Model Theory II

Winter Semester 2024

Paolo Marimon

October 17, 2024

Contents

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 $\aleph_\alpha$? 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 superstability, 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 NSOP$_1$ 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 $\mathbb{M}$. 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 $f : A \to \mathcal{M}$ can be extended to an elementary map $A \cup \{a\} \to M$;
- **strongly κ-homogeneous** if for all $A \subseteq M$ of size $< \kappa$, any elementary map $f : A \to M$ 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, $\mathrm{cf}(X)$ is the smallest cardinality of a cofinal subset of X. We say that an infinite cardinal is κ is **regular** if $\mathrm{cf}(\kappa) = \kappa$. 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 $\lambda < \kappa$;
- $\mathcal{M}_{\lambda^+}$ realises all types over subsets of $\mathcal{M}_\lambda$ 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 $|\mathcal{M}_\lambda| \leq 2^\kappa$, $\mathcal{M}_\lambda$ 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 $\mathcal{M}_{\lambda^+}$ 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 $\mathcal{M}_{\lambda^+}$. 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. □

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 $\mathcal{M}_{\lambda^+}$ 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 $A \subset \mathcal{N}$ 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 $\mathcal{M}_\lambda$ entirely contains $|A|$. Since $\mathcal{M}_\lambda$ is λ^+ saturated, it realised all types over A, and so does $\mathcal{N}$. □

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 $\mathcal{M}, \mathcal{N}, \ldots$ we will consider will be elementarily embedded into this monster model, all sets of parameters $A, B, \ldots$ 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 $\mathrm{Aut}(\mathbb{M}/A)$*-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 $\sigma \in \mathrm{Aut}(M/A)$, we have that

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

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

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

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 $\sigma \in \mathrm{Aut}(\mathbb{M}/A)$ 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 $\psi(y) \in \mathrm{tp}(b/A)$, $\models \theta(a)$. 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 $\mathcal{M}_\lambda$ 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 $\mathrm{cf}(\kappa)$-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 $\mathrm{cf}(\beth_\kappa(\aleph_0)) = \kappa$, 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 algebracity

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 $A, B, \ldots$ 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 $\mathrm{acl}(A)$ 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 $(c_1, \ldots, c_n)$ a sequence of elements not algebraic over A. Show that $\mathrm{tp}(c_1, \ldots, c_n/A)$ has a realisation which is disjoint from B.

Exercise 3.4. Show that $\mathrm{acl}(A)$ 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 $\phi \in \mathcal{L}(M)$ 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

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

We prove this is finitely satisfiable. Take $\phi(x) \in \pi(x)$ (note π is closed under conjunctions) and $\psi_1(x), \ldots, \psi_n(x)$ 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 compacness 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. □

One can actually prove a more general statement, where the "small" sets one is avoiding are charaterised 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, $I \subseteq \mathrm{Def}_x(\mathbb{M})$ is an **ideal** if it contains $\emptyset$, and it is closed under (definable) subsets and finite unions.

Exercise 3.13. Prove the following:
Let $I \subseteq \mathrm{Def}_x(\mathbb{M})$ 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 $a_1^0, \ldots, a_m^0$ and $a_1^1, \ldots, a_m^1$ are two sequences of realisations of p of length m which are algebraically independent in the sense that

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

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

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

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 $a_{m+1}^0 \notin \operatorname{acl}(A\bar{a}^0)$ and $a_{m+1}^1 \notin \operatorname{acl}(A\bar{a}^1)$ be realisatinos of p. Take $\sigma \in \operatorname{Aut}(\mathbb{M}/A)$ 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 $\tau \in \operatorname{Aut}(\mathbb{M}/A\bar{a}^1)$ 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 the notion of closure on 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]. Whitney's work originates from noticing various similarities between certain ideas of independence and ranks in graph theory and the behaviour of linear independence. Meanwhile, Van de Waerden independently defined the notion when trying to formalise the behaviour of linear independence in vector spaces. Nowadays matroid theory is a branch of mathematics with several applications in combinatorics [15]. Our interests differ from standard matroid theory because we are interested in 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

$$\operatorname{cl} : \mathcal{P}(X) \to \mathcal{P}(X)$$

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

- (Reflexivity) $A \subseteq \mathrm{cl}(A)$;
- (Finite Character) $\mathrm{cl}(A) = \bigcup\{\mathrm{cl}(A') | A' \subseteq A \text{ finite }\}$;
- (Transitivity) $\mathrm{cl}(\mathrm{cl}(A)) = \mathrm{cl}(A)$;
- (Exchange) if $a \in \mathrm{cl}(Ab) \setminus \mathrm{cl}(A)$, then $b \in \mathrm{cl}(Aa)$.

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

Theorem 4.3. *Let ϕ be a strongly minimal $\mathcal{L}$-formula. Let $\mathrm{cl} : \mathcal{P}(\mathbb{M}) \to \mathcal{P}(\mathbb{M})$ be defined by, for $A \subseteq \phi(\mathbb{M})$, $\mathrm{cl}(A) := \mathrm{acl}(A) \cap \phi(\mathbb{M})$. Then, $(\phi(\mathbb{M}), \mathrm{cl})$ 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 $a \notin \mathrm{acl}(\emptyset)$ and $b \notin \mathrm{acl}(a)$. We need to prove $a \notin \mathrm{acl}(b)$.
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 $a' \notin \mathrm{acl}(\emptyset)$ and $b' \notin \mathrm{acl}(a')$ have the same type $p(x, y)$.
Now, take $(a_i | i < \omega)$ an infinite sequence of realisations of $q(x)$ such that

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

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

👁 *Observation* 4.4. The above prove is 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 $a \notin \mathrm{acl}(b)$ also in M.

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

- A is **independent** if $a \notin \mathrm{cl}(A \setminus \{a\})$ for each $a \in A$;
- A is a **generating set** if $\mathrm{cl}(A) = X$;
- 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 $\mathrm{cl}(A) = \mathrm{cl}(A \cap S)$ for all $A \subseteq S$ be the **restriction** of (X, cl) to S;
- (X, cl_S) given by $\mathrm{cl}_S(A) = \mathrm{cl}(A \cup S)$ for all $A \subseteq S$ be the **relativisation** of (X, cl) by S;

We write $\dim(S)$ for $\dim((S, \mathrm{cl}))$, and $\dim(X/S)$ for $\dim((X, \mathrm{cl}_S))$. 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 $(\phi(M), \mathrm{cl})$ is well defined since $\phi(M) \subseteq \phi(\mathbb{M})$. Meanwhile, its relativisation by $A \subseteq M$, $(\phi(M), \mathrm{cl}_A)$ corresponds to the natural pregeometry on $(\phi(M_A), \mathrm{cl})$, where M_A is the expansion of M by constants naming the elements of A. We write $\dim_\phi(M)$ for the dimension $(\phi(M), \mathrm{cl})$, and $\dim_\phi(M/A)$ for the dimension of $(\phi(M_A), \mathrm{cl})$.

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

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 $f : \phi(M) \to \phi(N)$;*
2. $\dim_\phi(M/A) = \dim_\phi(N/A)$.

Proof. Without loss of generality we work over $\emptyset$ (we can always just work in $\mathrm{Th}(\mathbb{M}_A)$).
($\Rightarrow$) We know there is an elementary bijection $f : \phi(M) \to \phi(N)$. 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 $f : U \to V$ 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 $f' : \mathrm{acl}(U) \to \mathrm{acl}(V)$. Now $f'|_{\phi(M)}$ is an elementary bijection from $\phi(M)$ to $\phi(N)$. □

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

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

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 $i \in \{1, 2\}$:

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

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

References

[1] Tuna Altınel, Alexandre Borovik, and Gregory L Cherlin. *Simple groups of finite Morley rank*. Vol. 145. American Mathematical Society Providence, RI, 2008.

[2] Manuel Bodirsky. *Complexity of infinite-domain constraint satisfaction*. Vol. 52. Cambridge University Press, 2021.

[3] Elisabeth Bouscaren. *Model theory and algebraic geometry: an introduction to E. Hrushovski's proof of the geometric Mordell-Lang conjecture*. Springer, 2009.

[4] Samuel Braunfeld, Colin Jahel, and Paolo Marimon. "When invariance implies exchangeability (and applications to invariant Keisler measures)". In: *arXiv preprint arXiv:2408.08370* (2024).

[5] Peter J Cameron. "Oligomorphic permutation groups". In: *Perspectives in Mathematical Sciences II: Pure Mathematics*. World Scientific, 2009, pp. 37–61.

[6] Hunter Chase and James Freitag. “Model theory and machine learning”. In: *Bulletin of Symbolic Logic* 25.3 (2019), pp. 319–332.

[7] Artem Chernikov and Nicholas Ramsey. “On model-theoretic tree properties”. In: *Journal of Mathematical Logic* 16.02 (2016), p. 1650009.

[8] Yatir Halevi and Itay Kaplan. “Saturated models for the working model theorist”. In: *Bulletin of Symbolic Logic* 29.2 (2023), pp. 163–169.

[9] Byunghan Kim. *Simplicity theory*. Vol. 53. OUP Oxford, 2013.

[10] Michael C Laskowski. “Vapnik-Chervonenkis classes of definable sets”. In: *Journal of the London Mathematical Society* 2.2 (1992), pp. 377–384.

[11] Angus Macintyre. “On definable subsets of p-adic fields”. In: *The Journal of Symbolic Logic* 41.3 (1976), pp. 605–610.

[12] Maryanthe Malliaris and Saharon Shelah. “Regularity lemmas for stable graphs”. In: *Transactions of the American Mathematical Society* 366.3 (2014), pp. 1551–1585.

[13] David Marker et al. “Model theory of differential fields”. In: *Model theory, algebra, and geometry* 39 (2000), pp. 53–63.

[14] Michael Morley. “Categoricity in power”. In: *Transactions of the American Mathematical Society* 114.2 (1965), pp. 514–538.

[15] James G Oxley. *Matroid theory*. Vol. 3. Oxford University Press, USA, 2006.

[16] Anand Pillay. *Geometric stability theory*. Oxford University Press, 1996.

[17] Saharon Shelah. *Classification theory: and the number of non-isomorphic models*. Elsevier, 1990.

[18] Pierre Simon. *A guide to NIP theories*. Cambridge University Press, 2015.

[19] Katrin Tent and Martin Ziegler. *A course in model theory*. 40. Cambridge University Press, 2012.

[20] Bartel Leendert Van der Waerden. *Moderne Algebra*. Vol. 2. Springer, Berlin, 1937.

[21] Hassler Whitney. “On the Abstract Properties of Linear Dependence”. In: *American Journal of Mathematics* 57.3 (1935), pp. 509–533. ISSN: 00029327, 10806377. URL: `http://www.jstor.org/stable/2371182` (visited on 10/17/2024).