \mathcal{M}_i)$ such that \mathcal{M}' realises all n -types over \emptyset realised by \mathcal{N}_i . Then, by Lemma 6.5 (1) take a countable ω -homogeneous elementary extension $(\mathcal{N}_{i+1}, \mathcal{M}_{i+1}) \succeq (\mathcal{N}', \mathcal{M}')$. Note that since $(\mathcal{N}_{i+1}, \mathcal{M}_{i+1})$, we also have that both \mathcal{N}_{i+1} and \mathcal{M}_{i+1} are ω -homogeneous.

Now, consider the union of this elementary chain, $(\mathcal{N}, \mathcal{M})$. By construction and Lemma 6.5 (2) this is also ω -homogeneous, and so such that both \mathcal{N} and \mathcal{M} are ω -homogeneous. Furthermore, by construction \mathcal{M} and \mathcal{N} satisfy the same n -types over \emptyset . Hence, $(\mathcal{N}, \mathcal{M})$ satisfies all of the desired properties. \square

Theorem 6.8 (Vaught's two cardinal theorem). *Let T have a Vaughtian pair. Then, there is $\aleph^* \models T$ of cardinality \aleph_1 and $\phi \in \mathcal{L}(N^*)$ such that $|\phi(N^*)| = \aleph_0$.*

Proof. By Lemma 6.4, T has a countable Vaughtian pair and by Corollary 6.7 we can choose it so that \mathcal{M} and \mathcal{N} are countable, ω -homogeneous and realising the same n -types over \emptyset . In particular, $\mathcal{M} \cong \mathcal{N}$. We build an elementary chain

$$(\mathcal{N}_\alpha | \alpha < \omega_1)$$

such that

- $\mathcal{N}_0 = \mathcal{M}, \mathcal{N}_1 = \mathcal{N}$;
- $\mathcal{N}_\alpha \cong \mathcal{N}$;
- $(\mathcal{N}_{\alpha+1}, \mathcal{N}_\alpha) \cong (\mathcal{N}, \mathcal{M})$.

For the successor step, suppose that we have $\mathcal{N}_\alpha \cong \mathcal{N}$. Then, $\mathcal{N}_\alpha \cong \mathcal{M}$, and so it has an elementary extension $\mathcal{N}_{\alpha+1}$ such that $(\mathcal{N}_{\alpha+1}, \mathcal{N}_\alpha) \cong (\mathcal{N}, \mathcal{M})$, and so we are done. For the limit step, for $\alpha < \omega_1$ consider $\mathcal{N}_\alpha = \bigcup_{\beta < \alpha} \mathcal{N}_\beta$. Since $\alpha < \omega_1$, this is a countable union of countable sets and so is \mathcal{N}_α countable. By Lemma 6.5 (2), this is ω -homogeneous. Also, since any finite subset of \mathcal{N}_α is contained in some $\mathcal{N}_\beta \preceq \mathcal{N}_\alpha$ and $\mathcal{N}_\beta \cong \mathcal{N}$, \mathcal{N}_α realises all of the same n -types over \emptyset as \mathcal{N} . Thus, $\mathcal{N}_\alpha \cong \mathcal{N}$ as desired. Hence, we can build the desired elementary chain $(\mathcal{N}_\alpha | \alpha < \omega_1)$.

Take $\mathcal{N}^* = \bigcup_{\alpha < \omega_1} \mathcal{N}_\alpha$. Note that $|\mathcal{N}^*| = \aleph_1$: it must have size at least \aleph_1 since we are taking an uncountable union, where at each stage $\mathcal{N}_{\alpha+1} \supsetneq \mathcal{N}_\alpha$. It has size at most \aleph_1 being an uncountable union of countable sets. However, since $(\mathcal{N}_{\alpha+1}, \mathcal{N}_\alpha) \cong (\mathcal{N}, \mathcal{M})$, we have that

$$\phi(\mathcal{N}_{\alpha+1}) = \phi(\mathcal{N}_\alpha) = \dots = \phi(\mathcal{N}) = \phi(\mathcal{M}),$$

and so $\phi(\mathcal{N}^*) = \phi(\mathcal{M})$, which is a countable set. So the conclusion of the theorem holds. \square

👁 *Observation 6.9.* Note that if $\mathcal{M} \models T$ is saturated and $\phi(x) \in \mathcal{L}(\mathcal{M})$ is non-algebraic, then $|\phi(\mathcal{M})| = |\mathcal{M}|$. Suppose by contradiction $|\phi(\mathcal{M})| < |\mathcal{M}|$ and consider the following partial type:

$$\{\phi(x)\} \cup \{x \neq c \mid c \in \phi(\mathcal{M})\}.$$

This is a finitely satisfiable and over a set of cardinality $< |\mathcal{M}|$. So by saturation of \mathcal{M} it is realised in \mathcal{M} , yielding a contradiction.

Corollary 6.10. *Let T be κ -categorical in some uncountable κ . Then, T has no Vaughtian pairs.*

Proof. Suppose that T is κ -categorical. Since it is κ -categorical, it is \aleph_1 -categorical by the downwards Morley Theorem 5.15. Hence, all of its models of cardinality \aleph_1 are saturated. Hence, by Observation, for every uncountable model \mathcal{N} and $\mathcal{L}(\mathcal{N})$ -formula $\phi(x)$, $|\phi(\mathcal{N})| = \aleph_1$. By Vaught's two cardinal Theorem 6.8, this implies that T has no Vaughtian pair. \square

Definition 6.11. We say that T **eliminates the quantifier** $\exists^\infty x$ if for every \mathcal{L} -formula $\phi(x, \bar{y})$ there is $n_\phi \in \mathbb{N}$ such for all tuples $\bar{a} \in \mathbb{M}^{|\bar{y}|}$, if $|\phi(\mathbb{M}, \bar{a})| \geq n_\phi$, then $\phi(\mathbb{M}, \bar{a})$ is infinite.

Exercise 6.12. Show that if T has no Vaughtian pairs, then it eliminates the quantifier $\exists^\infty x$.

Exercise 6.13. Suppose that T eliminates the quantifier $\exists^\infty x$. Let $\mathcal{M} \models T$ and let $\phi(x) \in \mathcal{L}(\mathcal{M})$ be minimal in \mathcal{M} . Show that $\phi(x)$ is strongly minimal.

Definition 6.14. For infinite cardinals $\kappa > \lambda$, we say that T has a (λ, κ) -model if $|\mathcal{M}| = \kappa$ and for some $\phi(x) \in \mathcal{L}$, $|\phi(\mathcal{M})| = \lambda$.

Exercise 6.15. Prove the following:

1. If T has a (κ, λ) -model then it has a Vaughtian pair (and so an (\aleph_1, \aleph_0) -model) [Hint: this should be trivial];
2. Prove that if T is ω -stable and has an (\aleph_1, \aleph_0) -model, then for each $\kappa > \aleph_1$, T has a (κ, \aleph_0) -model [Hint: you may need to use Theorem 5.12].

★★ **Exercise 6.16.** We show that in Exercise 6.15 (2), the assumption of ω -stability is necessary. Let $\mathcal{L} = \{P_0, \dots, P_n, E_1, \dots, E_n\}$ for unary predicates P_i and binary relations E_i . Consider the \mathcal{L} -theory T stating that:

- the P_i are infinite and partition the domain;
- for each $i \in \{1, \dots, n\}$, $\forall xy(E_i(x, y) \rightarrow P_{i-1}(x) \wedge P_i(y))$;
- for each $i \in \{1, \dots, n\}$, $\forall xy((P_i(x) \wedge P_i(y) \wedge \forall z(E_i(z, x) \leftrightarrow E_i(z, y)) \rightarrow x = y)$.

For example, for X_0 an infinite, take $X_{i+1} = \mathcal{P}(X_i)$ for $i \in \{1, \dots, n\}$. Let \mathcal{M} be the disjoint union of the X_i with P_i naming each of the X_i and E_i being the membership relation restricted to $X_i \times x_{i+1}$. Then, $\mathcal{M} \models T$. Show that if $\mathcal{M} \models T$ and $|P_0(\mathcal{M})| = \aleph_0$, then $|\mathcal{M}| \leq \beth_n$. Hence, \mathcal{M} has a (\beth_n, \aleph_0) -model but it does not have a (κ, \aleph_0) -model for arbitrarily large κ . [Hint: I would only do the case of $n = 1$. Recall that $\beth_0 = \aleph_0$ and $\beth_{\alpha+1} = 2^{\beth_\alpha}$.]

7 The Baldwin-Lachlan Theorem and Morley's Theorem

Recall the following exercise from the Model Theory I course:

Fact 7.1. Let T be ω -stable and $\mathcal{M} \models T$. Then there is a $\mathcal{L}(\mathcal{M})$ -formula minimal in \mathcal{M} .

Theorem 7.2 (Baldwin & Lachlan). Let T be a countable theory. Then, T is κ -categorical in some uncountable cardinal κ if and only if it is ω -stable and has no Vaughtian pair.

Proof. (\Rightarrow) We have already proven that κ -categoricity implies ω -stability in the Model Theory I course. We proved that κ -categoricity implies having no Vaughtian pair in Corollary 6.10.

(\Leftarrow) Since T is ω -stable, it has a prime model \mathcal{M}_0 over \emptyset by Exercise 5.11. Note that by the downwards Lowenheim-Skolem Theorem and countability of T , \mathcal{M}_0 must be countable. By ω -stability, there is an $\mathcal{L}(\mathcal{M}_0)$ -formula $\phi(x)$ which is minimal in \mathcal{M}_0 by Fact 7.1. Now, since T has no Vaughtian pair, $\phi(x)$ is strongly minimal (by Exercises 6.12 and 6.13).

Now, consider two models $\mathcal{M}_1, \mathcal{M}_2$ of cardinality κ . We need to show that they are isomorphic. Since \mathcal{M}_0 is prime over \emptyset , it elementary embeds into both of the \mathcal{M}_i for $i \in \{1, 2\}$. We may assume without loss of generality that \mathcal{M}_0 is an elementary substructure of both \mathcal{M}_1 and \mathcal{M}_2 .

👁 **Observation 7.3.** For $i \in \{1, 2\}$, \mathcal{M}_i has no proper elementary substructure containing $\mathcal{M}_0 \cup \phi(\mathcal{M}_i)$.

If it did, we would have $\mathcal{M}_0 \cup \phi(\mathcal{M}_i) \subseteq \mathcal{N} \preceq \mathcal{M}_i$ with $\mathcal{N} \subsetneq \mathcal{M}_i$. Since $\mathcal{N} \preceq \mathcal{M}_i$, $\phi(\mathcal{N}) = \phi(\mathcal{M}_i)$. But then this would give a Vaughtian pair.

👁 **Observation 7.4.** For $i \in \{1, 2\}$, \mathcal{M}_i is prime over $\mathcal{M}_0 \cup \phi(\mathcal{M}_i)$.

Since T is ω -stable, there is $\mathcal{K} \preceq \mathcal{M}_i$ prime over $\mathcal{M}_0 \cup \phi(\mathcal{M}_i)$. By Observation 7.3, $\mathcal{K} = \mathcal{M}_i$.

Now, from Observation 7.3, we can deduce that $|\phi(\mathcal{M}_i)| = \kappa$. Otherwise, by the downwards Lowenheim-Skolem Theorem, and countability of T and \mathcal{M}_0 , we could find a proper elementary substructure of \mathcal{M}_i containing $\mathcal{M}_0 \cup \phi(\mathcal{M}_i)$. Now, we know from Theorem 4.3 (where we added parameters for the elements of \mathcal{M}_0), that $(\phi(\mathbb{M}), \text{cl})$ forms a pregeometry, where

$$\text{cl}(A) = \text{acl}(A \cup \mathcal{M}_0) \cap \phi(\mathbb{M}).$$

Hence,

$$\dim_\phi(\mathcal{M}_1/\mathcal{M}_0) = \dim_\phi(\mathcal{M}_2/\mathcal{M}_0) = \kappa.$$

This is because for any set A , $|\text{acl}(A)| \leq \max(|A|, |\mathcal{L}|)$ and since $\dim_\phi(\mathcal{M}_i/\mathcal{M}_0)$ is the cardinality of a generating set for $\phi(\mathcal{M}_i)$ (over \mathcal{M}_0), where \mathcal{M}_0 and $|\mathcal{L}|$ are countable.

From Lemma 4.12, there is an M_0 -elementary bijection $f : \phi(M_1) \rightarrow \phi(M_2)$. I.e. there is an elementary bijection $f : M_0 \cup \phi(M_1) \rightarrow M_0 \cup \phi(M_2) \subseteq \mathcal{M}_2$ fixing M_0 . Since \mathcal{M}_1 is prime over $M_0 \cup \phi(M_1)$, we can extend f to $f' : \mathcal{M}_1 \rightarrow \mathcal{M}_2$. Now, $f'(M_1) \preceq \mathcal{M}_2$ and $M_0 \cup \phi(M_2) \subseteq f'(M_1)$. Hence, from Observation 7.4, $f'(M_1) = M_2$, and so f' is an isomorphism between M_1 and M_2 , as desired. \square

Corollary 7.5 (Morley's Theorem). *Let T be a countable theory. Suppose that T is categorical in some uncountable cardinal. Then, T is categorical in all uncountable cardinals.*

Proof. If T is κ -categorical for some uncountable κ , by the Baldwin-Lachlan Theorem it is ω -stable with no Vaughtian pair. But again by the Baldwin-Lachlan Theorem it is categorical in all uncountable cardinals. \square

8 Getting familiar with more examples

Exercise 8.1. 1. Prove that $(\mathbb{N}; 0, 1, +, \times, <)$ is the prime model of $\text{Th}(\mathbb{N}; 0, 1, +, \times, <)$;
2. Prove that $\text{Th}(\mathbb{Z}, 0, +)$ does not have a prime model. [Hint: you may assume that augmenting $(\mathbb{Z}, 0, +)$ by predicates P_n for each $n \geq 2$ naming the elements divisible by n yields a theory with quantifier elimination];

Definition 8.2. Let κ be an infinite cardinal. We say that T is **κ -stable** if for all A such that $|A| \leq \kappa$, $|S_x(A)| \leq \kappa$. We say that T is **superstable** if it is κ -stable for all $\kappa \geq 2^{|T|}$. We say that T is **stable** if it is κ -stable for some κ .

Exercise 8.3. Let $\mathcal{L} := \{U_i \mid i < \omega\}$ be such that each U_i is a unary predicate. For X and Y disjoint finite subsets of \mathbb{N} , let $\phi_{X,Y}$ be the sentence

$$\exists x \bigwedge_{i \in X} U_i(x) \wedge \bigwedge_{i \in Y} \neg U_i(x).$$

Let $T := \{\phi_{X,Y} \mid X, Y \text{ disjoint finite subsets of } \mathbb{N}\}$. You may assume this theory is complete and has quantifier elimination.

1. Show that no type over \emptyset is isolated. Deduce that T has no prime models;
2. Show that T is κ -stable for all $\kappa \geq 2^{\aleph_0}$.

8.0.1 Equivalence relations

Example 8.4. Consider the following theories of equivalence relations for α an ordinal and κ a cardinal.

- **Refining equivalence relation with infinite splitting:** REI_α has equivalence relations $(E_i \mid i < \alpha)$ such that for $i < j < \alpha$, E_j refines E_i and each E_i class is refined into infinitely many E_{i+1} -classes. For this and all other examples below we assume each equivalence class of each equivalence relation is infinite;
- **Refining equivalence relation with finite splitting:** REF_α has equivalence relations $(E_i \mid i < \alpha)$ such that for $i < j < \alpha$, E_j refines E_i and each E_i class is refined into two E_{i+1} -classes;
- **Crosscutting Equivalence relation with finite splitting:** CEF_κ has equivalence relations $(E_i \mid i < \kappa)$ such that each E_i has only two classes and for all $i < \kappa$, E_{i+1} splits each equivalence class of E_i into two classes;
- **Crosscutting Equivalence relation with infinite splitting:** CEI_κ has equivalence relations $(E_i \mid i < \kappa)$ such that each E_i has infinitely many classes and for all $i < \kappa$, E_{i+1} splits each equivalence class of E_i into infinitely many classes. These theories are complete and have quantifier elimination.

Exercise 8.5. Show the following:

1. REI_α is stable. REI_ω is κ -stable if and only if $\kappa^{\aleph_0} = \kappa$. [More generally, if α is infinite, REI_α is not superstable];
2. REF_α is stable. If $\alpha \leq \omega$ it is superstable. If $\alpha \geq \omega \cdot \omega$ then it is not superstable;
3. if $\kappa \leq \omega$, then CEF_κ is superstable.

★★ **Exercise 8.6.** Compute the number of models of each of the examples in Example 8.4 in each cardinality.

8.0.2 Differentially closed fields

Definition 8.7. A **derivation** on a ring R is an additive homomorphism $D : R \rightarrow R$ such that

$$D(xy) = xD(y) + yD(x).$$

A **differential ring** is a ring equipped with a derivation. Given a derivation $D_0 : R \rightarrow R$, we call the **ring of differential polynomials** the differential ring

$$R\{X\} := R[X, X^{(1)}, X^{(2)}, X^{(3)}, \dots],$$

with derivation D extending D_0 by setting $D(X^{(n)}) = X^{(n+1)}$.

Definition 8.8. An ideal $I \subseteq R\{X\}$ is a **differential ideal** if for all $f \in I$, $D(f) \in I$.

Definition 8.9. If $f(X) \in R\{X\} \setminus R$, the **order** of f is the largest n such that $X^{(n)}$ occurs in f . We can write

$$f(X) = \sum_{i=0}^m g_i(X, X^{(1)}, \dots, X^{(n-1)})(X^{(n)})^i,$$

for $g_i \in R[X, X^{(1)}, \dots, X^{(n-1)}]$ and $g_m \neq 0$. We call m the **degree** of f . We write $g \leq f$ if either the order of g is strictly less than the order of f or if the orders are the same but g has lower degree than f .

Definition 8.10. A differential field K (of characteristic zero) which is algebraically closed is called **differentially closed** if for any non-constant differential polynomials f and g where the order of g is less than the order of f there is an x such that $f(x) = 0$ and $g(x) \neq 0$.

Note that the theory of differentially closed fields of characteristic zero is axiomatisable. We call it DCF_0 .

Fact 8.11. Every differential field k has an extension K which is differentially closed.

Fact 8.12. DCF_0 is complete and has quantifier elimination.

★★ **Exercise 8.13.** Let $K \models \text{DCF}_0$. Let $k \subseteq K$.

1. for $p \in S_1^K(k)$, the set of 1-types over k realised in K , let $I_p := \{f \in k\{X\} \mid f(x) = 0 \in p\}$. Show that I_p is a differential prime ideal [i.e. $I_p \subsetneq k\{X\}$ and if $f \cdot g \in I_p$, then either $f \in I_p$ or $g \in I_p$].
2. Show that if $I \subset k\{X\}$ is a differential prime ideal, then $I = I_p$ for some $p \in S_n^K$. So $p \mapsto I_p$ is a bijection between complete n -types and differential prime ideals in $k\{X\}$;
3. The Ritt-Raudenbusch Basis Theorem says that every differential prime ideal in $k\{X\}$ is finitely generated. Use this to show that DCF_0 is ω -stable;
4. Suppose that k is a differential field of characteristic zero and $k \subseteq K \models \text{DCF}_0$. We say that K is the **differential closure** of k if for all $L \supseteq k$ such that $K \models \text{DCF}_0$ there is a differential field embedding of K into L fixing k . Show that every field has a differential closure.

9 Stability

Definition 9.1. We say that the formula $\phi(x; y)$ has the **order property** if there is an infinite sequence $(a_i, b_i | i < \omega)$ such that

$$\models \phi(a_i, b_j) \text{ if and only if } i < j.$$

We say that $\phi(x; y)$ is **stable** if it does not have the order property.

Exercise 9.2. Let $\phi(x; y)$ and $\psi(x, z)$ be stable \mathcal{L} -formulas. Show the following:

1. $\phi^{\text{opp}}(y; x) := \phi(x; y)$ is stable;
2. $\neg\phi(x; y)$ is stable;
3. $\theta(x; yz) := \phi(x; y) \wedge \psi(x; z)$ is stable;
4. $\theta(x; yz) := \phi(x; y) \vee \psi(x; z)$ is stable;
5. For $y = uv$ and $c \in \mathbb{M}^{|v|}$, $\phi(x; u, c)$ is stable.

Theorem 9.3 (Erdős-Makkai). Let B be an infinite set and $\mathcal{F} \subseteq \mathcal{P}(B)$ with $|B| < |\mathcal{F}|$. Then, there are sequences $(b_i | i < \omega)$ of elements of B and $(S_i | i < \omega)$ of elements of \mathcal{F} such that for all $i, j \in \omega$, we have that

- EITHER $b_i \in S_j$ if and only if $j < i$;
- OR $b_i \in S_j$ if and only if $i < j$.

Exercise 9.4 (Proof of Erdős-Makkai). Note that there is $\mathcal{F}' \subseteq \mathcal{F}$ such that $|\mathcal{F}'| = |B|$ and for all $B_0, B_1 \subseteq B$ finite, if there is some $S \in \mathcal{F}$ such that $B_0 \subseteq S, B_1 \subseteq B \setminus S$, then there is some $S' \in \mathcal{F}'$ with $B_0 \subseteq S', B_1 \subseteq B \setminus S'$. Note that there is $S^* \in \mathcal{F}$ which is not a Boolean combination of elements of \mathcal{F}' . Now, prove Erdős-Makkai. [Hint: you need to construct appropriate sequences in $S^*, B \setminus S^*$ and \mathcal{F}' , and then use Ramsey's theorem.]

Definition 9.5. $\phi(x; y)$ does has the **binary tree property** if there is a binary tree of parameters $(b_s | s \in {}^{<\omega} 2)$ such that for each branch $\sigma \in {}^\omega 2$,

$$\{\phi^{\sigma(n)}(x; b_{\sigma|n}) | n < \omega\} \text{ is consistent,}$$

where $\phi^0 := \neg\phi$ and $\phi^1 := \phi$.

Definition 9.6. Let $\phi(x; y) \in \mathcal{L}$ and B be a set of parameters. A ϕ -type over B is a maximally consistent set of formulas of the form $\phi(x; b), \neg\phi(x; b)$. We denote the set of all ϕ -types over B by $S_\phi(B)$.

Theorem 9.7. Let $\phi(x; y) \in \mathcal{L}$. The following are equivalent:

- (a) ϕ is stable;
- (b) $|S_\phi(B)| \leq |B|$ for every infinite B ;
- (c) For some infinite cardinal λ we have $|B| \leq \lambda \Rightarrow |S_\phi(B)| \leq \lambda$;
- (d) ϕ does not have the binary tree property.

Proof. Every direction that we prove for this theorem will be a proof by contrapositive.

(a) \Rightarrow (b) Suppose that $|S_\phi(B)| > |B|$ for some infinite B . For any $a \in \mathbb{M}^{|x|}$ let

$$S_a := \{b \in B^{|y|} \mid \vdash \phi(a; b)\}.$$

Note that $\text{tp}_\phi(a/B) = \text{tp}_\phi(a'/B)$ if and only if $S_a = S_{a'}$. Let $\mathcal{F} := (S_a | a \in \mathbb{M}^{|x|})$. By the observation above,

$$|\mathcal{F}| = |S_\phi(B)| > |B| = |B^{|y|}|,$$

where the inequality is our original assumption. Thus, we can apply Erdős-Makkai (Theorem 9.3) to see there are $(b_i | i < \omega)$ in $B^{|y|}$ and $(S_{a_i} | i < \omega)$ from \mathcal{F} such that

- either $b_i \in S_{a_j}$ if and only if $j < i$;
- or $b_i \in S_{a_j}$ if and only if $i < j$.

Note that $b_i \in S_{a_j}$ if and only if $\models \phi(a_j; b_i)$. So the first case is equivalent to the statement of $\phi(x; y)$ having the order property. The second case is equivalent to ϕ^{opp} (obtained from swapping the variables of ϕ) having the order property, which we know implies that ϕ also has the order property. So we conclude that ϕ has the order property as desired.

(b) \Rightarrow (c) is trivial. We move to (c) \Rightarrow (d). Pick an arbitrary infinite λ . First, choose μ minimal such that $2^\mu > \lambda$. Then, the tree $I = {}^{<\mu} 2$ has cardinality $\leq \mu$ since

$$|I| \leq \left| \bigcup_{\nu < \mu} 2^\nu \right| \leq \lambda,$$

where the last inequality holds since we are taking a union of $\leq \mu$ -many sets of cardinality $\leq \lambda$. Now, suppose by contrapositive that $\phi(x; y)$ has the binary tree property. Note that by compactness we can take the binary tree to be I -indexed¹. By definition, each branch yields a consistent set of formulas which can be completed to a ϕ -type over B . By construction all these ϕ -types are disjoint: if $\sigma, \nu \in {}^\mu 2$ have meet $\tau \in {}^{<\mu} 2$, then the sets of formulas associated with σ and ν disagree on whether $\phi(x, b_\tau)$ is true. So

$$|B| \leq \lambda < 2^\mu \leq S_\phi(B),$$

yielding the negation of (c).

Finally, we prove (d) \Rightarrow (a). Say that $\phi(x; y)$ has the order property. By compactness, there are $(a_i b_i \vdash i \in [0, 1])$ such that

$$\phi(a_i, b_j) \text{ if and only if } i < j.$$

Pick $b'_0 = b_{\frac{1}{2}}$. By construction, for $i < 1/2$, $\models \phi(a_i, b'_0)$ and for $i \geq 1/2$, $\models \neg \phi(a_i, b'_0)$. Now, pick $b'_1 = b_{\frac{1}{4}}$ and $b_2 = b_{\frac{3}{4}}$ and keep building the tree of parameters $(b_s \mid s \in {}^{<\omega} 2)$ by splitting the intervals. Now, for each branch $\sigma \in {}^\omega 2$, it is easy to see that $\{\phi^{\sigma(n)}(x; b_{\sigma|n}) \mid n < \omega\}$ is finitely satisfiable. So it is satisfiable and gives the desired binary tree, completing the final part of the proof. \square

Exercise 9.8. Show that the following are equivalent:

1. T is stable (in the sense of being κ -stable for some infinite κ);
2. every \mathcal{L} -formula $\phi(x; y)$ is stable for T ;
3. T is κ -stable for all κ such that $\kappa^{|T|} = \kappa$.

Definition 9.9. For κ an infinite cardinal, let

$$\text{ded}(\kappa) := \sup\{|I| : I \text{ is a linear ordering with a dense subset of size } \kappa\}.$$

It is easy to see that $\kappa < \text{ded}(\kappa) \leq 2^\kappa$.

¹At this stage you are supposed to know how to run a standard compactness proof. In this case, you should expand T by constants c_s for $s \in I$ and consider the sets of formulas

$$\bigcup_{\sigma \in {}^\mu 2} \{\phi^{\sigma(v)}(x; c_{\sigma|v}) \mid v < \mu\}.$$

Any finite subset is finitely satisfiable by assigning to the c_s the appropriate b_s from the original binary tree, thus completing the compactness proof.

Definition 9.10. Let T be a countable theory. Write $f_T : \text{Card} \rightarrow \text{Card}$ for the function on cardinals given by

$$f_T(\kappa) := \sup\{|S_n(M)| : \mathcal{M} \models T, |M| = \kappa, n \in \omega\}.$$

[It is easy to see that if we fixed n in the definition above, we would still get f_T .]

Exercise 9.11. Prove that if T is unstable, then $f_T(\kappa) \geq \text{ded}(\kappa)$ for all cardinals $\kappa \geq |T|$.

Recall the following definitions and lemmas from the Model Theory course:

Definition 9.12. Let I be an infinite linear order and A a set of parameters. We say that $(a_i | i \in I)$ is **indiscernible** over A if for every $\mathcal{L}(A)$ -formula $\phi(x_1, \dots, x_n)$ and $i_1 < \dots < i_n, j_1 < \dots < j_n$ from I , we have that

$$\models \phi(a_{i_1}, \dots, a_{i_n}) \leftrightarrow \phi(a_{j_1}, \dots, a_{j_n}). \quad (2)$$

We say that the sequence is **totally indiscernible** over A if the condition 2 holds for any $\{i_1, \dots, i_n\}, \{j_1, \dots, j_n\}$ from I of size n .

For a sequence $(a_i | i \in I)$, its **EM-type** (i.e. Ehrenfeucht-Motowski type) over A is given by

$$\text{EM}(a_i | i \in I) := \{\phi(x_1, \dots, x_n) \in \mathcal{L}(A) \mid \models \phi(a_{i_1}, \dots, a_{i_n}) \text{ for all } i_1 < \dots < i_n, n < \omega\}.$$

Lemma 9.13 (Extracting indiscernible sequences). *Let A be a set of parameters and $(b_i | i \in I)$ a infinite sequence. Let J be a linear order. Then, there is a sequence $(a_j | j \in J)$ which is indiscernible over A and realising the EM-type of $(b_i | i \in I)$.*

Exercise 9.14. • Show that T is unstable if and only if there is an infinite sequence $(a_i | i < \omega)$ and a formula $\phi(x, y)$ such that $\models \phi(a_i, a_j)$ if and only if $i < j$;

- Show that if T is unstable there is an indiscernible sequence which is not totally indiscernible;
- Show that if T is stable then every indiscernible sequence is totally indiscernible. [Hint: Say that we have an indiscernible sequence $(a_i | i < \omega)$ which is not totally indiscernible. Show that there is a formula $\phi(x_1, \dots, x_n)$ such that for some transposition τ switching only two consecutive variables

$$\vdash \phi(a_1, \dots, a_n) \wedge \neg \phi(a_{\tau(1)}, \dots, a_{\tau(n)}).$$

Use this formula to find an unstable formula in T .]

Definition 9.15. We say that $\phi(x, y)$ has the **independence property**, IP, if there are $(b_i | i < \omega)$ and $(a_s | s \subseteq \omega)$ such that

$$\models \phi(a_s, b_i) \Leftrightarrow i \in s.$$

We say that $\phi(x, y)$ is NIP if it does not have the independence property. A theory is NIP if all of its formulas are NIP.

Example 9.16. The random graph has the independence property.

Exercise 9.17. Prove that a formula $\phi(x, y)$ has IP if and only if there is an indiscernible sequence $(b_i | i \in I)$ and a parameter a such that

$$\models \phi(a, b_i) \text{ if and only if } i \text{ is even.}$$

Definition 9.18. We say that $\phi(x, y)$ has the **strict order property**, SOP if there is an infinite sequence $(b_i)_{i < \omega}$ such that $\phi(\mathbb{M}, b_i) \subsetneq \phi(\mathbb{M}, b_j)$ for all $i < j < \omega$. We say that $\phi(x, y)$ is NSOP if it does not have the strict order property, and we say that a theory T is NSOP if all of its formulas are NSOP.

Exercise 9.19. Prove that T is stable if and only if it is NIP and NSOP. [Hint: For the (\Leftarrow) direction, consider an unstable theory with NIP and prove it must have the SOP.]

Definition 9.20. Let R be an associative ring with identity. Let $\mathcal{L}_R := \{+, 0, (\mu_r)_{r \in R}\}$, where the μ_r are unary function symbols. The theory of (left) R -modules T_R asserts of a model M that $(M, +, 0)$ is an Abelian group, and each f_r is an endomorphism of this group with f_1 being the identity map. Note that this theory is not complete.

Definition 9.21. An \mathcal{L} -formula is called **primitive positive** if it is an existential quantification of a conjunction of atomic formulas. That is, if it is of the form

$$\exists \bar{y} \bigwedge_{i \leq n} \psi_i(\bar{x}, \bar{y}),$$

where the formulas $\psi_i(\bar{x}, \bar{y})$ are atomic.

Fact 9.22. The theory T_R has elimination of quantifiers up to primitive positive formulas. That is, for every \mathcal{L}_R -sentence, $\phi(\bar{x})$ there is a Boolean combination of primitive positive formulas $\psi(\bar{x})$ such that $T_R \models \forall \bar{x} \phi(\bar{x}) \leftrightarrow \psi(\bar{x})$.

Exercise 9.23. Consider a primitive positive \mathcal{L}_R -formula $\phi(\bar{x}, \bar{z})$ and let M be an R -module. Show that $\phi(\bar{x}, \bar{0})$, where $\bar{0}$ is a string of 0's of length $|\bar{z}|$ defines either \emptyset or a subgroup of $M^{|\bar{x}|}$. Show that for any tuple \bar{a} such that $\phi(\bar{x}, \bar{a})$ is consistent, $\phi(M, \bar{a})$ is a coset of $\phi(\bar{x}, \bar{0})$. Deduce that that for any tuples \bar{a}, \bar{b} , $\phi(\bar{x}, \bar{a})$ and $\phi(\bar{x}, \bar{b})$ are either mutually inconsistent or equivalent. Using elimination of quantifiers up to pp-formulas, prove that for any R -module M , its theory is stable.

Definition 9.24. A group G satisfies the ω -stable descending chain condition if there is no infinite proper descending chain of definable subgroups of G ,

$$\cdots < H_{i+1} < H_i < \cdots < H_1 < G.$$

Exercise 9.25. Show that if G is an ω -stable group (i.e. a group whose theory is ω -stable), then G satisfies the ω -stable descending chain condition. Show that for an R -module M with R countable, the following are equivalent:

- M is ω -stable;
- M has the ω -stable descending chain condition;
- For any set of pp-formulas in a single variable $\{\phi_n(x) | n < \omega\}$ there is some $n \in \omega$ such that for all $m \in \omega$, $M \models \forall x (\bigwedge_{i < n} \phi_i(x) \rightarrow \phi_m(x))$.

10 Imaginaries

Remark 10.1. Today we work in a multisorted setting. By this, we mean that our theory will have a set S of sorts indicating separate domains on which our structure lives, so that

- variables and quantifiers are always restricted to a fixed sort $s \in S$. In particular, we have variables x^s and quantifiers $\forall x^s$ and $\exists x^s$ for each sort $s \in S$;
- Constants, domains and codomains of functions or relations are always restricted to some fixed sorts. (we do allow different arguments to come from different sorts, such as a relation $R(x^{s_1}, x^{s_2})$ for sorts $s_1, s_2 \in S$);
- Equality is also restricted to elements of a fixed sort. So we only have formulas $t_1 = t_2$ where t_1 and t_2 are terms in the same sort (but our language does not even contain the formulas $t_1 = t_2$ for t_1 and t_2 of different sorts).

An S -sorted structure will have (disjoint) domains $(M_s | s \in S)$, and symbols, terms, and formulas from the associated S -sorted language are interpreted in the obvious way (keeping in mind that variables and quantifiers are always restricted to a fixed sort).

Example 10.2. Consider the multi-sorted structure

$$M^\infty := (M_1, M_2, \dots)$$

consisting of countably many sorts where the structure on each sort is an infinite set with equality. Note a fundamental difference between the multi-sorted theory T_S^∞ of M^∞ and the theory T_P^∞ of an infinite set partitioned by infinitely many infinite predicates $(P_i | i < \omega)$. In fact, by compactness, T_P^∞ has models with an element not contained in any of the infinitely many predicates. Meanwhile, by nature of being a multisorted theory, any element in any model of T_S^∞ will be inside one of the sorts.

10.1 construction of \mathcal{M}^{eq}

Let \mathcal{M} be an \mathcal{L} -structure with theory T .

The idea behind the construction of \mathcal{M}^{eq} is that we add sorts for each quotient by a 0-definable equivalence relation and add projections to these quotients from M to induce the natural structure on them.

Definition 10.3. Let $\text{ER}(T)$ be the set of 0-definable equivalence relations $E(\bar{x}, \bar{y})$ on n_E -tuples on M . Note that this depends only on T since the theory already tells us which definable relations are equivalence relations and which ones yield the same or distinct equivalence relations.

Definition 10.4 (\mathcal{M}^{eq}). Consider the multi-sorted structure

$$\mathcal{M}^{eq} := (M, (M^{n_E} / E)_{E \in \text{ER}(T)})$$

with \mathcal{M} , the **real** (or **home**) **sort** being the original \mathcal{L} -structure \mathcal{M} identified with $M / (x = x)$ (in the sort $S_=$) with variables and quantifiers restricted accordingly. Additionally, for each $E \in \text{ER}(T)$ we have the projection to the quotient

$$\pi_E : M^{n_E} \rightarrow M/E.$$

We call elements in \mathcal{M}^{eq} **imaginary**.

Note that in \mathcal{L}^{eq} we added to \mathcal{L} for each $E \in \text{ER}(T)$ a sort S_E with variables x^E and quantifiers $\forall x^E$ and $\exists x^E$ and the n_E -ary function symbol π_E with domain $(S_=)^{n_E}$ and codomain S_E . Note that since there are only $|\mathcal{L}|$ -many definable equivalence relations, $|\mathcal{L}| = |\mathcal{L}^{eq}|$, where in the cardinality of a multi-sorted language we include the number of sorts.

We now prove that defining T^{eq} as $\text{Th}(\mathcal{M}^{eq})$ does not depend on the choice of model, but only on T .

Lemma 10.5. 1. Let $f : M \rightarrow N$ be an elementary embedding. Then, f extends uniquely to an elementary embedding $\tilde{f} : \mathcal{M}^{eq} \rightarrow \mathcal{N}^{eq}$;

2. $M \equiv N$ implies that $\mathcal{M}^{eq} \equiv \mathcal{N}^{eq}$.
So T^{eq} does not depend on the choice of model of T ;

3. If $M^* \models T^{eq}$, $M^* = \mathcal{M}^{eq}$ for some $M \models T$;

4. Any automorphism of M extends uniquely to an automorphism of \mathcal{M}^{eq} ;

5. Let $\mathcal{M} \equiv \mathcal{N}$ and $\bar{a} \in M, \bar{b} \in N$. Then, if $\text{tp}_M(\bar{a}) = \text{tp}_N(\bar{b})$, we also have $\text{tp}_{\mathcal{M}^{eq}}(\bar{a}) = \text{tp}_{\mathcal{N}^{eq}}(\bar{b})$.

Proof. For (1) note that there is only one way in which we can extend f to an elementary embedding, which is by setting $\tilde{f}(\bar{a}/E) = f(\bar{a})/E$ for each n_E -tuple \bar{a} and $E \in \text{ER}(T)$. It is easy to prove the map \tilde{f} is elementary by the Tarski-Vaught test.

For (2), since $M \equiv N$, $N \preceq \mathbb{M}$ and $M \preceq \mathbb{M}$, where \mathbb{M} is the monster model for $\text{Th}(M)$. So by (1), $N^{eq} \preceq \mathbb{M}^{eq}$ and $M^{eq} \preceq \mathbb{M}^{eq}$, meaning that $M^{eq} \equiv N^{eq}$.

(3) is obvious by restricting \mathcal{M}^* to the home sort, and (5) is an obvious consequence of (4) by considering the monster model. For (4) note that by (1) any $\sigma \in \text{Aut}(M)$ extends uniquely to an elementary embedding $\tilde{\sigma}$ of M^{eq} into itself. This is surjective since every element of M^{eq} is of the form $\bar{a}/E = \pi_E(\bar{a})$. Hence $\tilde{\sigma}$ is an automorphism. \square

Remark 10.6. With the same ideas it is possible to prove that T^{eq} is axiomatized by T joined with, for each $E \in \text{ER}(T)$, formulas asserting that π_E is surjective and that it maps elements in the same E -class to the same element.

Corollary 10.7. For $E_1, \dots, E_k \in \text{ER}(T)$ and $\phi(x_1^{E_1}, \dots, x_k^{E_k})$ an \mathcal{L}^{eq} -formula, there is an \mathcal{L} -formula $\psi(\bar{y}_1, \dots, \bar{y}_k)$ such that

$$T^{eq} \vdash \forall \bar{y}_1 \dots \bar{y}_k (\psi(\bar{y}_1 \dots \bar{y}_k) \leftrightarrow \phi(\pi_{E_1}(\bar{y}_1) \dots \pi_{E_k}(\bar{y}_k))).$$

Exercise 10.8. Let F be the forgetful map

$$F : S_{(S=)^n}(T^{eq}) \rightarrow S_n(T)$$

sending types of real n -tuples in T^{eq} to their restriction to an n -type in T . Show that F is a homeomorphism. Prove Corollary 10.7.

Exercise 10.9. Let κ be an infinite cardinal. Show the following:

- If \mathcal{M} is κ -saturated, then \mathcal{M}^{eq} is κ -saturated;
- If \mathcal{M} is strongly κ -homogeneous, then \mathcal{M}^{eq} is strongly κ -homogeneous;
- If T is κ -categorical, then T^{eq} is κ -categorical.
- If T is κ -stable, then T^{eq} is κ -stable;
- If T is stable, then T^{eq} is stable;
- If T is NIP, then T^{eq} is NIP;
- If T is NSOP, then T^{eq} is NSOP.

For X a non-empty set and $G \curvearrowright X$ we can endow G with the pointwise-convergence topology, where stabilizers of finite sets G_A for $A \subseteq X$ finite form a basis of clopen neighbourhoods of the identity. Hence, the cosets of stabilizers of finite sets gG_A for $A \subseteq X$ finite and $g \in G$ form a basis of clopen sets.

Exercise 10.10. Consider $\text{Aut}(M) \curvearrowright M$ for M countable and ω -categorical. Note that $\text{Aut}(M) = \text{Aut}(M^{eq})$. Prove that the open subgroups of $\text{Aut}(M)$ are precisely the stabilizers of imaginaries $\text{Aut}(M/e)$ for $e \in M^{eq}$. [Hint: the (\Leftarrow) direction does not use ω -categoricity. For the (\Rightarrow) direction, note that for any $H \leq \text{Aut}(M)$ and $\bar{a} \in \text{Aut}(M)$ the equivalence relation E on the $\text{Aut}(M)$ -orbit of \bar{a} $\text{Orb}(\bar{a})$ given by

$$E(g_1\bar{a}, g_2\bar{a}) \text{ if and only if } g_2^{-1}g_1 \in H$$

is 0-definable.]

11 How to eliminate your new imaginary friends

Let $X := \phi(\mathbb{M}, b)$ be a definable set. We can code information about X by an element in \mathbb{M}^{eq} as we explain below.

Definition 11.1. Let $X \subseteq \mathbb{M}$ be definable (possibly with parameters). We say that a (possibly imaginary) tuple d is a **canonical parameter** for X if for all $\sigma \in \text{Aut}(\mathbb{M})$,

$$\sigma(X) = X \text{ setwise if and only if } \sigma(d) = d.$$

Now, for $X := \phi(\mathbb{M}, b)$, consider the equivalence relation \sim on tuples of the same arity as b given by

$$a \sim c \text{ if and only if } \phi(\mathbb{M}, a) = \phi(\mathbb{M}, c).$$

Then, it is easy to see that $\tilde{b} := b / \sim$ is a canonical parameter for X .

👁 *Observation 11.2.* The canonical parameter $\tilde{b} := b / \sim$ we just constructed depends on the choice of formula ϕ . However, it is easy to see that any two canonical parameters are interdefinable. That is, if d and e are canonical parameters for the same definable set X , then $d \in \text{dcl}^{eq}(e)$ and $e \in \text{dcl}^{eq}(d)$. In fact, from Lemma 2.15, $d \in \text{dcl}^{eq}(e)$ if and only if

$$\text{for all } \sigma \in \text{Aut}(\mathbb{M}), \sigma(d) = d \Leftrightarrow \sigma(e) = e,$$

and since both e and d are canonical parameters for the same set, they must be preserved by exactly the same automorphisms. Conversely, any tuple interdefinable with a canonical parameter is also a canonical parameter.

Exercise 11.3. Let X be a definable subset of \mathbb{M}^n . Let A be a set of parameters, and let b be a canonical parameter for X .

- Show that X is definable over A if and only if $b \in \text{dcl}^{eq}(A)$;
- Show that the following are equivalent:
 - X is **almost A definable**, i.e. there is an A -definable equivalence relation E on n -tuples with finitely many classes and such that X is a union of E -classes;
 - $\{\sigma(X) \mid \sigma \in \text{Aut}(\mathbb{M}/A)\}$ is finite;
 - $\{\sigma(X) \mid \sigma \in \text{Aut}(\mathbb{M}/A)\} < |\mathbb{M}|$;
 - $b \in \text{acl}^{eq}(A)$.

Definition 11.4. T has **elimination of imaginaries** (EI) if for every $e \in \mathbb{M}^{eq}$ there is a real tuple \bar{b} from \mathbb{M} such that

$$e \in \text{dcl}^{eq}(\bar{b}) \text{ and } \bar{b} \in \text{dcl}^{eq}(e).$$

Lemma 11.5. T has EI if and only if every definable $X \subseteq \mathbb{M}$ has a real (i.e. in \mathbb{M}) canonical parameter.

Proof. (\Rightarrow) This direction is trivial since you can just pick a canonical parameter for X and then choose the real tuple interdefinable with it, which will also be a canonical parameter for X . (\Leftarrow) Consider the imaginary element e . We know $e = b/E$ for some real tuple b and an \emptyset -definable equivalence relation E . Consider $X := E(\mathbb{M}, b)$ and let d be a real canonical parameter for X . Since they are preserved by the same automorphisms $e \in \text{dcl}^{eq}(d)$ and $d \in \text{dcl}^{eq}(e)$. \square

Exercise 11.6. Show that T has EI if and only if for each $\phi(\bar{x}) \in \mathcal{L}(\mathbb{M})$ there is $\psi(x, y) \in \mathcal{L}$ such that there is a unique $\bar{a} \in \mathbb{M}$ such that $\phi(\mathbb{M}) = \psi(\mathbb{M}, \bar{a})$.

Exercise 11.7. Show that T^{eq} eliminates imaginaries. [Hint/thoughts: technically, there is no problem in defining imaginaries for a multi-sorted structure and so check the original definition. However, it is probably more convenient to show that definable subsets of \mathbb{M}^{eq} have canonical parameters in \mathbb{M}^{eq} .]

Definition 11.8. T has **weak elimination of imaginaries** (WEI) if for every $e \in \mathbb{M}^{eq}$ there is a real tuple \bar{b} from \mathbb{M} such that

$$e \in \text{dcl}^{eq}(\bar{b}) \text{ and } \bar{b} \in \text{acl}^{eq}(e).$$

Exercise 11.9. Show that the following are equivalent

1. T has weak elimination of imaginaries;
2. For every definable X there is a finite set $\{\bar{a}_1, \dots, \bar{a}_n\}$ such that for all $\sigma \in \text{Aut}(\mathbb{M})$

$$\sigma(X) = X \text{ if and only if } \sigma \text{ permutes the } \bar{a}_i;$$
3. For each $\phi(\bar{x}) \in \mathcal{L}(\mathbb{M})$ there is $\psi(\bar{x}, \bar{y})$ such that there is only a finite number of \bar{a} such that $\phi(\mathbb{M}) = \psi(\mathbb{M}, \bar{a})$;
4. For every definable X there is a smallest (real) algebraically closed set A such that X is A -definable.

Example 11.10. The theory of an infinite set with equality T_∞ has weak elimination of imaginaries but does not eliminate imaginaries. Let e be a canonical parameter for the definable set $\{a, b\}$ where a, b are real elements from \mathbb{M} . Note that

$$\text{dcl}^{eq}(e) \cap \mathbb{M} = \emptyset$$

since there is an automorphism fixing e but moving every element of \mathbb{M} (which swaps a and b). However,

$$\text{acl}^{eq}(e) \cap \mathbb{M} = \{a, b\}$$

and $e \in \text{dcl}^{eq}(ab)$. More generally, WEI can be deduced from the following exercise:

Exercise 11.11. Let \mathcal{M} be the countable model of an ω -categorical theory. The following are equivalent:

- $\text{Th}(\mathcal{M})$ has WEI;
- for all $A, B \subseteq \mathcal{M}$ algebraically closed, we have

$$\text{Aut}(\mathcal{M}/A \cap B) = \langle \text{Aut}(\mathcal{M}/A), \text{Aut}(\mathcal{M}/B) \rangle.$$

Lemma 11.12. Let T be strongly minimal and such that $\text{acl}^{eq} \cap \mathbb{M}$ is infinite. Then, T has WEI.

Proof. Let $e \in \mathbb{M}^{eq}$. So, $e = \bar{b}/E$ for E some \mathcal{O} -definable equivalence relation. Let

$$M_0 := \text{acl}^{eq}(e) \cap \mathbb{M}.$$

By assumption, M_0 is infinite. We wish to find c_1, \dots, c_n in M_0 such that $e = \pi_E(\bar{c})$, where π_E is the projection to the sort of E -classes. We prove this by induction. For the inductive hypothesis, suppose that we have c_1, \dots, c_{i-1} in M_0 such that for some d_i, \dots, d_n in \mathbb{M} ,

$$e = \pi_E(c_1, \dots, c_{i-1}, d_i, \dots, d_n).$$

For the inductive step we find c_i . First, let X be defined by

$$\phi(x_i) := \exists x_{i+1} \dots x_n (e = \pi_E(c_1, \dots, c_{i-1}, x_i, x_{i+1}, \dots, x_n)).$$

Whilst $\psi(x_i)$ has imaginary parameters, we know that X is also $\mathcal{L}(\mathbb{M})$ -definable by Corollary 10.7. So, since T is strongly minimal we have that X is either finite or cofinite. If X is finite, we have

$$X \subseteq \text{acl}^{eq}(ec_1 \dots c_{i-1}) \cap \mathbb{M} = M_0,$$

where the last equality follows from the fact that the c_j are already in M_0 by hypothesis. Hence, take c_i to be any element in X , and it will already satisfy the assumption. Otherwise, suppose that X is cofinite. Then, since M_0 is infinite, $X \cap M_0$ is non-empty and so pick $c_i \in X \cap M_0$. At the end of this inductive process, we found $\bar{c} \in \text{acl}^{eq}(e) \cap \mathbb{M}$ such that $e = \pi_E(\bar{c})$ (and so $e \in \text{dcl}^{eq}(\bar{c})$), proving WEI. \square

Lemma 11.13 (Chow coordinates). *Let F be a field. Let $\bar{b}_1, \dots, \bar{b}_m$ be n -tuples from F . Then, there is a tuple \bar{c} from F such that for all $\sigma \in \text{Aut}(F)$,*

$$\sigma(\bar{c}) = \bar{c} \text{ if and only if } \sigma \text{ permutes the } \bar{b}_i.$$

Proof. For $\bar{b}_i = (b_i^1 \dots b_i^n)$ let $p(X_1, \dots, X_n, Y)$ be the polynomial

$$\prod_{i=1}^m (Y - \sum_{j=1}^n b_i^j X_j).$$

Let \bar{c} be the coefficient of p . Let $\sigma \in \text{Aut}(F)$. Since $F[X_1, \dots, X_n, Y]$ is a unique factorisation domain, if σ fixes \bar{c} , then it must permute the \bar{b}_i . Conversely, every automorphism permuting the \bar{b}_i must fix \bar{c} . Hence, \bar{c} is the desired tuple. \square

Corollary 11.14. *The theory of algebraically closed fields in characteristic p , ACF_p , has EI.*

Proof. Let X be definable in $\mathbb{M} \models \text{ACF}_p$. We know this theory is strongly minimal and $\text{acl}(\emptyset)$ is infinite. So, by Lemma 11.12, it has weak elimination of imaginaries. By Exercise 11.9, there are $\{\bar{b}_1, \dots, \bar{b}_n\}$ such that for all $\sigma \in \text{Aut}(\mathbb{M})$

$$\sigma(X) = X \text{ if and only if } \sigma \text{ permutes the } \bar{b}_i.$$

But by Lemma ??, we can then find \bar{c} that is fixed by an automorphism if and only if that automorphism permutes the \bar{b}_i , meaning that \bar{c} is a canonical parameter for X . Thus, ACF_p has EI. \square

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