

Part III – Model Theory

Based on lectures by Dr. S. Barbina
Notes taken by Bhavik Mehta, revised by Tim Seppelt

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0 Introduction

Lecture 1 Model theory is a part of logic that began by looking at algebraic objects such as groups and combinatorial objects such like graphs, described in formal language. The basic question in model theory is: ‘how powerful is our description of these objects to pin them down’? In Logic and Set Theory, the focus was on what was provable from a theory and language, but here we focus on whether or not a model exists.

1 Languages and structures

Definition 1.1 (Language). A **language** L consists of

- (i) a set \mathcal{F} of function symbols, and for each $f \in \mathcal{F}$ a positive integer m_f the **arity** of f .
- (ii) a set \mathcal{R} of relation symbols, and for each $R \in \mathcal{R}$, a positive integer m_R .
- (iii) a set \mathcal{C} of constant symbols.

Note: each of \mathcal{F} , \mathcal{R} and \mathcal{C} can be empty.

Example. Take $L = \{\{\cdot, {}^{-1}\}, \{1\}\}$, for \cdot a binary function and ${}^{-1}$ an unary function, 1 a constant. This is the **language** of groups, call it L_{gp} . Also, $L_{\text{lo}} = \{<\}$ a single binary relation, for linear orders.

Definition 1.2 (L -structure). Given a **language** L , say, an **L -structure** consists of

- (i) a non-empty set M , the **domain**,
- (ii) for each $f \in \mathcal{F}$, a function $f^{\mathcal{M}} : M^{m_f} \rightarrow M$,
- (iii) for each $R \in \mathcal{R}$, a relation $R^{\mathcal{M}} \subseteq M^{m_R}$,
- (iv) for each $c \in \mathcal{C}$, an element $c^{\mathcal{M}} \in M$.

$f^{\mathcal{M}}, R^{\mathcal{M}}, c^{\mathcal{M}}$ are the **interpretations** of f, R, c respectively.

Remark 1.3. We often fail to distinguish between the **symbols** in L and their **interpretations** in a **structure**, if the interpretations are clear from the context.

We may write $\mathcal{M} = \langle M, \mathcal{F}, \mathcal{R}, \mathcal{C} \rangle$.

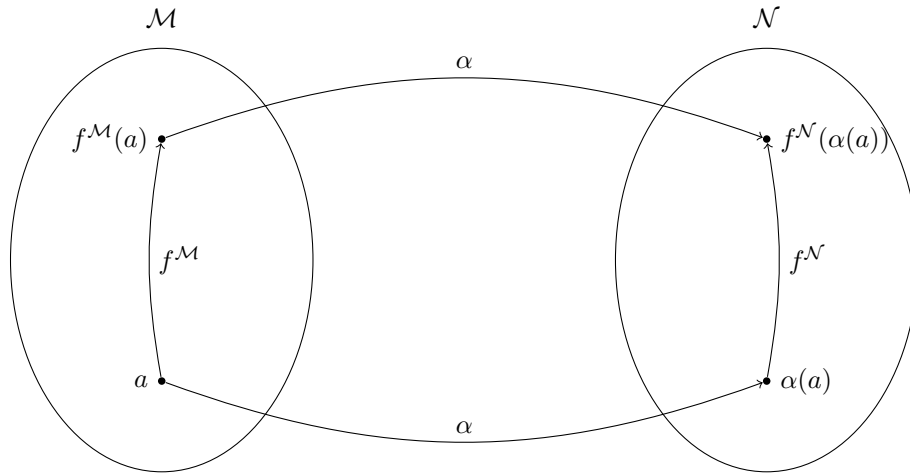
Example 1.4.

- (a) $\mathcal{R} = \langle \mathbb{R}^+, \{\cdot, {}^{-1}\}, 1 \rangle$ is an L_{gp} -**structure**.
- (b) $\mathcal{Z} = \langle \mathbb{Z}, \{+, -\}, 0 \rangle$ is an L_{gp} -**structure**.
- (c) $\mathcal{Q} = \langle \mathbb{Q}, < \rangle$ is an L_{lo} -**structure**.

Definition 1.5 (Embedding). Let L be a **language**, let \mathcal{M}, \mathcal{N} be **L -structures**. An **embedding** of \mathcal{M} into \mathcal{N} is an injective mapping $\alpha : M \rightarrow N$ such that

- (i) for all $f \in \mathcal{F}$, and $a_1, \dots, a_{m_f} \in M$,

$$\alpha(f^{\mathcal{M}}(a_1, \dots, a_{m_f})) = f^{\mathcal{N}}(\alpha(a_1), \dots, \alpha(a_{m_f}))$$



(ii) for all $R \in \mathcal{R}$, and $a_1, \dots, a_{m_R} \in M$

$$(a_1, \dots, a_{m_R}) \in R^{\mathcal{M}} \iff (\alpha(a_1), \dots, \alpha(a_{m_R})) \in R^{\mathcal{N}}$$

(iii) for all $c \in \mathcal{C}$, $\alpha(c^{\mathcal{M}}) = c^{\mathcal{N}}$.

An **isomorphism** of \mathcal{M} into \mathcal{N} is a surjective embedding (onto), written $\mathcal{M} \simeq \mathcal{N}$.

Exercise 1.6. Let G_1, G_2 be groups, regarded as L_{gp} -structures. Check that $G_1 \simeq G_2$ in the usual algebra sense if and only if there is an **isomorphism** $\alpha : G_1 \rightarrow G_2$ in the sense of [Definition 1.5](#).

2 Review: Terms, formulae and their interpretations

In addition to the [symbols](#) of L , we also have

- (i) infinitely many variables $\{x_i\}_{i \in I}$
- (ii) logical connectives \wedge, \neg (also expresses \vee, \implies, \iff)
- (iii) quantifier \exists (also expresses \forall)
- (iv) $(\ , \)$
- (v) equality symbol $=$

Definition 2.1 (L -terms). L -terms are defined recursively as follows:

- any variable x_i is a term
- any constant symbol is a term
- for any $f \in \mathcal{F}$, $f(t_1, \dots, t_{m_f})$ for any terms t_1, \dots, t_{m_f} is a term
- nothing else is a term

Notation: we write $t(x_1, \dots, x_m)$ to mean that the variables appearing in t are among x_1, \dots, x_m .

Lecture 2 **Example.** Take $\mathcal{R} = \langle \mathbb{R}^*, \{\cdot, {}^{-1}\}, 1 \rangle$. Then $\cdot(x_1, x_2), x_3$ is a [term](#), usually written $(x_1 \cdot x_2) \cdot x_3$. Also, $(\cdot(1, x_1))^{-1}$ is a [term](#), written $(1 \cdot x)^{-1}$

Definition 2.2. If \mathcal{M} is an L -structure, to each L -term $t(x_1, \dots, x_k)$ we assign a function a function $t^{\mathcal{M}} : M^k \rightarrow M$ defined as follows:

- (i) If $t = x_i$, $t^{\mathcal{M}}[a_1, \dots, a_k] = a_i$
- (ii) If $t = c$, $t^{\mathcal{M}}[a_1, \dots, a_k] = c^{\mathcal{M}}$.
- (iii) If $t = f(t_1(x_1, \dots, x_k), \dots, t_{m_f}(x_1, \dots, x_k))$, then

$$t^{\mathcal{M}}(a_1, \dots, a_k) = f^{\mathcal{M}}(t_1^{\mathcal{M}}(a_1, \dots, a_k), \dots, t_{m_f}^{\mathcal{M}}(a_1, \dots, a_k)).$$

Notice in L_{gp} , the term $x_2 \cdot x_3$ can be described as $t_1(x_1, x_2, x_3)$ or $t_2(x_1, x_2, x_3, x_4)$, or infinitely many other ways. In these cases, t_1 is [assigned](#) to $t_1^{\mathcal{M}} : M^3 \rightarrow M$, with $(a_1, a_2, a_3) \mapsto (a_2, a_3)$, and t_2 is assigned to $t_2^{\mathcal{M}} : M^4 \rightarrow M$, with $(a_1, a_2, a_3, a_4) \mapsto a_2 \cdot a_3$.

Fact 2.3. Let \mathcal{M}, \mathcal{N} be L -structures, and let $\alpha : \mathcal{M} \rightarrow \mathcal{N}$ be an [embedding](#). For any L -term $t(x_1, \dots, x_k)$ and $a_1, \dots, a_k \in M$ we have

$$\alpha(t^{\mathcal{M}}(a_1, \dots, a_k)) = t^{\mathcal{N}}(\alpha(a_1), \dots, \alpha(a_k))$$

Proof. By induction on the complexity of t . Let $\bar{a} = (a_1, \dots, a_k)$ and $\bar{x} = (x_1, \dots, x_k)$. Then

- (i) if $t = x_i$, then $t^{\mathcal{M}}(\bar{a}) = a_i$, and $t^{\mathcal{N}}(\alpha(a_1), \dots, \alpha(a_k)) = \alpha(a_i)$, so the conclusion holds.
- (ii) if $t = c$ a constant, then $t^{\mathcal{M}}(\bar{a}) = c^{\mathcal{M}}$, and $t^{\mathcal{N}}(\alpha(a_1), \dots, \alpha(a_k)) = c^{\mathcal{N}}$, and $\alpha(c^{\mathcal{M}}) = c^{\mathcal{N}}$, as required.

(iii) if $t = f(t_1(\bar{x}), \dots, t_{m_f}(\bar{x}))$, then

$$\alpha(f^{\mathcal{M}}(t_1^{\mathcal{M}}(\bar{a}), \dots, t_{m_f}^{\mathcal{M}}(\bar{a}))) = f^{\mathcal{N}}(\alpha(t_1^{\mathcal{M}}(\bar{a})), \dots, \alpha(t_{m_f}^{\mathcal{M}}(\bar{a})))$$

since α is an [embedding](#). $t_1(\bar{x}), \dots, t_{m_f}(\bar{x})$ have lower complexity than t , so inductive hypothesis applies. \square

Exercise 2.4. Conclude the proof of [Fact 2.3](#).

Definition 2.5 (Atomic formula). The set of **atomic formulas** of L is defined as follows

- (i) if t_1, t_2 are L -terms, then $t_1 = t_2$ is an atomic formula
- (ii) if R is a relation symbol and t_1, \dots, t_{m_R} are terms, then $R(t_1, \dots, t_{m_R})$ is an atomic formula
- (iii) nothing else is an atomic formula.

Definition 2.6 (Formula). The set of **L -formulas** is defined as follows

- (i) any [atomic formula](#) is an L -formula
- (ii) if φ is an L -formula, then so is $\neg\varphi$
- (iii) if φ and ψ are L -formulas, then so is $\varphi \wedge \psi$
- (iv) if φ is an L -formula, for any $i \geq 1$, $\exists x_i \varphi$ is an L -formula
- (v) nothing else is an L -formula

Example. In L_{gp} , $x_1 \cdot x_1 = x_2$ and $x_1 \cdot x_2 = 1$ are [atomic formulas](#), and $\exists x_1 (x_1 \cdot x_2) = 1$ is an L_{gp} -formula.

A variable occurs freely in a formula if it does not occur within the scope of a quantifier \exists (the variable is **free**). Otherwise the variable is **bound**. For instance, in $\exists x_1 (x_1 \cdot x_2) = 1$, x_1 is bound and x_2 is free.

Important convention: no variable occurs both [freely](#) and as a bound variable in the same formula.

A **sentence** is a [formula](#) with no [free](#) variables.

$$\exists x_1 \exists x_2 (x_1 \cdot x_2 = 1)$$

is an L_{gp} -sentence. Notation: $\varphi(x_1, \dots, x_k)$ means that the free variables in φ are among x_1, \dots, x_k .

Definition 2.7 (\models). Let $\varphi(x_1, \dots, x_k)$ be an L -formula, let \mathcal{M} be an L -structure, and let $\bar{a} = (a_1, \dots, a_k)$ be elements of M . We define $\mathcal{M} \models \varphi(\bar{a})$ recursively as follows.

- (i) if φ is $t_1 = t_2$, then $\mathcal{M} \models \varphi(\bar{a})$ if and only if $t_1^{\mathcal{M}}(\bar{a}) = t_2^{\mathcal{M}}(\bar{a})$.
- (ii) if φ is $R(t_1, \dots, t_{m_k})$ then $\mathcal{M} \models \varphi(\bar{a})$ iff

$$(t_1^{\mathcal{M}}(\bar{a}), \dots, t_{m_k}^{\mathcal{M}}(\bar{a})) \in R^{\mathcal{M}}.$$

- (iii) if φ is $\psi \wedge \chi$, then $\mathcal{M} \models \varphi(\bar{a})$ iff $\mathcal{M} \models \psi(\bar{a})$ and $\mathcal{M} \models \chi(\bar{a})$.
- (iv) if $\varphi = \neg\psi$ then $\mathcal{M} \models \varphi(\bar{a})$ iff $\mathcal{M} \not\models \psi(\bar{a})$. (this is well-defined since $\psi(\bar{a})$ is shorter than $\varphi(\bar{a})$)

(v) if φ is $\exists x_j \chi(x_1, \dots, x_k, x_j)$ (where $x_j \neq x_i$ for $i = 1, \dots, k$). Then $\mathcal{M} \models \varphi(\bar{a})$ iff there is $b \in \mathcal{M}$ such that $\mathcal{M} \models \chi(a_1, \dots, a_k, b)$.

Example. For $\mathcal{R} = \langle \mathbb{R}^*, \cdot, ^{-1}, 1 \rangle$, if $\varphi(x_1) = \exists x_2 (x_2 \cdot x_2) = x_1$ then $\mathcal{R} \models \varphi(1)$ but $\mathcal{R} \not\models \varphi(-1)$.

Notation 2.8 (Useful abbreviations). We write

- $\varphi \vee \psi$ for $\neg(\neg\varphi \wedge \neg\psi)$
- $\varphi \rightarrow \psi$ for $\neg\varphi \vee \psi$
- $\varphi \leftrightarrow \psi$ for $(\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi)$
- $\forall x_i \varphi$ for $\neg\exists x_i (\neg\varphi)$

Proposition 2.9. Let \mathcal{M}, \mathcal{N} be L -structures, let $\alpha : \mathcal{M} \rightarrow \mathcal{N}$ be an **embedding**. Let $\varphi(\bar{x})$ be **atomic** and $\bar{a} \in M^{|\bar{x}|}$, then

$$\mathcal{M} \models \varphi(\bar{a}) \iff \mathcal{N} \models \varphi(\alpha(\bar{a})).$$

Question: If φ is an L -formula, not necessarily **atomic**, does **Proposition 2.9** hold?

Lecture 3 Proof of **Proposition 2.9**. Cases:

- (i) $\varphi(\bar{x})$ is of the form $t_1(\bar{x}) = t_2(\bar{x})$ where t_1, t_2 are terms. (Exercise: complete this case, using **Fact 2.3**)
- (ii) $\varphi(\bar{x})$ is of the form $R(t_1(\bar{x}), \dots, t_{m_R}(\bar{x}))$. Then $\mathcal{M} \models R(t_1(\bar{a}), \dots, t_{m_R}(\bar{a}))$ if and only if $(t_1^{\mathcal{M}}(\bar{a}), \dots, t_{m_R}^{\mathcal{M}}(\bar{a})) \in R^{\mathcal{M}}$. Apply **Fact 2.3**.

□

Exercise 2.10. Show that **Proposition 2.9** holds if $\varphi(\bar{x})$ is a formula without quantifiers (a quantifier-free formula).

Example 2.11. Do **embeddings** preserve *all* **formulas**? No. Take $\mathcal{Z} = (\mathbb{Z}, <)$ and $\mathcal{Q} = (\mathbb{Q}, <)$ an L_{lo} -structure. Then $\alpha : \mathbb{Z} \rightarrow \mathbb{Q}$ (inclusion) is an embedding, but

$$\begin{aligned} \varphi(x_1, x_2) &= \exists x_3 (x_1 < x_3 \wedge x_3 < x_2). \\ \mathcal{Q} &\models \varphi(1, 2) \text{ but } \mathcal{Z} \not\models \varphi(1, 2). \end{aligned}$$

Fact 2.12. Let $\alpha : \mathcal{M} \rightarrow \mathcal{N}$ be an **isomorphism**. Then if $\varphi(\bar{x})$ is an L -formula and $\bar{a} \in M^{|\bar{x}|}$, then

$$\mathcal{M} \models \varphi(\bar{a}) \iff \mathcal{M} \models \varphi(\alpha(\bar{a})).$$

Proof. Exercise.

□

3 Theories and elementarity

Throughout, L is a [language](#), \mathcal{M}, \mathcal{N} are L -structures.

Definition 3.1 (L -theory). An L -theory T is a set of L -sentences. \mathcal{M} is a **model** of T if $\mathcal{M} \models \sigma$ for all $\sigma \in T$. We write $\mathcal{M} \models T$. The class of all the models of T is written $\text{Mod}(T)$. The theory of \mathcal{M} is the set

$$\text{Th}(\mathcal{M}) = \{ \sigma \mid \sigma \text{ is an } L\text{-sentence and } \mathcal{M} \models \sigma \}.$$

Example 3.2. Let T_{gp} be the set of L_{gp} -sentences

- (i) $\forall x_1 x_2 x_3 (x_1 \cdot (x_2 \cdot x_3) = (x_1 \cdot x_2) \cdot x_3)$
- (ii) $\forall x_1 (x_1 \cdot 1 = 1 \cdot x_1 = x_1)$
- (iii) $\forall x_1 (x_1 \cdot x_1^{-1} = x_1^{-1} \cdot x_1 = 1)$

Clearly for a group G , $G \models T_{\text{gp}}$. For a specific G , clearly $\text{Th}(G)$ is larger than T_{gp} !

Definition 3.3 (Elementarily equivalent). Say \mathcal{M} and \mathcal{N} are **elementarily equivalent** if $\text{Th}(\mathcal{M}) = \text{Th}(\mathcal{N})$. We write $\mathcal{M} \equiv \mathcal{N}$.

Clearly if $\mathcal{M} \simeq \mathcal{N}$, then $\mathcal{M} \equiv \mathcal{N}$ but if \mathcal{M} and \mathcal{N} are not [isomorphic](#), establishing whether $\mathcal{M} \equiv \mathcal{N}$ can be highly non-trivial!

We'll see $(\mathbb{Q}, <) \equiv (\mathbb{R}, <)$ as L_{lo} -structures.

Definition 3.4 (Elementary substructure).

- (i) an [embedding](#) $\beta : \mathcal{M} \rightarrow \mathcal{N}$ is **elementary** if for all [formulas](#) $\varphi(\bar{x})$ and $\bar{a} \in M^{|\bar{x}|}$,

$$\mathcal{M} \models \varphi(\bar{a}) \iff \mathcal{N} \models \varphi(\beta(\bar{a})).$$

- (ii) if $M \subseteq N$ and $\text{id} : \mathcal{M} \rightarrow \mathcal{N}$ is an embedding, then \mathcal{M} is said to be a **substructure** of \mathcal{N} , written $\mathcal{M} \subseteq \mathcal{N}$.
- (iii) if $M \subseteq N$ and $\text{id} : \mathcal{M} \rightarrow \mathcal{N}$ is an elementary embedding, then \mathcal{M} is said to be an **elementary substructure** of \mathcal{N} , written $\mathcal{M} \preceq \mathcal{N}$.

Example 3.5. Consider $\mathcal{M} = [0, 1] \subseteq \mathbb{R}$, an L_{lo} -structure, where $<$ is the usual order, and $\mathcal{N} = [0, 2] \subseteq \mathbb{R}$ in the same way. Then $\mathcal{M} \simeq \mathcal{N}$ as L_{lo} -structures.

Is $\mathcal{M} \equiv \mathcal{N}$? Yes: they are isomorphic!

Is $\mathcal{M} \subseteq \mathcal{N}$? Yes (the ordering $<$ coincides on \mathcal{M} and \mathcal{N} .)

But $\mathcal{M} \not\preceq \mathcal{N}$, since if $\varphi(x) = \exists y (x < y)$, then

$$\mathcal{N} \models \varphi(1) \quad \text{and} \quad \mathcal{M} \not\models \varphi(1).$$

Definition 3.6 (Parameter). Let \mathcal{M} be an L -structure, $A \subseteq M$, then define

$$L(A) := L \cup \{ c_a \mid a \in A \}$$

for c_a each constant symbols. An [interpretation](#) of \mathcal{M} as an L -structure extends to an interpretation of \mathcal{M} as an $L(A)$ -structure in the obvious way ($c_a^{\mathcal{M}} = a$). The elements of A are called **parameters**. If \mathcal{M}, \mathcal{N} are L -structures and $A \subseteq M \cap N$, then we write $\mathcal{M} \equiv_A \mathcal{N}$ when \mathcal{M}, \mathcal{N} satisfy exactly the same $L(A)$ -sentences.

Lecture 4 **Exercise 3.7.** $\mathcal{M} \preceq \mathcal{N} \iff \mathcal{M} \equiv_M \mathcal{N}$ (where M is the [domain](#) of \mathcal{M}).

Lemma 3.8 (Tarski-Vaught test). Let \mathcal{N} be an L -structure, let $A \subseteq N$. The following are equivalent:

- (i) A is the domain of a structure \mathcal{M} such that $\mathcal{M} \preccurlyeq \mathcal{N}$.
- (ii) for every $L(A)$ -formula $\varphi(x)$ with one free variable, if $\mathcal{N} \models \exists x \varphi(x)$, then $\mathcal{N} \models \varphi(b)$ for some $b \in A$.

Proof.

- (i) \Rightarrow (ii) Suppose $\mathcal{N} \models \exists x \varphi(x)$. Then by elementarity, $\mathcal{M} \models \exists x \varphi(x)$, and so $\mathcal{M} \models \varphi(b)$ for some $b \in \mathcal{M}$, so again by elementarity $\mathcal{N} \models \varphi(b)$.
- (ii) \Rightarrow (i) First we prove that A is the domain of a substructure $\mathcal{M} \subseteq \mathcal{N}$. By an exercise¹ on examples sheet 1, it is enough to check:

- (a) for each constant c , $c^{\mathcal{N}} \in A$.
- (b) for each function symbol f , $f^{\mathcal{N}}(\bar{a}) \in A$ (for all $\bar{a} \in A^{m_f}$).

For (a), use property (ii) with $\exists x (x = c)$. For (b) use property (ii) with $\exists x (f(\bar{a}) = x)$.

So we now have $\mathcal{M} \subseteq \mathcal{N}$, and the domain of \mathcal{M} is A . It remains to verify elementarity. Let $\chi(\bar{x})$ be an L -formula. We show that for $\bar{a} \in A^{|\bar{x}|}$,

$$\mathcal{M} \models \chi(\bar{a}) \iff \mathcal{N} \models \chi(\bar{a}). \quad (*)$$

By induction on the complexity of $\chi(\bar{x})$:

- if $\chi(\bar{x})$ is atomic $(*)$ follows from $\mathcal{M} \subseteq \mathcal{N}$ (\mathcal{M} is a substructure), cf. Proposition 2.9.
- if $\chi(\bar{x})$ is $\neg\psi(\bar{x})$ or $\chi(\bar{x})$ is $\psi(\bar{x}) \wedge \xi(\bar{x})$: straightforward induction.
- if $\chi(\bar{x}) = \exists y \psi(\bar{x}, y)$ where $\psi(\bar{x}, y)$ is an L -formula, suppose that $\mathcal{M} \models \chi(\bar{a})$. Then $\mathcal{M} \models \exists y \psi(\bar{a}, y)$, hence $\mathcal{M} \models \psi(\bar{a}, b)$ for some $b \in A = \text{dom } \mathcal{M}$. But then $\mathcal{N} \models \psi(\bar{a}, b)$ by inductive hypothesis, so $\mathcal{N} \models \chi(\bar{a})$.
Now let $\mathcal{N} \models \chi(\bar{a})$, i.e. $\mathcal{N} \models \exists y \psi(\bar{a}, y)$. By property (ii), $\mathcal{N} \models \psi(\bar{a}, b)$ for some $b \in A = \text{dom}(\mathcal{M})$. By inductive hypothesis, $\mathcal{M} \models \psi(\bar{a}, b)$ and so $\mathcal{M} \models \chi(\bar{a})$. \square

Remark 3.9. We define the cardinality $|L|$ of the language L to be

$$|\{\varphi(\bar{x}) \mid \varphi \text{ is a } L\text{-formula}\}|$$

Assume that the set of variables is countably infinite. Then informally, $|L| = |L| + \omega$, so $|L|$ is at least ω . In other words, if you start with a finite set of symbols, you still get an at least countably infinite set of formulas. Furthermore, for a set of parameter A , $|L(A)| = |L| + |A|$.

Definition 3.10 (Chain). Let λ be an ordinal. Then a **chain of length** λ of sets is a sequence $\langle M_i : i < \lambda \rangle$, where $M_i \subseteq M_j$ for all $i \leq j < \lambda$. A **chain of L -structures** is a sequence $\langle \mathcal{M}_i : i < \lambda \rangle$ such that $\mathcal{M}_i \subseteq \mathcal{M}_j$ for $i \leq j < \lambda$.

The **union** of this chain is the L -structure \mathcal{M} is defined as follows:

- the domain of \mathcal{M} is $\bigcup_{i < \lambda} M_i$

¹For an L -structure \mathcal{N} and a subset $A \subseteq N$ of the domain, A is the domain of a substructure if and only if for every constant c of L , $c^{\mathcal{N}} \in A$, and for every function f of L and $\bar{a} \in A^{n_f}$, $f^{\mathcal{N}}(\bar{a}) \in A$.

- $c^{\mathcal{M}} = c^{\mathcal{M}_i}$ for any $i < \lambda$ (c is a constant).
- if f is a function symbol, $\bar{a} \in M^{m_f}$, $f^{\mathcal{M}}(\bar{a}) = f^{\mathcal{M}_i}(\bar{a})$ where i is such that $\bar{a} \in M_i^{m_f}$.
- if R is a relation symbol, then $R^{\mathcal{M}} = \bigcup_{i < \lambda} R^{\mathcal{M}_i}$

Theorem 3.11 (Downward Löwenheim-Skolem). Let \mathcal{N} be an L -structure, and $|N| \geq |L| + \omega$. Let $A \subseteq N$. Then for any cardinal λ such that $|L| + |A| + \omega \leq \lambda \leq |\mathcal{N}|$, there is $\mathcal{M} \preceq \mathcal{N}$ such that

- (i) $A \subseteq M$, and
- (ii) $|\mathcal{M}| = \lambda$.

It helps to think about the case $|L| \leq \omega$, $|A| = \omega$ and $|N|$ is uncountable. For instance, think of $(\mathbb{C}, +, \cdot, -, ^{-1}, 0, 1)$ as a field. Then $\mathbb{Q} \subseteq \mathbb{C}$: it is a subset and a substructure. In particular, the property of being algebraically closed is in the theory of \mathbb{C} . Thus Theorem 3.11 gives a algebraically closed field, which is countable and contains \mathbb{Q} . A possibility is the algebraic closure of \mathbb{Q} .

Proof. We inductively build a chain $\langle A_i : i < \omega \rangle$, with $A_i \subseteq N$, such that $|A_i| = \lambda$. Our goal is to define $M = \bigcup_{i < \omega} A_i$.

Let $A_0 \subseteq N$ be such that $A \subseteq A_0$ and $|A_0| = \lambda$. At stage $i + 1$, assume that A_i has been built, with $|A_i| = \lambda$. Let $\langle \varphi_k(x) : k < \lambda \rangle$ be an enumeration of those $L(A_i)$ -formulas such that $\mathcal{N} \models \exists x \varphi_k(x)$. Observe there are no more than λ , since $|L(A)| = |L| + |A| + \omega \leq \lambda$. Let a_k be such that $\mathcal{N} \models \varphi_k(a_k)$ and let $A_{i+1} = A_i \cup \{a_k : k < \lambda\}$. Then $|A_{i+1}| = \lambda$.

Now let $M = \bigcup_{i < \omega} A_i$. We use the Tarski-Vaught test to show that M is the domain of a structure $\mathcal{M} \preceq \mathcal{N}$, and $|M| = \lambda$:

Let $\mathcal{N} \models \exists x \psi(x, \bar{a})$, where \bar{a} is a tuple in M . Then \bar{a} is a *finite* tuple, so there is an i such that \bar{a} is in A_i . Then A_{i+1} , by construction, contains b such that $\mathcal{N} \models \psi(b, \bar{a})$. But $A_{i+1} \subseteq M$, so $b \in M$. \square

4 Two relational structures

4.1 Dense linear orders

Lecture 5 **Definition 4.1** (Dense linear orders). A **linear order** is an $L_{lo} = \{<\}$ -structure such that

- (i) $\forall x \neg(x < x)$,
- (ii) $\forall xyz ((x < y \wedge y < z) \rightarrow x < z)$,
- (iii) $\forall xy ((x < y) \vee (y < x) \vee (x = y))$.

A linear order is **dense** if it also satisfies

- (iv) $\exists xy (x < y)$,
- (v) $\forall xy (x < y \rightarrow \exists z (x < z < y))$ (density).

A linear order has **no endpoints** if

- (vi) $\forall x (\exists y (x < y) \wedge \exists z (z < x))$.

T_{dlo} is the **theory** that includes axioms (i) to (vi), T_{lo} is the theory that includes axioms (i) to (iii) only.

Remark: (iv) and (v) imply that if $\mathcal{M} \models T_{dlo}$ then $|\mathcal{M}| \geq \omega$. Any model of T_{dlo} must be infinite.

Definition 4.2 ((Finite) Partial embedding, partially isomorphic). If $\mathcal{M}, \mathcal{N} \models T_{lo}$, then an injective map $p : A \subseteq M \rightarrow N$ is called a **partial embedding** if for all $a, b \in A$,

$$\mathcal{M} \models a < b \iff \mathcal{N} \models p(a) < p(b).$$

If $|\text{dom}(p)| < \omega$, then p is a **finite partial embedding**.

The structures \mathcal{M} and \mathcal{N} are said to be **partially isomorphic** if there is a collection I of partial embeddings such that

- (i) if $p \in I$ and $a \in M$, then there is $\hat{p} \in I$ such that $p \subseteq \hat{p}$ and $a \in \text{dom } \hat{p}$,
- (ii) if $p \in I$ and $b \in N$, then there is $\hat{p} \in I$ such that $p \subseteq \hat{p}$ and $b \in \text{img } \hat{p}$.

Lemma 4.3 (Back and Forth). Let \mathcal{M} and \mathcal{N} be L -structures that are countable and **partially isomorphic**. Then $M \simeq N$.

Proof. Enumerate $M = \langle a_i \mid i < \omega \rangle$ and $N = \langle b_i \mid i < \omega \rangle$. We define a chain of partial embeddings $\langle p_i \mid i < \omega \rangle$ such that $a_{i-1} \in \text{dom } p_i$, $b_{i-1} \in \text{img } p_i$ and $p_i \in I$, the collection that makes \mathcal{M} and \mathcal{N} **partially isomorphic**.

Let $p_0 \in I$ be any partial embedding. At stage $i+1$, let p_i be given. Use property (i) to extend p_i to \hat{p} such that $a_i \in \text{dom } \hat{p}$, and property (ii) to extend \hat{p} to $p_{i+1} \supseteq \hat{p}$ such that $b_i \in \text{img } p_{i+1}$. Then $\bigcup_{i < \omega}$ is the required isomorphism. \square

Lemma 4.4 (Extension lemma for dense linear orders). Suppose $\mathcal{M} \models T_{dlo}$, $\mathcal{N} \models T_{dlo}$, let $p : \text{dom } p \subseteq M \rightarrow N$ be a **finite partial embedding**. Then if $c \in M$, there is a finite partial embedding \hat{p} such that $p \subseteq \hat{p}$ and $c \in \text{dom}(\hat{p})$.

Proof. Enumerate $\text{dom } p = \langle a_i \mid i < n+1 \rangle$ and let $c \in M$ such that $c \notin \text{dom } p$. Split into three cases:

1. $c < a_0$. Use axiom (vi), which asserts that there are no endpoints, to find $d \in N$ such that $d < p(a_0)$ and let $\hat{p} := p \cup \{\langle c, d \rangle\}$.
2. $a_i < c < a_{i+1}$ for some $a_i, a_{i+1} \in \text{dom}(p)$. Then $\mathcal{N} \models p(a_i) < p(a_{i+1})$, so by density, there exists d such that $\mathcal{N} \models p(a_i) < d < p(a_{i+1})$.
3. $c > a_n$. Similar to case 1. □

Theorem 4.5. Let $\mathcal{M}, \mathcal{N} \models T_{\text{dlo}}$ such that $|M| = |N| = \omega$. Then $\mathcal{M} \simeq \mathcal{N}$.

Proof. By Lemma 4.4, the collection I of finite partial embeddings satisfies Items (i) and (ii) in Definition 4.2. Since $\emptyset : \mathcal{M} \rightarrow \mathcal{N}$ is a finite partial embedding, $I \neq \emptyset$ and Lemma 4.3 applies. □

Definition 4.6 (Consistent, complete, \vdash). An L -theory T is **consistent** if there is \mathcal{M} such that $\mathcal{M} \models T$. If T is a theory in L and φ is an L -sentence, then we write $T \vdash \varphi$ if for all \mathcal{M} such that $\mathcal{M} \models T$, we also have $\mathcal{M} \models \varphi$. We say T **entails** φ . An L -theory T is **complete** if for all L -sentences φ , either $T \vdash \varphi$ or $T \vdash \neg\varphi$.

Is T_{dlo} complete?

Lecture 6 **Definition 4.7** (ω -categorical). A theory T in a countable language with a countably infinite model is called **ω -categorical** if any two countable models of T are isomorphic.

Corollary 4.8 (of Theorem 4.5). T_{dlo} is ω -categorical.

Proof. Say $\mathcal{M}, \mathcal{N} \models T_{\text{dlo}}$, and $|M| = |N| = \omega$. Then \emptyset (the empty map) is a finite partial embedding. By Theorem 4.5, $\mathcal{M} \simeq \mathcal{N}$. Instead of the empty map, we can also use any $\{\langle a, b \rangle\}$ where $a \in M, b \in N$ as initial finite partial embedding. □

Theorem 4.9. If T is an ω -categorical theory in a countable language, and T has no finite models then T is complete.

Proof. Let $\mathcal{M} \models T$ and φ be an L -sentence.

If $\mathcal{M} \models \varphi$, suppose $\mathcal{N} \models T$. Then by Downward Löwenheim-Skolem, there are $\mathcal{M}' \preceq \mathcal{M}$, $\mathcal{N}' \preceq \mathcal{N}$ such that $|\mathcal{M}'| = |\mathcal{N}'| = \omega$. By ω -categoricity, $\mathcal{M}' \simeq \mathcal{N}'$, so in particular $\mathcal{M}' \models \varphi$ and so $\mathcal{N}' \models \varphi$.

If $\mathcal{M} \models \neg\varphi$, similar. □

Corollary 4.10. T_{dlo} is complete.

Definition 4.11 ((Partial) elementary map). If \mathcal{M}, \mathcal{N} are L -structures, an injective map f such that $\text{dom } f \subseteq M$ and $\text{img } f \subseteq N$ is called a **(partial) elementary map** if for all L -formulae $\varphi(\bar{x})$ and $\bar{a} \in (\text{dom } f)^{|\bar{x}|}$, then

$$\mathcal{M} \models \varphi(\bar{a}) \iff \mathcal{N} \models \varphi(f(\bar{a})).$$

Remark 4.12. A map f is **elementary** iff every finite restriction of f is elementary.

Proof.

\Leftarrow Suppose f is not elementary. Then there are $\varphi(\bar{x})$ and $\bar{a} \in (\text{dom } f)^{|\bar{x}|}$ such that

$$\mathcal{M} \models \varphi(\bar{a}) \not\iff \mathcal{N} \models \varphi(f(\bar{a})).$$

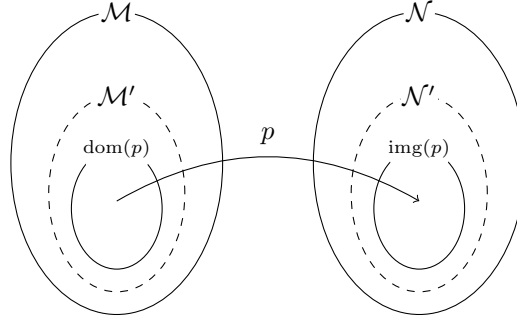
Then $f|_{\bar{a}}$ is a finite restriction of f that is not elementary.

\Rightarrow Clear. □

Proposition 4.13. Let $\mathcal{M}, \mathcal{N} \models T_{\text{dlo}}$ and let $p : A \subseteq M \rightarrow N$ be a **partial embedding**. Then p is **elementary**.

Proof. By [Remark 4.12](#) and the proof of [Lemma 4.3](#), it suffices to consider p finite. By [Downward Löwenheim-Skolem](#), we choose $\mathcal{M}', \mathcal{N}'$ such that

- (i) $|\mathcal{M}'| = |\mathcal{N}'| = \omega$.
- (ii) $\mathcal{M}' \preccurlyeq \mathcal{M}, \mathcal{N}' \preccurlyeq \mathcal{N}$
- (iii) $\text{dom}(p) \subseteq \mathcal{M}', \text{img}(p) \subseteq \mathcal{N}'$



Now p is a **finite partial embedding** between countable models, so p extends to an **isomorphism** $\pi : \mathcal{M}' \rightarrow \mathcal{N}'$ by [Lemma 4.4](#). In particular, π is an **elementary map** between \mathcal{M} and \mathcal{N} . \square

Corollary 4.14. $(\mathbb{Q}, <) \preccurlyeq (\mathbb{R}, <)$.

Proof. Use [Proposition 4.13](#) with $\text{id} : \mathbb{Q} \rightarrow \mathbb{R}$. \square

4.2 Random graphs

Definition 4.15 (Random graph). Let $L_{\text{gph}} = \{R\}$, a binary relation symbol. An L_{gph} -**structure** is a **graph** if

- (i) $\forall x \neg R(x, x)$,
- (ii) $\forall xy (R(x, y) \leftrightarrow R(y, x))$.

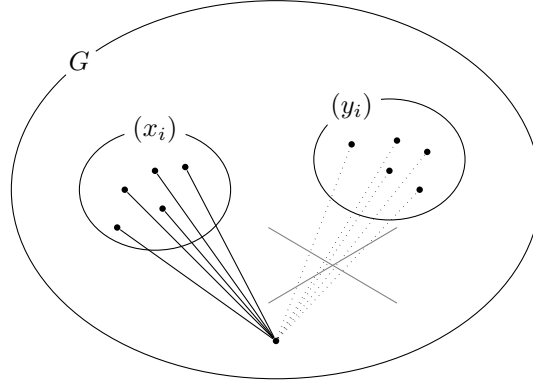
In other words, a graph contains no loops and is undirected.

An L_{gph} -**structure** is a **random graph** if it is a graph such that, for all $n \in \omega$, axiom (r_n) holds:

$$\forall x_0 \dots x_n, y_0 \dots y_n \left(\bigwedge_{i,j=0}^n x_i \neq y_j \rightarrow \exists z \left(\bigwedge_{i=0}^n (z \neq x_i) \wedge (z \neq y_i) \wedge R(z, x_i) \wedge \neg R(z, y_i) \right) \right)$$

- (iii) $\exists xy (x \neq y)$.

Axiom (r_n) effectively says that for disjoint subsets (x_i) and (y_i) each of size n , there is a (different) node z connected to each x_i and none of the y_i .



Remark. A [random graph](#) is infinite. Given a finite subset, we can always find a vertex that is connected to every vertex in the subset (likewise for not connected).

Fact 4.16. There is a [random graph](#).

Proof. Let the domain be ω , let $i, j \in \omega$ such that $i < j$. Write j as a sum of distinct powers of 2. Then $\{i, j\}$ is an edge iff 2^i appears in the sum. \square

Exercise. Prove that ω with this definition of R is a [random graph](#).

Remark. [Fact 4.16](#) shows that T_{rg} is consistent.

Definition 4.17 (Graph theories, partial embedding). T_{gph} consists of the axioms (i),(ii) above, and $T_{\text{rg}} = T_{\text{gph}} \cup \{(iii), (r_n) : n \in \omega\}$. If $\mathcal{M}, \mathcal{N} \models T_{\text{gph}}$, a **partial embedding** is an injective map $p : A \subseteq M$ to N such that

$$\mathcal{M} \models R(a, b) \iff \mathcal{N} \models R(p(a), p(b))$$

for all a, b in the domain. Just as before, if $|\text{dom}(p)| < \omega$ then p is called a **finite partial embedding**.

Lemma 4.18 (Extension lemma for random graphs). Let $\mathcal{M} \models T_{\text{gph}}$, $\mathcal{N} \models T_{\text{rg}}$, let $p : A \subseteq M \rightarrow N$ be a [finite partial embedding](#), and let $c \in M$. Then there is a finite partial embedding $\hat{p} : \hat{A} \subseteq M \rightarrow N$ such that, $c \in \text{dom}(\hat{p})$, and $p \subseteq \hat{p}$.

Proof. Assume that $c \notin \text{dom } p$ and let

$$\begin{aligned} U &:= \{a \in \text{dom } p \mid R(a, c)\}, \\ V &:= \{b \in \text{dom } p \mid \neg R(b, c)\}. \end{aligned}$$

Since p is finite, U and V are finite. Since N is a random graph, we can find $d \in N \setminus (p(U) \cup p(V))$ such that

- (i) $R(d, p(a))$ for all $a \in U$,
- (ii) $\neg R(d, p(b))$ for all $b \in V$.

Then $\hat{p} := p \cup \langle c, d \rangle$ is the desired extension. \square

Theorem 4.19. Let $\mathcal{M}, \mathcal{N} \models T_{\text{rg}}$ and $|\mathcal{M}| = |\mathcal{N}| = \omega$, and $p : A \subset M \rightarrow N$ a [finite partial embedding](#). Then $\mathcal{M} \simeq \mathcal{N}$, by an isomorphism that extends p .

Proof. Same as proof of [Theorem 4.5](#), but with [Lemma 4.18](#) instead of [Lemma 4.3](#). \square

Corollary 4.20. T_{rg} is ω -categorical and complete. Moreover, every [finite partial embedding](#) between [models](#) of T_{rg} is an [elementary map](#).

Remark 4.21. The unique (up to isomorphism) countable model of T_{rg} is *the* countable random graph, or the **Rado graph**. It is universal with respect to finite and countable graphs (i.e. it embeds them all). It is **ultrahomogeneous** i.e. every [isomorphism](#) between finite [substructures](#) extends to an automorphism of the whole graph.

Further information about random graphs can be found in the work of Peter Cameron.

5 Compactness

Section 11 contains an alternative version of the first part of this chapter.

Definition 5.1 (Filter). Let I be a set. Then a **filter** F on I is a subset of the power set 2^I such that

- (i) $I \in F$,
- (ii) if $X, Y \in F$, then $X \cap Y \in F$,
- (iii) if $X \in F$ and $X \subseteq Y \subseteq I$, then $Y \in F$.

A filter is **proper** if $F \neq 2^I$, or equivalently if $\emptyset \notin F$. An **ultrafilter** U on I is a proper filter such that for all $X \subseteq I$ either $X \in U$ or $I \setminus X \in U$.

Remark. Informally, a filter tells whether a set is large. The entire set I is large, the intersection of two large sets is large, and all supersets of large sets are large. An ultrafilter decides for every set whether its large or small, in which case its complement is large.

Fact 5.2. The following are equivalent for a proper filter U on I .

- (i) U is an ultrafilter,
- (ii) U is maximal among the proper filters on I ,
- (iii) if $X \cup Y \in U$ then either $X \in U$ or $Y \in U$.

Proof. Exercise. □

Definition 5.3 (Direct product). Let $\langle \mathcal{M}_i \mid i \in I \rangle$ be a collection of L -structures for a not necessarily ordered index set I . The **direct product** $\prod_{i \in I} \mathcal{M}_i$ is the set

$$\left\{ f : I \rightarrow \bigcup_{i \in I} M_i \mid \forall i \in I : f(i) \in M_i \right\}.$$

We will write X for $\prod_{i \in I} \mathcal{M}_i$ when the \mathcal{M}_i and I are understood. We write $a = \langle a(i) \mid i \in I \rangle$. Let U be an ultrafilter on I . Define a relation \sim_U on X as follows,

$$a \sim_U b \iff \{i \in I \mid a(i) = b(i)\} \in U.$$

Fact 5.4. For every filter U , the relation \sim_U is an equivalence relation.

Proof. Reflexivity and symmetry are clear. Let $a \sim_U b$ and $b \sim_U c$. Furthermore let $A := \{i \in I \mid a(i) = b(i)\}$ and similarly $B := \{i \in I \mid b(i) = c(i)\}$. By assumption, $A, B \in U$. Then $A \cap B \subseteq \{i \in I \mid a(i) = c(i)\}$ which implies $\{i \in I \mid a(i) = c(i)\} \in U$, so $a \sim_U c$. □

Remark. For **Fact 5.4**, U did not need to be an ultrafilter.

Write a_U for the equivalence class of $a \in X$ under \sim_U . We aim at making X/\sim_U into an L -structure. Call $X_U := \prod_{i \in I} \mathcal{M}_i / \sim_U$ the **ultraproduct** of the \mathcal{M}_i .

Fact 5.5. Let $a^k, b^k \in X$ for $k = 1, \dots, n$ be such that $a^k \sim_U b^k$ for all k . Then

- (i) if f is an n -ary function symbol, then

$$\langle f^{\mathcal{M}_i}(a^1(i), \dots, a^n(i)) \mid i \in I \rangle_U = \langle f^{\mathcal{M}_i}(b^1(i), \dots, b^n(i)) \mid i \in I \rangle_U.$$

(ii) if R is an n -ary relation symbol, then

$$\{i \in I \mid (a^1(i), \dots, a^n(i)) \in R^{\mathcal{M}_i}\} \in U \iff \{i \in I \mid (b^1(i), \dots, b^n(i)) \in R^{\mathcal{M}_i}\} \in U.$$

Sketch of the Proof of Fact 5.5. For **Item (i)**, consider for an ease of notation the case $n = 1$. Let $a, b \in X$ such that $a \sim_U b$. Let $A := \{i \in I \mid a(i) = b(i)\}$ and $C := \{i \in I \mid f^{\mathcal{M}_i}(a(i)) = f^{\mathcal{M}_i}(b(i))\}$. Clearly, $A \subseteq C$, so if $A \in U$, then $C \in U$.

Item (ii) similar. \square

Definition 5.6. Let $\langle \mathcal{M}_i \mid i \in I \rangle$ as in **Definition 5.3**. Let U be an ultrafilter on I . Then X_U is an L -structure where

(i) if c is a constant, then $c^{X_U} := \langle c^{\mathcal{M}_i} \mid i \in I \rangle_U$,

(ii) if f is an n -ary function symbol, then for a_U^1, \dots, a_U^n ,

$$f^{X_U}(a_U^1, \dots, a_U^n) := \langle f^{\mathcal{M}_i}(a^1(i), \dots, a^n(i)) \mid i \in I \rangle_U,$$

(iii) if R is an n -ary relation symbol, then for a_U^1, \dots, a_U^n ,

$$(a_U^1, \dots, a_U^n) \in R^{X_U} \iff \{i \in I \mid (a^1(i), \dots, a^n(i)) \in R^{\mathcal{M}_i}\} \in U.$$

Remark. **Fact 5.5** ensures that f^{X_U} and R^{X_U} are well-defined.

Theorem 5.7 (Łoś). Let $\langle \mathcal{M}_i \mid i \in I \rangle$ as in **Definition 5.3**, U an ultrafilter. Then,

(i) for all L -terms $t(x_1, \dots, x_n)$ and $a_U^1, \dots, a_U^n \in X_U$,

$$t^{X_U}(a_U^1, \dots, a_U^n) = \langle t^{\mathcal{M}_i}(a^1(i), \dots, a^n(i)) \mid i \in I \rangle_U,$$

(ii) for all L -formulas $\varphi(x_1, \dots, x_n)$ and $a_U^1, \dots, a_U^n \in X_U$,

$$X_U \models \varphi(a_U^1, \dots, a_U^n) \iff \{i \in I \mid \mathcal{M}_i \models \varphi(a^1(i), \dots, a^n(i))\} \in U,$$

(iii) for all L -sentences σ ,

$$X_U \models \sigma \iff \{i \in I \mid \mathcal{M}_i \models \sigma\} \in U.$$

Proof. **Item (i)** is an easy induction on the complexity of t , **Item (iii)** is an immediate consequence of **Item (ii)**. We prove **Item (ii)**.

The case of φ atomic is an easy induction. Let $\psi = \neg\chi$ for an L -formula $\chi(x_1, \dots, x_n)$ and let $A_\chi := \{i \in I \mid \mathcal{M}_i \models \chi(a^1(i), \dots, a^n(i))\}$. By the induction hypothesis, $X_U \models \chi(a_U^1, \dots, a_U^n)$ if and only if $A_\chi \in U$. Equivalently, $X_U \not\models \chi(a_U^1, \dots, a_U^n)$ iff $A_\chi \notin U$. But U is an ultrafilter, so $A_\chi \notin U$ implies $I \setminus A_\chi \in U$.

If $\varphi = \chi \wedge \psi$, let A_φ , A_ψ and A_χ as before. Then $A_\varphi = A_\psi \cap A_\chi$ and since U is a filter, $A_\varphi \in U$ iff $A_\chi \in U$ and $A_\psi \in U$. The required result follows from the inductive hypothesis on ψ and χ .

If $\varphi = \exists y \psi(\bar{x}, y)$, define A_φ as usual. Suppose there is $b_U \in X_U$ such that $X_U \models \psi(a_U^1, \dots, a_U^n, b_U)$. We have $\{i \in I \mid \mathcal{M}_i \models \psi(a^1(i), \dots, a^n(i), b(i))\} \subseteq A_\varphi$. By inductive hypothesis, this set is in U and so is A_φ . For the other implication, suppose $A_\varphi \in U$. For $i \in A_\varphi$ find $b_i \in M_i$ such that $\mathcal{M}_i \models \psi(a^1(i), \dots, a^n(i), b_i)$ and for $i \notin A_\varphi$ let b_i be arbitrary in M_i . Define $b \in X_U$ by $b(i) := b_i$. Define $A_\psi = \{i \in I \mid \mathcal{M}_i \models \psi(a^1(i), \dots, a^n(i), b(i))\}$. Then $A_\varphi \subseteq A_\psi$, and so $A_\psi \in U$. By inductive hypothesis, $X_U \models \psi(a^1, \dots, a^n, b)$, so $X_U \models \exists y \psi(\bar{a}, y)$. \square

Definition 5.8 (Finite intersection property). A subset $S \subseteq 2^I$ has the **finite intersection property** if for all $n \in \omega$ and $A_1, \dots, A_n \in S$, it holds that,

$$\bigcap_{i=1}^n A_i \neq \emptyset.$$

Remark. Proper filters have the finite intersection property.

Lemma 5.9. (i) If $S \subseteq 2^I$ has the **finite intersection property**, then it can be extended to a proper filter $F \supseteq S$.

(ii) A proper filter can always be extended to an ultrafilter assuming the axiom of choice.

Proof. For **Item (i)**, let F be the extension of S defined as follows,

$$F := \{X \subseteq I \mid X \text{ contains a finite intersection of elements from } S\}.$$

For **Item (ii)**, if F is a proper filter, let

$$\mathcal{F} := \{G \subseteq 2^I \mid G \supseteq F \text{ and } G \text{ is a proper filter}\}.$$

\mathcal{F} is partially ordered by inclusion. Check that the union of a chain in \mathcal{F} is in \mathcal{F} and apply Zorn's lemma. By **Fact 5.2**, the maximal element is the required ultrafilter. \square

Definition 5.10. A theory T is said to be

- (i) **consistent** or **satisfiable** if it has a model,
- (ii) **finitely consistent** or **finitely satisfiable** if every finite subset of T has a model.

Theorem 5.11 (Compactness). An L -theory T is consistent if and only if it is finitely consistent.

Proof. \Rightarrow immediate.

\Leftarrow Let $S \subseteq T$ be finite. Let $\mathcal{M}_S \models S$ be a model of S . Let $I = \{S \subseteq T \mid |S| < \omega\}$. The idea is to define an ultrafilter U on I such that $\prod_{S \in I} \mathcal{M}_S / \sim_U \models T$. By **Theorem 5.7**, it is enough to find U such that for all $\varphi \in T$, $\{S \in I \mid \varphi \in S\} \in U$. Let $\varphi \in T$ and define $A_\varphi = \{S \in I \mid \varphi \in S\}$.

We claim that $\{A_\varphi \mid \varphi \in T\}$ has the **finite intersection property**. Let $\varphi_1, \dots, \varphi_n \in T$. Then $\{\varphi_1, \dots, \varphi_n\} \in I$ and $\{\varphi_1, \dots, \varphi_n\} \subseteq \bigcap_{i=1}^n A_{\varphi_i} \neq \emptyset$. Then by **Lemma 5.9**, $\{A_\varphi \mid \varphi \in T\}$ extends to an ultrafilter U . By **Theorem 5.7**, $\prod_{S \in I} \mathcal{M}_S / \sim_U \models \varphi$ iff $\{S \in I \mid \mathcal{M}_S \models \varphi\} \in U$. But $A_\varphi \in U$ and $A_\varphi \subseteq \{S \in I \mid \mathcal{M}_S \models \varphi\} \in U$. \square

Definition 5.12 (Type). Let L be a **language**. An L -**type** $p(\bar{x})$ is a set of L -**formulas** whose **free** variables are in \bar{x} (and $\bar{x} = \langle x_i : i < \lambda \rangle$).

A type $p(\bar{x})$ is said to be

- (i) **satisfiable in an L -structure \mathcal{M}** if there is $\bar{a} \in M^{|\bar{x}|}$ such that $\mathcal{M} \models \varphi(\bar{a})$ for all $\varphi(\bar{x}) \in p(\bar{x})$,
- (ii) **satisfiable** if it is satisfiable in some L -structure \mathcal{M} ,
- (iii) **finitely satisfiable in \mathcal{M}** if all its finite subsets are satisfiable in \mathcal{M} ,

(iv) **finitely satisfiable** if all its finite subsets are satisfiable in some (possibly different) \mathcal{M} .

If $p(\bar{x})$ is satisfied in \mathcal{M} by a tuple \bar{a} , write $\mathcal{M} \models p(\bar{a})$ or $\mathcal{M}, \bar{a} \models p(\bar{x})$. We say \bar{a} **realizes** $p(\bar{x})$ in \mathcal{M} . Some authors use *consistent* instead of *satisfiable*.

Remark. An L -type may be **finitely satisfiable** in \mathcal{M} (i.e. every finite subset is **satisfiable** in \mathcal{M}) but not satisfiable in \mathcal{M} .

Example. Take $\mathcal{M} = (\mathbb{N}, <)$. Let $\varphi_n(x)$ say ‘there are at least n elements less than x ’.

$$p(x) := \{ \varphi_n(x) \mid n < \omega \}$$

Is $p(x)$ **finitely satisfiable** in \mathcal{M} ? Yes. But $p(x)$ is not **satisfiable** in \mathcal{M} .

Theorem 5.13 (Compactness theorem for types). Every **finitely satisfiable** L -type $p(\bar{x})$ is **satisfiable**.

Proof. Let $\bar{x} = \langle x_i : i < \lambda \rangle$, let $\langle c_i : i < \lambda \rangle$ be new constants (not in L). Expand L to $L' = L \cup \{c_i : i < \lambda\}$. Then $p(\bar{c})$ is a **finitely satisfiable** L' -theory and **Theorem 5.11** applied to $p(\bar{c})$ gives an L' -structure \mathcal{M}' such that $\mathcal{M}' \models p(\bar{c})$. But \mathcal{M}' reduces to an L structure \mathcal{M} , so $\mathcal{M}, \bar{c}^{\mathcal{M}'} \models p(\bar{x})$. \square

Lecture 9 **Lemma 5.14.** Let \mathcal{M} be a **structure**, let $\bar{a} = \langle a_i : i < \lambda \rangle$ an enumeration of \mathcal{M} . Let

$$q(\bar{x}) = \{ \varphi(\bar{x}) \mid \mathcal{M} \models \varphi(\bar{a}) \},$$

where $|\bar{x}| < \lambda$. Then $q(\bar{x})$ is **satisfiable** in \mathcal{N} iff there is $\beta : \mathcal{M} \rightarrow \mathcal{N}$ that is an **elementary embedding**.

Proof.

(\Rightarrow) If $q(\bar{x})$ is **satisfiable** in \mathcal{N} , there is $\bar{b} \in N^{|\bar{x}|}$ such that

$$\mathcal{N} \models \varphi(\bar{b}) \quad \forall \varphi(\bar{x}) \in q(\bar{x}).$$

Then $\beta : a_i \mapsto b_i$ for $i < \lambda$ is an **elementary embedding**. (β preserves, for example, **atomic formulas** of the form $f(a_{i_1}, \dots, a_{i_n}) = a_{i_{n+1}}$). More generally, for any $\varphi(\bar{x})$ an L -formula,

$$\mathcal{M} \models \varphi(\bar{a}) \iff \mathcal{N} \models \varphi(\bar{b})$$

but $\beta(\bar{a}) = \bar{b}$ so we have **elementarity**.

(\Leftarrow) If $\beta : \mathcal{M} \rightarrow \mathcal{N}$ is elementary, then $\beta(\bar{a})$ satisfies $q(\bar{x})$ in \mathcal{N} . \square

This lemma is sometimes also called the **Diagram Lemma**, and stated as: Suppose $\text{Th}(\mathcal{M}_M)$ is a theory in $L(M)$. Then if $\mathcal{N} \models \text{Th}(\mathcal{M}_M)$, then \mathcal{M} **embeds elementarily** in \mathcal{N} .

Remark 5.15. We can consider types in $L(A)$, where $A \subseteq M$. In particular, we can have $M = A$.

Types of this kind are said to have **parameters in** A (or to be over A). If $p(\bar{x})$ is a type over M , then there is \bar{a} , an enumeration of M , and a type $p'(\bar{x}, \bar{z})$ in L where the \bar{z} are new constants, $|\bar{z}| = |\bar{a}|$, and $p(\bar{x}) = p'(\bar{x}, \bar{a})$.

Theorem 5.16. If \mathcal{M} is a **structure**, and $p(\bar{x})$ is a **type** in $L(M)$ that is **finitely satisfiable** in \mathcal{M} , then $p(\bar{x})$ is **satisfiable** in some \mathcal{N} such that $\mathcal{M} \preceq \mathcal{N}$.

Example. Take $\mathcal{M} = (\mathbb{Q}, <)$, and let $\langle a_i : i < \omega \rangle$ a sequence in \mathbb{Q} that converges to $\sqrt{2}$ from below, and let $\langle b_i : i < \omega \rangle \subseteq \mathbb{Q}$ tend to $\sqrt{2}$ from above. Set $\varphi_n(x) := a_n < x < b_n$. Then let $p(x) = \{ \varphi_n(x) \mid n < \omega \}$. Then $p(x)$ is an $L(\mathbb{Q})$ -type which is **finitely satisfiable** in \mathbb{Q} . But $p(x)$ is not **satisfiable** in \mathcal{M} . It is, however, satisfiable in $(\mathbb{R}, <) \succ (\mathbb{Q}, <)$.

Example. Take the interval $(0, 1) \subseteq \mathbb{Q}$ and let $\mathcal{M} = ((0, 1), <)$. Let $a_n = 1 - 1/n$ for $n \in \omega \setminus \{0\}$. Let $\varphi_n(x) = (a_n < x)$. Then $p(x) = \{ \varphi_n(x) \mid n \in \omega \setminus \{0\} \}$ is finitely satisfiable in \mathcal{M} but not satisfiable. However, $p(x)$ is satisfiable in $(\mathbb{R}, <) \succ \mathcal{M}$.

Proof of Theorem 5.16. Let $\langle a_i : i < \lambda \rangle$ enumerate \mathcal{M} , let

$$q(\bar{z}) := \{ \varphi(\bar{z}) \mid \mathcal{M} \models \varphi(\bar{a}) \}$$

where $|\bar{z}| = \lambda$ and the z_i are new variables (so not among the \bar{x}). Write $p(\bar{x})$ as $p'(\bar{x}, \bar{a})$ for some $p'(\bar{x}, \bar{z})$ (an L -type).

Claim: $p'(\bar{x}, \bar{z}) \cup q(\bar{z})$ is **finitely satisfiable** in \mathcal{M} .

Proof: $p'(\bar{x}, \bar{a})$ is finitely satisfiable by hypothesis and $q(\bar{z})$ is **realized** by \bar{a} .

Then, by **Compactness theorem for types**, $p'(\bar{x}, \bar{z}) \cup q(\bar{z})$ is satisfiable. That is, there is \mathcal{N} and $\bar{b} \in \mathcal{N}^{|\bar{x}|}$ and $\bar{c} \in \mathcal{N}^{|\bar{z}|}$ such that

$$\mathcal{N} \models p'(\bar{c}, \bar{b}) \cup q(\bar{b}).$$

In particular, $\mathcal{N} \models q(\bar{b})$, then by **Lemma 5.14**, $\beta : a_i \mapsto b_i$ is an **elementary embedding**. \square

Theorem 5.17 (Upward Löwenheim-Skolem). Let \mathcal{M} be such that $|\mathcal{M}| \geq \omega$. Then for any $\lambda \geq |\mathcal{M}| + |L|$, there is \mathcal{N} such that $\mathcal{M} \preceq \mathcal{N}$, and $|\mathcal{N}| = \lambda$.

Proof. Let $\bar{x} = \langle x_i : i < \lambda \rangle$ a tuple of distinct variables. Let

$$p(\bar{x}) = \{ x_i \neq x_j \mid i < j < \lambda \}.$$

Then $p(\bar{x})$ is **finitely consistent** in \mathcal{M} . By **Theorem 5.16**, $p(\bar{x})$ is **realized** in some $\mathcal{M} \preceq \mathcal{N}$, and $|\mathcal{N}| \geq \lambda$. By **Downward Löwenheim-Skolem**, we may assume $|\mathcal{N}| = \lambda$. \square

6 Saturation

Anything that might happen does happen.

Definition 6.1 (Saturated). Let λ be an infinite cardinal, let $|\mathcal{M}| \geq \omega$. Then \mathcal{M} is λ -saturated if \mathcal{M} realizes every type $p(x)$ with one free variable such that

- (i) $p(x)$ has parameters in $A \subseteq M$ and $|A| < \lambda$.
- (ii) $p(x)$ is finitely consistent in \mathcal{M} .

\mathcal{M} is saturated if it is $|\mathcal{M}|$ -saturated.

Can \mathcal{M} be λ -saturated if $\lambda > |\mathcal{M}|$? If so, \mathcal{M} would satisfy finitely satisfiable types in $L(M)$. For example,

$$p(x) = \{x \neq a_i \mid i < |\mathcal{M}|\}$$

where $\langle a_i : i < |\mathcal{M}| \rangle$ enumerates M . $p(x)$ is finitely satisfiable, but not satisfied in \mathcal{M} .

Lecture 10 **Definition 6.2** (Type of tuple). Let \mathcal{M} be an L -structure, $A \subseteq M$, \bar{b} a tuple in M (possibly infinite). The **type of \bar{b} over A** is the following $L(A)$ -type:

$$\text{tp}_{\mathcal{M}}(\bar{b}/A) := \{ \varphi(\bar{x}) \in L(A) \mid \mathcal{M} \models \varphi(\bar{b}) \}.$$

The subscript \mathcal{M} is often omitted if clear from context.

Remark 6.3.

- (i) $\text{tp}_{\mathcal{M}}(\bar{b}/A)$ is complete, i.e. for every $L(A)$ -formula $\varphi(\bar{x})$, either $\varphi(\bar{x}) \in \text{tp}(\bar{b}/A)$ or $\neg\varphi(\bar{x}) \in \text{tp}(\bar{b}/A)$.
- (ii) If $\mathcal{M} \preceq \mathcal{N}$, then for $A \subseteq M$, \bar{b} a tuple:

$$\text{tp}_{\mathcal{M}}(\bar{b}/A) = \text{tp}_{\mathcal{N}}(\bar{b}/A).$$

Fact 6.4.

- (i) If $f : A \subseteq \mathcal{M} \rightarrow \mathcal{N}$ is a (partial) elementary map, then in particular f preserves L -sentences, so $\mathcal{M} \equiv \mathcal{N}$.
- (ii) If $\mathcal{M} \equiv \mathcal{N}$, then \emptyset , the empty map, is an elementary map, as it preserves sentences.
- (iii) If $f : A \subseteq \mathcal{M} \rightarrow \mathcal{N}$ is elementary, and \bar{a} is an enumeration of $A = \text{dom}(f)$, then

$$\text{tp}_{\mathcal{M}}(\bar{a}/\emptyset) = \text{tp}_{\mathcal{N}}(f(\bar{a})/\emptyset).$$

More generally, if $f : \mathcal{M} \rightarrow \mathcal{N}$ is (partial) elementary and there is $A \subseteq M \cap N$ such that $A \subseteq \text{dom } f$, $f|_A = \text{id}$, then for every \bar{b} , a tuple in $\text{dom}(f)$,

$$\text{tp}_{\mathcal{M}}(\bar{b}/A) = \text{tp}_{\mathcal{N}}(f(\bar{b})/A).$$

- (iv) Let \bar{a} enumerate $A \subseteq M$, $A = \text{dom}(f)$ where $f : \mathcal{M} \rightarrow \mathcal{N}$ is elementary. Let $p(\bar{x}, \bar{a})$ be a type in $L(A)$ that is finitely satisfiable in \mathcal{M} . Then $p(\bar{x}, f(\bar{a}))$ is finitely satisfiable in \mathcal{N} :

Let

$$\{\varphi_1(\bar{x}, \bar{a}), \dots, \varphi_n(\bar{x}, \bar{a})\} \subseteq p(\bar{x}, \bar{a}).$$

By finite satisfiability of $p(\bar{x}, \bar{a})$,

$$\mathcal{M} \models \exists \bar{x} \bigwedge_{i=1}^n \varphi_i(\bar{x}, \bar{a}).$$

Then

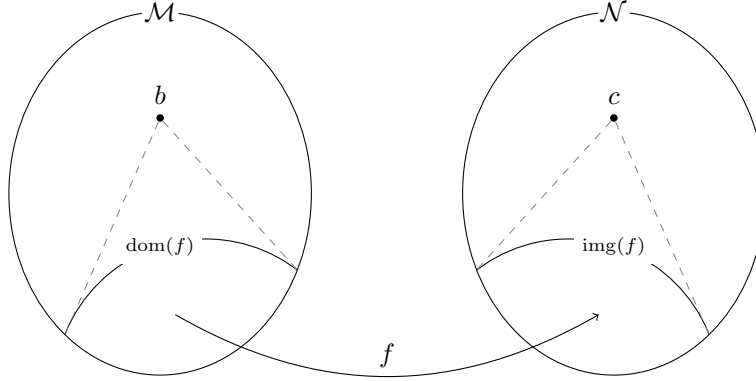
$$\mathcal{N} \models \exists x \bigwedge_{i=1}^m \varphi_i(\bar{x}, f(\bar{a}))$$

by elementarity of f . (Does $p(\bar{x}, \bar{a})$ satisfiable in \mathcal{M} imply $p(\bar{x}, f(\bar{a}))$ satisfiable in \mathcal{N} ? No.)

Theorem 6.5. Let \mathcal{N} be such that $|\mathcal{N}| \geq \lambda \geq |L|$. The following are equivalent:

- (i) \mathcal{N} is λ -saturated.
- (ii) if $b \in M$ and $f : \mathcal{M} \rightarrow \mathcal{N}$ partial elementary map such that $|f| < \lambda$, so in particular $\mathcal{M} \equiv \mathcal{N}$, then there is a partial elementary $\hat{f} \supseteq f$ and such that $b \in \text{dom}(\hat{f})$.
- (iii) If $p(\bar{z})$ is an $L(A)$ -type where $|\bar{z}| \leq \lambda$, $A \subseteq N$, $|A| < \lambda$ and $p(\bar{z})$ is finitely satisfiable in \mathcal{N} , then $p(\bar{z})$ is satisfiable in \mathcal{N} .

Proof. (i) \Rightarrow (ii). Let $f : \mathcal{M} \rightarrow \mathcal{N}$ be as in (ii), let $b \in M$. Let \bar{a} be an enumeration of $\text{dom}(f)$, so $|\bar{a}| < \lambda$. Let $p(x, \bar{a}) := \text{tp}_{\mathcal{M}}(b/\bar{a})$.



Then $p(x, \bar{a})$ is finitely satisfiable in \mathcal{M} , hence $\text{tp}_{\mathcal{N}}(x/f(\bar{a}))$ is finitely satisfiable in \mathcal{N} (by Fact 6.4(iv)). Since $|f(\bar{a})| < \lambda$ and \mathcal{N} is λ -saturated, $\text{tp}(x/f(\bar{a}))$ is realized in \mathcal{N} by some c . Then $f \cup \{ \langle b, c \rangle \}$ is the required extension of f :

$$\mathcal{M} \models \varphi(b, \bar{a}) \iff \mathcal{N} \models \varphi(c, f(\bar{a})).$$

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(ii) \Rightarrow (iii) Let $p(\bar{z})$ be as in (iii). Then by Theorem 5.16, $p(\bar{z})$ is realized by \bar{b} in some $\mathcal{M} \succcurlyeq \mathcal{N}$ where $|\bar{b}| = |\bar{z}|$. Then $\text{id}_A : \mathcal{M} \rightarrow \mathcal{N}$ is an elementary map. Idea: extend id_A to $f : \mathcal{M} \rightarrow \mathcal{N}$ such that $\bar{b} \in \text{dom } f$. We build f in stages using (ii). Let $f_0 := \text{id}_A$. At stage $i + 1$, use (ii) to put b_i in $\text{dom } f_{i+1}$. At limit stages $\mu < \lambda$, let $f_\mu = \bigcup_{i < \mu} f_i$. We get that $\bigcup_{i < \lambda} f_i$ is elementary and $\bar{b} \in \text{dom } f$. Then $f(\bar{b}) \in N$ and $\mathcal{N} \models p(f(\bar{b}))$.

(iii) \Rightarrow (i) is trivial. \square

Corollary 6.6. If \mathcal{M} and \mathcal{N} are saturated and $\mathcal{M} \equiv \mathcal{N}$ and $|\mathcal{M}| = |\mathcal{N}|$ then any elementary $f : \mathcal{M} \rightarrow \mathcal{N}$ such that $|f| < |\mathcal{M}|$ extends to an isomorphism (in particular $\mathcal{M} \simeq \mathcal{N}$).

Proof. Use [Theorem 6.5\(ii\)](#) to extend $f : \mathcal{M} \rightarrow \mathcal{N}$ to an **isomorphism** by back-and-forth (take unions at limit stages). Since $\mathcal{M} \equiv \mathcal{N}$, \emptyset is elementary. \square

Corollary 6.7. Models of T_{dlo} and T_{rg} are ω -saturated.

Proof. By [Theorem 6.5](#) and [Lemma 4.4](#) and [Remark 4.12](#) for T_{dlo} and [Theorem 4.19](#) for T_{rg} . \square

So $(\mathbb{Q}, <)$ and $(\mathbb{R}, <)$ are ω -saturated. Is $(\mathbb{R}, <)$ ω_1 -saturated? No, it does not realize

$$p(x) := \{x > q \mid q \in \mathbb{Q}\}.$$

Definition 6.8 (Automorphism). An isomorphism $\alpha : \mathcal{N} \rightarrow \mathcal{N}$ is called an **auto-morphism**. The automorphisms of \mathcal{N} form a group denoted by $\text{Aut}(\mathcal{N})$. If $A \subseteq N$, then

$$\text{Aut}(\mathcal{N}/A) := \{\alpha \in \text{Aut}(\mathcal{N}) \mid \alpha|_A = \text{id}\}.$$

Definition 6.9 (Universality, homogeneity).

- (i) An L -structure \mathcal{N} is λ -**universal** if for every $\mathcal{M} \equiv \mathcal{N}$ such that $|\mathcal{M}| \leq \lambda$ there is an **elementary embedding** $\beta : \mathcal{M} \rightarrow \mathcal{N}$.
- (ii) \mathcal{N} is λ -**homogeneous** if every elementary map $f : \mathcal{N} \rightarrow \mathcal{N}$ such that $|f| < \lambda$ extends to an **isomorphism** of \mathcal{N} .

An L -structure \mathcal{N} is said to be **homogeneous** if it is $|\mathcal{N}|$ -homogeneous. \mathcal{N} is **universal** if it is $|\mathcal{N}|$ -universal.

Remark. The difference between \leq and $<$ in the assertions is crucial. Some authors refer to universality as λ^+ -universality and to homogeneity as strong homogeneity.

Countable models of T_{rg} and T_{dlo} are universal and homogeneous.

Theorem 6.10. Let \mathcal{N} be such that $|\mathcal{N}| \geq |L|$. The following are equivalent

- (i) \mathcal{N} is **saturated**,
- (ii) \mathcal{N} is **universal** and **homogeneous**.

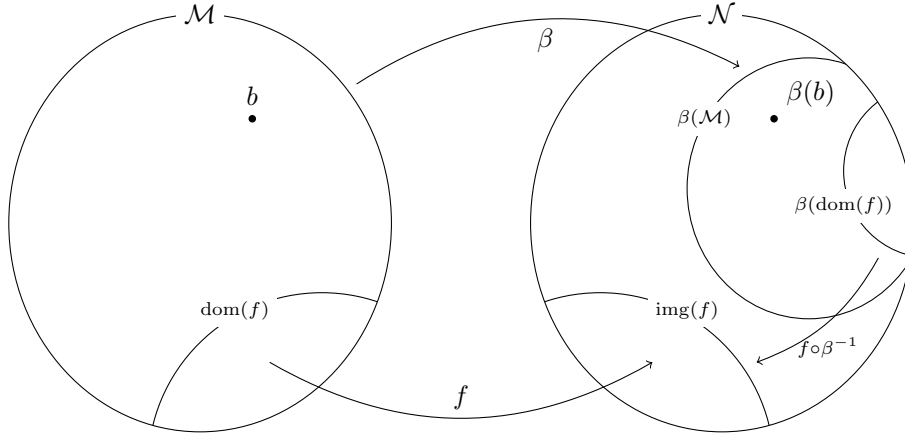
Proof. (i) \Rightarrow (ii). Assume \mathcal{N} is **saturated**, and $\mathcal{M} \equiv \mathcal{N}$ is such that $|\mathcal{M}| \leq |\mathcal{N}|$. Then let \bar{a} enumerate \mathcal{M} , let $p(\bar{x}) = \text{tp}_{\mathcal{M}}(\bar{a}/\emptyset)$. Then $p(\bar{x})$ is **finitely satisfiable** in \mathcal{M} .

Claim: $p(\bar{x})$ is finitely satisfiable in \mathcal{N} . Indeed, let $\{\varphi_1(\bar{x}), \dots, \varphi_n(\bar{x})\} \subseteq p(\bar{x})$, $\mathcal{M} \models \exists \bar{x} \bigwedge_{i=1}^n \varphi_i(\bar{x})$, and so $\mathcal{N} \models \exists \bar{x} \bigwedge_{i=1}^n \varphi_i(\bar{x})$ since $\mathcal{M} \equiv \mathcal{N}$.

Since $|\bar{x}| \leq |\mathcal{N}|$, \mathcal{N} realizes $p(\bar{x})$ by saturation ([Theorem 6.5](#)). **Homogeneity** follows from [Corollary 6.6](#) with $\mathcal{N} = \mathcal{M}$.

(ii) \Rightarrow (i). We show that if $\mathcal{M} \equiv \mathcal{N}$, $b \in M$, $f : \mathcal{M} \rightarrow \mathcal{N}$ **elementary** such that $|f| < |\mathcal{N}|$ then there is $\hat{f} \supseteq f$ **elementary** defined on b .

By working in $\mathcal{M}' \preccurlyeq \mathcal{M}$ such that $\text{dom}(f) \cup \{b\} \subseteq \mathcal{M}'$ if necessary (using [Theorem 3.11](#)), we may assume $|\mathcal{M}| \leq |\mathcal{N}|$. Since $\mathcal{M} \equiv \mathcal{N}$, by **universality** there is an **elementary embedding** $\beta : \mathcal{M} \rightarrow \mathcal{N}$. Then $\beta(\mathcal{M}) \preccurlyeq \mathcal{N}$.



Then the map $f \circ \beta^{-1} : \beta(\text{dom}(f)) \rightarrow \text{img}(f)$ is as composition of elementary maps elementary. By [homogeneity](#), there is $\alpha \in \text{Aut}(\mathcal{N})$ such that $f \circ \beta^{-1} \subseteq \alpha$. Then $f \cup \{ \langle b, \alpha(\beta(b)) \rangle \}$ is elementary (it is a restriction of $\alpha \circ \beta$). \square

Definition 6.11 (Orbit, defined set). Let \bar{a} be a tuple in \mathcal{N} and $A \subseteq N$. The **orbit** of \bar{a} over A is the set

$$O_{\mathcal{N}}(\bar{a}/A) := \{ \alpha(\bar{a}) \mid \alpha \in \text{Aut}(\mathcal{N}/A) \}.$$

If $\varphi(\bar{x})$ is an $L(A)$ -formula, then

$$\varphi(\mathcal{N}) := \left\{ \bar{a} \in N^{|\bar{x}|} \mid \mathcal{N} \models \varphi(\bar{a}) \right\}$$

is the **set defined by** $\varphi(\bar{x})$. A set is **definable** over A if it is defined by some $L(A)$ -formula. There are analogous notions of a type defining a set, and a set being type-definable.

Lecture 12 **Remark 6.12.** If \bar{a}, \bar{b} are tuples in \mathcal{N} of the same length, and $A \subseteq N$, then the following are equivalent.

- (i) $\text{tp}_{\mathcal{N}}(\bar{a}/A) = \text{tp}_{\mathcal{N}}(\bar{b}/A)$
- (ii) $\{ a_i \mapsto b_i \mid i < |\bar{a}| \} \cup \text{id}_A$ is an [elementary map](#) from \mathcal{N} to \mathcal{N}

Proposition 6.13. Let \mathcal{N} be λ -homogeneous, $A \subseteq N$, with $|A| < \lambda$ and let \bar{a} a tuple in \mathcal{N} such that $|\bar{a}| < \lambda$. Then

$$O_{\mathcal{N}}(\bar{a}/A) = p(\mathcal{N})$$

where $p(\bar{x}) = \text{tp}_{\mathcal{N}}(\bar{a}/A)$.

Proof. If $\alpha(\bar{a}) = \bar{b}$, where $\alpha \in \text{Aut}(\mathcal{N}/A)$, then $\text{tp}_{\mathcal{N}}(\bar{a}/A) = \text{tp}_{\mathcal{N}}(\bar{b}/A)$.

If $\text{tp}_{\mathcal{N}}(\bar{a}/A) = \text{tp}_{\mathcal{N}}(\bar{b}/A)$, then $\{ \langle a_i, b_i \rangle \mid i < |\bar{a}| \} \cup \text{id}_A$ is [elementary](#) and has cardinality less than λ . By [homogeneity](#) it extends to $\alpha \in \text{Aut}(\mathcal{N})$, and in particular $\alpha \in \text{Aut}(\mathcal{N}/A)$. Thus, $\bar{b} \in O_{\mathcal{N}}(\bar{a}/A)$. \square

7 The Monster Model

Given a **complete theory** T with an infinite **model**, we work in a **saturated structure** \mathcal{U} (sometimes denoted \mathbb{M}) that is a model of T , which is sufficiently large such that any other model of T we might be interested in is an **elementary substructure** of \mathcal{U} . \mathcal{U} is an expository device. See Tent/Ziegler for more details, also Marker.

Establishing the existence of the monster \mathcal{U} requires set-theoretic assumptions or the use of specific properties of T .

Definition 7.1 (Terminology and conventions). When working in \mathcal{U} , we say

- ‘ $\varphi(\bar{x})$ **holds**’ to mean that $\mathcal{U} \models \forall \bar{x} \varphi(\bar{x})$,
- ‘ $\varphi(\bar{x})$ is **consistent**’ to mean $\mathcal{U} \models \exists \bar{x} \varphi(\bar{x})$,
- ‘the type $p(\bar{x})$ is **consistent/satisfiable**’ to mean $\mathcal{U} \models \exists \bar{x} p(\bar{x})$, write $\mathcal{U} \models p(\bar{a})$ if \bar{a} witnesses $p(\bar{x})$ in \mathcal{U} ,
- a cardinality λ is **small** if $\lambda < |U|$ (usually denote $|U|$ by κ ,
- a **model** is some $\mathcal{M} \preceq \mathcal{U}$ such that $|M|$ is small.

Conventions:

- all tuples assumed to have small length, unless specified otherwise,
- **formulas** have parameters in U , unless specified otherwise,
- **types** have parameters in small sets, otherwise they are *global types* and not relevant in this course,
- **definable sets** have the form $\varphi(U)$ for some $L(U)$ -formula $\varphi(\bar{x})$,
- **type definable sets** have the form $p(U)$ for some type $p(\bar{x}, A)$ where $|A| < \kappa$,
- Orbits and types of tuples are within \mathcal{U} , so $\text{tp}(\bar{a}/A)$ means $\text{tp}_{\mathcal{U}}(\bar{a}/A)$,

$$O(\bar{a}/A) = O_{\mathcal{U}}(\bar{a}/A),$$

- If $p(\bar{x})$, $q(\bar{x})$ are **types**, we write $p(\bar{x}) \rightarrow q(\bar{x})$ to mean $p(\mathcal{N}) \subseteq q(\mathcal{N})$ (think of $p(\bar{x})$ as an infinite conjunction of formulas),
- small subsets of U will be denoted by letters A, B, C , etc.,
- sets of arbitrary cardinality will be denoted by $\mathcal{A}, \mathcal{B}, \mathcal{C}$, etc.

Fact 7.2. Let $p(\bar{x})$ be a **satisfiable $L(A)$ -type**, and $q(\bar{x})$ a **satisfiable $L(B)$ -type**, such that

$$p(\bar{x}) \rightarrow \neg q(\bar{x})$$

(explicitly, $p(\bar{x})$ and $q(\bar{x})$ have no common realisations).

Then there are $\varphi_i(\bar{x}) \in p(\bar{x})$ and $\psi_i(\bar{x}) \in q(\bar{x})$ such that

$$\bigwedge_{i=1}^n \varphi_i(\bar{x}) \rightarrow \neg \left(\bigwedge_{i=1}^m \psi_i(\bar{x}) \right).$$

Proof. $p(\bar{x}) \cup q(\bar{x})$ is not **realized** in \mathcal{U} . By **saturation** of \mathcal{U} , $p(\bar{x}) \cup q(\bar{x})$ is not **finitely satisfiable**, hence there exist finite subsets $\{\varphi_1(\bar{x}), \dots, \varphi_n(\bar{x})\} \subseteq p(\bar{x})$, $\{\psi_1(\bar{x}), \dots, \psi_m(\bar{x})\} \subseteq q(\bar{x})$ such that their union is not satisfiable. Then

$$\bigwedge \varphi_i(\bar{x}) \rightarrow \neg \left(\bigwedge \psi_i(\bar{x}) \right). \quad \square$$

Remark 7.3. Let $\varphi(\mathcal{U}, \bar{b})$ be such that $\varphi(\bar{x}, \bar{z})$ is an L -formula, $\bar{b} \in \mathcal{U}^{|\bar{z}|}$. If $\alpha \in \text{Aut}(\mathcal{U})$, then

$$\begin{aligned}\alpha[\varphi(\mathcal{U}, \bar{b})] &= \{ \alpha(\bar{a}) \mid \varphi(\bar{a}, \bar{b}), \bar{a} \in \mathcal{U}^{|\bar{x}|} \} \\ &= \{ \alpha(\bar{a}) \mid \varphi(\alpha(\bar{a}), \alpha(\bar{b})), \bar{a} \in \mathcal{U}^{|\bar{x}|} \} \\ &= \varphi(\mathcal{U}, \alpha(\bar{b}))\end{aligned}$$

So $\text{Aut}(\mathcal{U})$ acts on the definable sets in a natural way. (Similarly for the type-definable sets).

Also if $p(\bar{x}, \bar{z})$ is a type in L and $\bar{b} \in \mathcal{U}^{|\bar{z}|}$, then $\alpha(p(\mathcal{U}, \bar{b})) = p(\mathcal{U}, \alpha(\bar{b}))$.

Definition 7.4 (Invariant). An arbitrary large subset $\mathcal{D} \subseteq \mathcal{U}^\lambda$ for a small cardinal λ is **invariant** under $\text{Aut}(\mathcal{U}/A)$ (**invariant over** A) if $\alpha(\mathcal{D}) = \mathcal{D}$ for every $\alpha \in \text{Aut}(\mathcal{U}/A)$.

Equivalently, for all $\bar{a} \in \mathcal{D}$, $O(\bar{a}/A) \subseteq \mathcal{D}$.

If $\bar{a} \in \mathcal{D}$, $q(\bar{x}) = \text{tp}(\bar{a}/A)$ and $\bar{b} \models q(\bar{x})$, then $\bar{b} \in \mathcal{D}$. ($\text{tp}(\bar{b}/A) = \text{tp}(\bar{a}/A)$, so there is $\alpha \in \text{Aut}(\mathcal{U}/A)$ s.t. $\alpha(\bar{a}) = \bar{b}$ by **homogeneity** of \mathcal{U}). Hence we could also define invariance over A as

$$\forall \bar{a} \in \mathcal{D}, \quad \bar{b} \equiv_A \bar{a} \implies \bar{b} \in \mathcal{D}.$$

Proposition 7.5. Let $\varphi(\bar{x})$ be an $L(U)$ -formula and let $A \subseteq U$, then the following are equivalent:

- (i) $\varphi(\bar{x})$ is equivalent to some $L(A)$ -formula $\psi(\bar{x})$, i.e. $\forall \bar{x} (\varphi(\bar{x}) \leftrightarrow \psi(\bar{x}))$,
- (ii) $\varphi(\mathcal{U})$ is **invariant** over A .

Proof. (i) \Rightarrow (ii) is clear by **Remark 7.3** since $\alpha \in \text{Aut}(\mathcal{U}/A)$ fixes $\psi(\mathcal{U})$ setwise.

(ii) \Rightarrow (i): Let $\varphi(\bar{x}, \bar{z})$ be an L -formula such that $\varphi(\mathcal{U}, \bar{b})$ is **invariant** over A , for suitable $\bar{b} \in \mathcal{U}^{|\bar{z}|}$.

Let $q(\bar{z})$ be the **type** $\text{tp}(\bar{b}/A)$. If $\bar{c} \models q(\bar{z})$, then there is $\alpha \in \text{Aut}(\mathcal{U}/A)$ such that $\alpha(\bar{b}) = \bar{c}$. Then

$$\begin{aligned}\varphi(\mathcal{U}, \bar{c}) &= \alpha(\varphi(\mathcal{U}, \bar{b})) && \text{by Remark 7.3} \\ &= \varphi(\mathcal{U}, \bar{b}) && \text{by invariance}\end{aligned}$$

Hence

$$q(\bar{z}) \rightarrow \forall \bar{x} (\varphi(\bar{x}, \bar{z}) \leftrightarrow \varphi(\bar{x}, \bar{b})).$$

By an argument similar to **Fact 7.2**, there is $\theta(\bar{z}) \in q(\bar{z})$ such that $\theta(\bar{z}) \rightarrow \forall \bar{x} (\varphi(\bar{x}, \bar{z}) \leftrightarrow \varphi(\bar{x}, \bar{b}))$. Then $\theta(\bar{z})$ is an $L(A)$ -formula and $\exists z [\theta(\bar{z}) \wedge \varphi(\bar{x}, \bar{z})]$ defines $\varphi(\mathcal{U}, \bar{b})$. \square

Lecture 13 **Definition 7.6.** An injective map $p : A \subseteq \mathcal{M} \rightarrow \mathcal{N}$ is a **partial embedding** if for all tuples in $A = \text{dom}(p)$, p satisfies conditions (i), (ii), (iii) in **Definition 1.5**.

Idea: a **partial embedding** preserves quantifier-free formulas.

Proposition 7.7. Let $\varphi(\bar{x})$ be an L -formula. The following are equivalent:

- (i) there is $\psi(\bar{x})$, a quantifier-free L -formula such that

$$\forall \bar{x} [\varphi(\bar{x}) \leftrightarrow \psi(\bar{x})].$$

- (ii) for all **partial embeddings** $p : \mathcal{U} \rightarrow \mathcal{U}$, for all \bar{a} from $\text{dom}(p)$,

$$\varphi(\bar{a}) \leftrightarrow \varphi(p(\bar{a}))$$

Proof. (i) \Rightarrow (ii): clear since partial embeddings preserve the truth of quantifier-free formulas.

(ii) \Rightarrow (i). For $\bar{a} \in U$, set

$$\text{qftp}(\bar{a}) := \{ \psi(\bar{x}) \in \text{tp}(\bar{a}/\emptyset) \mid \psi(\bar{x}) \text{ is quantifier free} \},$$

the type consisting of all quantifier-free formulas that are satisfied by \bar{a} . Let

$$D := \{ q(\bar{x}) \mid q(\bar{x}) = \text{qftp}(\bar{a}) \text{ for some } \bar{a} \text{ such that } \varphi(\bar{a}) \}$$

be the collection of these types for \bar{a} which satisfy $\varphi(\bar{x})$. We claim that

$$\varphi(\mathcal{U}) = \bigcup_{q(\bar{x}) \in D} q(\mathcal{U}).$$

It is clear that $\varphi(\mathcal{U}) \subseteq \bigcup_{q(\bar{x}) \in D} q(\mathcal{U})$. For \supseteq , let $q(\bar{x}) \in D$, say $q(\bar{x}) = \text{qftp}(\bar{a})$. Let $\bar{b} \models q(\bar{x})$. Then $a_i \mapsto b_i$ is a **partial embedding**, so by (ii), $\varphi(\bar{b})$ holds in \mathcal{U} . Thus, $\bar{b} \in \varphi(\mathcal{U})$. So, $q(\mathcal{U}) \subseteq \varphi(\mathcal{U})$, and hence $\varphi(\mathcal{U}) = \bigcup_{q(\bar{x}) \in D} q(\mathcal{U})$.

This shows that $q(\bar{x}) \rightarrow \varphi(\bar{x})$. By (an argument similar to) **Fact 7.2**, there is $\theta_q(\bar{x})$ in $q(\bar{x})$ a finite conjunction of formulas such that $\theta_q(\bar{x}) \rightarrow \varphi(\bar{x})$. So we have

$$\varphi(\bar{x}) \leftrightarrow \bigvee_{q(\bar{x}) \in D} \{ \theta_q(\bar{x}) \}.$$

By **Fact 7.2**, there are $\psi_{q_1}(\bar{x}), \dots, \psi_{q_m}(\bar{x})$ such that

$$\varphi(\bar{x}) \leftrightarrow \bigvee_{i=1}^n \psi_{q_i}(\bar{x}).$$

So $\bigvee \psi_{q_i}(\bar{x})$ is the required quantifier-free formula. \square

Definition 7.8. An L -theory T has **quantifier elimination** if for every L -formula $\varphi(\bar{x})$ there is $\psi(\bar{x})$ quantifier free such that

$$T \vdash \forall \bar{x} (\varphi(\bar{x}) \leftrightarrow \psi(\bar{x})).$$

Remark. Usually, quantifier elimination with additional assumptions is used to show that a theory is complete.

Theorem 7.9. Let T be a complete theory with an infinite model. Then the following are equivalent:

- (i) T has **quantifier elimination**,
- (ii) every $p : \mathcal{U} \rightarrow \mathcal{U}$ **partial embedding** is **elementary**,
- (iii) If $p : \mathcal{U} \rightarrow \mathcal{U}$ is partial embedding and $|\text{dom } p| < |\mathcal{U}|$ and $b \in \mathcal{U}$, then there is a partial embedding $\hat{p} \supseteq p$ such that $b \in \text{dom } \hat{p}$.

Proof. (i) \Leftrightarrow (ii). Follows from **Proposition 7.7**.

(ii) \Rightarrow (iii). If $p : \mathcal{U} \rightarrow \mathcal{U}$ is a **partial embedding**, then it is **elementary**. Let $b \in \mathcal{U}$. By **homogeneity** of \mathcal{U} , there is $\alpha \in \text{Aut}(\mathcal{U})$ such that $p \subseteq \alpha$, and so $p \cup \{ \langle b, \alpha(b) \rangle \}$ is the required extension of p .

(iii) \Rightarrow (ii). Let $p : \mathcal{U} \rightarrow \mathcal{U}$ be a partial embedding. Consider $p_0 \subseteq p$, p_0 finite or small. Use property (iii) and saturation to extend p_0 to $\alpha \in \text{Aut}(U)$ by back and forth. So p_0 is elementary. The assumption on smallness is needed for the back-and-forth argument. \square

Remark. There is a fourth condition equivalent to (i), (ii), (iii):

- (iv) for every finite partial embedding $p : \mathcal{U} \rightarrow \mathcal{U}$ and $b \in \mathcal{U}$ there is $\hat{p} \supseteq p$, a partial embedding such that $b \in \text{dom}(\hat{p})$.

Proof: Later, exercise.

This gives [quantifier elimination](#) for T_{rg} and T_{dlo} .

Remark. If T has [quantifier elimination](#) and $\mathcal{M} \models T$, any [substructure](#) of \mathcal{M} is an [elementary substructure](#) (T is ‘model-complete’). Under certain conditions, model completeness implies completeness.

Definition 7.10. An element $a \in \mathcal{U}$ is **definable** over a small set $A \subseteq U$ if there is an $L(A)$ -formula $\varphi(x)$ such that $\varphi(U) = \{a\}$. (In particular, any element of A is definable over A ; $x = a$ for $a \in A$).

An element $a \in \mathcal{U}$ is **algebraic** over $A \subseteq U$ if there is an $L(A)$ -formula $\varphi(x)$ such that $|\varphi(U)| < \omega$ and $a \in \varphi(U)$.

The **definable closure** of A is

$$\text{dcl}(A) = \{a \in \mathcal{U} \mid a \text{ definable over } A\}$$

and the **algebraic closure** of A is

$$\text{acl}(A) = \{a \in \mathcal{U} \mid a \text{ algebraic over } A\}.$$

A is **algebraically closed** if $\text{acl}(A) = A$.

Proposition 7.11. For $a \in \mathcal{U}$ and $A \subseteq \mathcal{U}$, the following are equivalent

- (i) $a \in \text{dcl}(A)$,
- (ii) $O(a/A) = \{a\}$.

Proof. For (i) \Rightarrow (ii), let $\varphi(x)$ define a over A . Then $\varphi(U)$ is invariant over A , so $O(a/A) \subseteq \varphi(U)$ and so $O(a/A) = \{a\}$. For (ii) \Rightarrow (i), we use that $O(a/A)$ is invariant over A , so by [Proposition 7.5](#) there is an $L(A)$ -formula that defines $O(a/A) = \{a\}$. \square

Theorem 7.12. Let $A \subseteq \mathcal{U}$, $a \in \mathcal{U}$, the following are equivalent:

- (i) $a \in \text{acl}(A)$,
- (ii) $|O(a/A)| < \omega$,
- (iii) $a \in \mathcal{M}$ for any [model](#)² \mathcal{M} which contains A .

Lecture 14 Proof. (i) \Rightarrow (ii). If $a \in \text{acl}(A)$, then there is an $L(A)$ -formula $\varphi(x)$ such that $\varphi(a)$ holds and $|\varphi(U)| < \omega$. But $\varphi(U)$ is [invariant](#) over A , and so $O(a/A) \subseteq \varphi(U)$, and so $|O(a/A)| < \omega$.

(ii) \Rightarrow (i). If $|O(a/A)| < \omega$, then $O(a/A)$ is [definable](#) by $\bigvee_{i=1}^n (x = a_i)$ where $O(a/A) = \{a_1, \dots, a_n\}$. Also $O(a/A)$ is [invariant](#) over A , so by [Proposition 7.5](#), there is an $L(A)$ -formula $\varphi(x)$ that defines $O(a/A)$.

(i) \Rightarrow (iii). $a \in \text{acl}(A)$, so there is $\varphi(x)$, an $L(A)$ -formula such that there is $n \in \omega \setminus \{0\}$ with

$$\varphi(a) \wedge \exists^{=n} x \varphi(x),$$

²In the setup of this section, \mathcal{M} is a small elementary substructure of \mathcal{U} .

i.e. there exist precisely n witnesses for $\varphi(x)$. Then by [elementarity](#), $\varphi(a) \wedge \exists^{=n} x \varphi(x)$ holds in every $\mathcal{M} \supseteq A$, and the n realizations of $\varphi(x)$ in \mathcal{U} must coincide with the realizations in \mathcal{M} . Therefore $a \in \mathcal{M}$.

(iii) \Rightarrow (i). Suppose $a \notin \text{acl}(A)$, let $p(x) = \text{tp}(a/A)$. Then for all $\varphi(x) \in p(x)$, $|\varphi(\mathcal{U})| \geq \omega$. Then from the second examples sheet³, $|p(\mathcal{U})| \geq \omega$. And we can show⁴ that $|p(\mathcal{U})| = |\mathcal{U}|$.

Let $\mathcal{M} \supseteq A$, then $p(\mathcal{U}) \setminus \mathcal{M} \neq \emptyset$ by cardinality considerations. So there is $b \in p(\mathcal{U}) \setminus \mathcal{M}$. Since $\text{tp}(a/A) = \text{tp}(b/A)$, there is $\alpha \in \text{Aut}(\mathcal{U}/A)$ such that $\alpha(b) = a$ by homogeneity. But then $\alpha[\mathcal{M}]$ is a [model](#) that contains A , but $a \notin \alpha[\mathcal{M}]$ while $a = \alpha(b)$. \square

Proposition 7.13. Let $a \in \mathcal{U}$, $A \subseteq \mathcal{U}$. Then:

- (i) if $a \in \text{acl}(A)$, then there is finite $A_0 \subseteq A$ such that $a \in \text{acl}(A_0)$.
- (ii) if $A \subseteq B$, then $\text{acl}(A) \subseteq \text{acl}(B)$.
- (iii) $\text{acl}(A) = \text{acl}(\text{acl}(A))$
- (iv) $A \subseteq \text{acl}(A)$.
- (v) $\text{acl}(A) = \bigcap_{A \subseteq \mathcal{M}} \mathcal{M}$ where \mathcal{M} is a [small elementary substructure](#) of \mathcal{U} .

Proof.

- (i) A_0 contains the parameters of the formula that make a algebraic.
- (ii) $a \in A$ is [definable](#) over A , hence [algebraic](#).
- (iii) $\text{acl}(A) \subseteq \text{acl}(\text{acl}(A))$ by monotonicity. For \supseteq , let $a \in \text{acl}(\text{acl}(A))$. By [Theorem 7.12](#), $a \in \mathcal{M}$ for every $\mathcal{M} \supseteq \text{acl}(A)$. But $\text{acl}(A) \subseteq \mathcal{M} \iff A \subseteq \mathcal{M}$, so $a \in \mathcal{M}$ for every $\mathcal{M} \supseteq A$, i.e. $a \in \text{acl}(A)$.
- (v) follows from [Theorem 7.12](#). \square

Remark. [Proposition 7.13](#)(i)-(iv) show that acl in the monster is a closure operator of finite character.

Proposition 7.14. If $\beta \in \text{Aut}(\mathcal{U})$, $A \subseteq \mathcal{U}$ is small, then $\beta[\text{acl}(A)] = \text{acl}(\beta[A])$.

Proof. \subseteq : Let $a \in \text{acl}(A)$, let $\varphi(x, \bar{z})$ be an L -formula such that $\varphi(a, \bar{b})$ holds for \bar{b} in A and $|\varphi(\mathcal{U}, \bar{b})| < \omega$. Then $\varphi(\beta(a), \beta(\bar{b}))$ holds, $|\varphi(\mathcal{U}, \beta(\bar{b}))| < \omega$, and so $\beta(a)$ is [algebraic](#) over $\beta[\bar{b}]$.

The same proof with β^{-1} in place of β and $\beta[A]$ in place of A shows \supseteq . \square

³Question 6 on examples sheet 2: Let \mathcal{N} be saturated and let $p(x)$ be a type with parameters in $A \subseteq N$ such that $|A| < |N|$. Suppose $p(x)$ is closed under conjunction, i.e. if $\varphi(x)$ and $\psi(x)$ are in $p(x)$, then also $\varphi(x) \wedge \psi(x)$. Then the following are equivalent:

- (i) $p(x)$ has finitely many realizations,
- (ii) $p(x)$ contains a formula with finitely many realizations.

⁴Question 5 on example sheet 2: Let \mathcal{N} be a saturated L -structure, and let $p(x)$ be a type (with one free variable) in $L(A)$, where $A \subseteq N$ and $|A| < |N|$. Let $p(\mathcal{N}) = \{a \in N \mid \mathcal{N} \models p(a)\}$. Then the following are equivalent:

- (i) $p(\mathcal{N})$ is infinite,
- (ii) $|p(\mathcal{N})| = |\mathcal{N}|$.

8 Strongly Minimal Theories

We continue to work in the monster \mathcal{U} .

Definition 8.1 (Cofinite). For \mathcal{M} a **structure**, $A \subseteq M$ is **cofinite** if $M \setminus A$ is finite.

Remark 8.2. Finite and **cofinite** sets are **definable** in every **structure**.

In this chapter, we'll look at **structures** where these are the only **definable** sets.

Definition 8.3 (Minimality, strong minimality). A **structure** \mathcal{M} is **minimal** if all its **definable** subsets are finite or **cofinite**. \mathcal{M} is **strongly minimal** if it is minimal and all its elementary extensions are minimal.

If T is a **consistent** theory without finite **models**, T is **strongly minimal** if for every formula $\varphi(x, \bar{z})$ there is $n \in \omega \setminus \{0\}$ such that

$$T \vdash \forall \bar{z} [\exists^{\leq n} x \varphi(x, \bar{z}) \vee \exists^{\leq n} x \neg \varphi(x, \bar{z})].$$

Example. Take $L = \{E\}$, a binary relation, let \mathcal{M} be the L -**structure** where E is an equivalence relation with exactly one class of size n for all $n \in \omega$ and no infinite classes. Then can show \mathcal{M} is **minimal** (can only say things like ‘ x is in the same class as a ’).

But, there is $\mathcal{N} \succ \mathcal{M}$ where \mathcal{N} has an infinite class. Then if the equivalence class of $a \in \mathcal{N}$ is infinite, the set defined by $E(x, a)$ is infinite/coinfinite, so \mathcal{M} is not **strongly minimal**.

(Remark: **strongly minimal theories** have **monster models**). From now on: T is strongly minimal, **complete**, and has an infinite **model**.

Definition 8.4 (Independence). Let $a \in \mathcal{U}$, $B \subseteq \mathcal{U}$. Then a is **independent** from B if $a \notin \text{acl}(B)$. The set B is **independent** if for all $a \in B$, $a \notin \text{acl}(B \setminus \{a\})$.

Example.

Lecture 15

- Vector spaces. Fix an infinite field K , and use $L = \{+, -, \mathbf{0}, \{\lambda\}_{\lambda \in K}\}$, where λ are unary functions (for scalar multiplication). The theory of vector spaces over K , T_{VSK} includes:
 - axioms in $\{+, -, \mathbf{0}\}$ for abelian group
 - axiom schemata for scalar multiplication:
 - * $\forall xy [\lambda(x + y) = \lambda x + \lambda y]$ for each $\lambda \in K$, λx means $\lambda(x)$.
 - * \vdots
 - * $\forall x [1x = x]$ (since $1 \in K$).
 - * $\exists x (x \neq \mathbf{0})$.

Then it can be shown T_{VSK} is **complete** and has **quantifier elimination**.

Atomic formulas express equality of linear combinations, any atomic formula in one variable and with parameters is equivalent to ‘ $\lambda x = a$ ’, so atomic formulas in one variable define singletons. Quantifier-free formulas in one variable and with parameters define sets that are either finite or **cofinite**.

By **quantifier elimination**, T_{VSK} is **strongly minimal**. Also, $\text{acl}(A) = \langle A \rangle$, the linear span, and a is **independent** from A if a is linearly independent from A , and A is independent if it is linearly independent.

- Fields. Take $L_{\text{ring}} = \{+, \cdot, -, 0, 1\}$. Then ACF is the theory that includes

- axioms for abelian group in $\{+, -, 0\}$
- axioms for multiplicative monoids in $\{\cdot, 1\}$
- $\forall xyz [x \cdot (y + z) = x \cdot y + x \cdot z]$
- $\forall x [x = 0 \vee \exists y (x \cdot y) = 1]$
- $0 \neq 1$
- axioms for algebraic closure: for all n ,

$$\forall x_0 \cdots x_n \exists y [x_n y^n + \cdots + x_1 y + x_0 = 0].$$

If

$$\chi_p \equiv \underbrace{1 + 1 + \cdots + 1}_{p \text{ times}} = 0,$$

for p prime, then $ACF \cup \{\chi_p\} =: ACF_p$, which can be shown to be **complete** and have **quantifier elimination**. By adding $\{\neg \chi_n \mid n \in \omega\}$ to ACF , get ACF_0 (also complete with quantifier elimination).

Now, atomic formulas with parameters are polynomial equations. An atomic formula with one variable (and parameters in A) is equivalent to $p(x) = 0$, where $p(x)$ is a polynomial in the subfield generated by A . So such atomic formulas define finite sets, and quantifier free formulas define finite or cofinite sets, and so by quantifier elimination, ACF_p (ACF_0) is strongly minimal. If $a \in \mathcal{M} \models ACF_p$, $A \subseteq \mathcal{M}$, then $a \in \text{acl}(A)$ if a is algebraic over the field generated by A .

Notation. We write $\text{acl}(a, B)$ for $\text{acl}(\{a\} \cup B)$ and $\text{acl}(B \setminus a)$ for $\text{acl}(B \setminus \{a\})$.

Theorem 8.5 (Exchange lemma). Let $B \subseteq \mathcal{U}$, and $a, b \notin \text{acl}(B)$. ($a, b \in \mathcal{U} \setminus \text{acl}(B)$). Then

$$b \in \text{acl}(a, B) \iff a \in \text{acl}(b, B).$$

Proof. Let $a, b \in \text{acl}(B)$. Assume $b \notin \text{acl}(a, B)$ and $a \in \text{acl}(b, B)$. Let $\varphi(x, y)$ be an $L(B)$ -formula such that for some n ,

$$\varphi(a, b) \wedge \exists^{\leq n} x \varphi(x, b).$$

Since $b \notin \text{acl}(a, B)$

$$\psi(a, y) := \varphi(a, y) \wedge \exists^{\leq n} x \varphi(x, y)$$

is such that $|\psi(a, \mathcal{U})| \geq \omega$. By question 7, example sheet 2, $|\psi(a, U)| = |\mathcal{U}|$. By **strong minimality**, $|\neg \psi(a, U)| < \omega$. By cardinality considerations, if $\mathcal{M} \supseteq B$, then \mathcal{M} contains c such that $\psi(a, c)$. But then $a \in \text{acl}(c, B)$, so $a \in \mathcal{M}$. Therefore a is in all **models** that contain B , so $a \in \text{acl}(B)$ by **Theorem 7.12**, a contradiction. \square

Definition 8.6 (Basis). Let $B \subseteq C \subseteq \mathcal{U}$. Then B is a **basis** of C if

- (i) B is **independent**,
- (ii) $C \subseteq \text{acl}(B)$ (or equivalently, $\text{acl}(B) = \text{acl}(C)$).

Lemma 8.7. If B is **independent** and $a \notin \text{acl}(B)$, then $\{a\} \cup B$ is independent.

Proof. Let $a \notin \text{acl}(B)$, and suppose (for contradiction) that $\{a\} \cup B$ is not independent. Then there is $b \in B$ such that $b \in \text{acl}(a, B \setminus b)$. But $b \notin \text{acl}(B \setminus b)$. Since $a \notin \text{acl}(B \setminus b)$, by **Theorem 8.5** we have

$$a \in \text{acl}(b, B \setminus b) = \text{acl}(B),$$

a contradiction. \square

Corollary 8.8. If $B \subseteq C$, the following are equivalent:

- (i) B is a **basis** of C ,
- (ii) if $B \subseteq B' \subset C$ and B' is **independent**, then $B = B'$.

Proof. By [Lemma 8.7](#). □

Theorem 8.9. Let $C \subseteq \mathcal{U}$, then

- (i) every **independent** subset $B \subseteq C$ can be extended to a **basis**,
- (ii) if A, B are bases of C , then $|A| = |B|$.

Proof.

- (i) If $\langle B_i : i < \lambda \rangle$ is a chain of **independent** sets containing B , then $\bigcup_{i < \lambda} B_i$ is independent (by [Proposition 7.13\(i\)](#)). By Zorn's lemma, there is a maximal independent subset of C that contains B . By [Corollary 8.8](#), that maximal subset is a **basis** of C .

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- (ii) Let $|B| \geq \omega$, assume (for contradiction) that $|A| < |B|$. Then $a \in A$ is also in $\text{acl}(B)$. Let $D_a \subseteq B$ be finite such that $a \in \text{acl}(D_a)$. Let $D = \bigcup_{a \in A} D_a$. Then $A \subseteq \text{acl}(D)$ and $C \subseteq \text{acl}(D)$, but $|D| < |B|$ contradicting the independence of B .

If A and B are finite, show that $|A| \leq |B|$ (and the converse symmetrically) by using: if there is $a \in A \setminus B$, then there is $b \in B \setminus A$ such that $\{b\} \cup (A \setminus \{a\})$ is independent. This holds because if $a \in A \setminus B$, then since $a \in \text{acl}(B)$, we have that $B \not\subseteq \text{acl}(A \setminus \{a\})$ (otherwise A is not independent). So let $b \in B \setminus \text{acl}(A \setminus a)$. Then $\{b\} \cup (A \setminus a)$ is independent by [Lemma 8.7](#).

Use finite induction argument to get $|A| \leq |B|$. □

Definition 8.10 (Dimension). Let $C \subseteq \mathcal{U}$ be **algebraically closed**. Then the **dimension** of C is $\dim(C) = |A|$ where A is any **basis** of C .

Proposition 8.11. Let $f : \mathcal{U} \rightarrow \mathcal{U}$ be **(partial) elementary**. Let $b \notin \text{acl}(\text{dom}(f))$ and $c \notin \text{acl}(\text{img}(f))$. Then $f \cup \{\langle b, c \rangle\}$ is elementary.

Proof. Let \bar{a} enumerate $\text{dom}(f)$, let $\varphi(x, \bar{a})$ be a formula with parameters in \bar{a} . Claim: $\varphi(b, \bar{a}) \leftrightarrow \varphi(c, f(\bar{a}))$. Cases:

- 1. $|\varphi(\mathcal{U}, \bar{a})| < \omega$. Then $|\varphi(\mathcal{U}, f(\bar{a}))| < \omega$. Then $b \notin \varphi(\mathcal{U}, \bar{a})$ (because $b \notin \text{acl}(\bar{a})$) and $c \notin \varphi(\mathcal{U}, f(\bar{a}))$. Then

$$\neg \varphi(b, \bar{a}) \wedge \neg \varphi(c, f(\bar{a})).$$

- 2. $|\varphi(\mathcal{U}, \bar{a})| \geq \omega$. Then by strong minimality, $|\neg \varphi(\mathcal{U}, \bar{a})| < \omega$, and so

$$\varphi(b, \bar{a}) \wedge \varphi(c, f(\bar{a})).$$

□

Corollary 8.12. Every bijection between **small independent** subsets of \mathcal{U} is **elementary**.

Proof. Pick $A, B \subseteq \mathcal{U}$ **independent** and let $f : A \rightarrow B$ be any bijection. Let \bar{a} enumerate A , write $f(a_i) = b_i$. Then $a_0 \notin \text{acl}(\emptyset)$ and $b_0 \notin \text{acl}(\emptyset)$ (otherwise A, B not independent). By [Proposition 8.11](#), $\{\langle a_0, b_0 \rangle\}$ is an elementary map.

At stage $i + 1$, $a_{i+1} \notin \text{acl}(a_0, \dots, a_i)$ and $b_{i+1} \notin \text{acl}(b_0, \dots, b_i)$ so use the same argument. □

Remark 8.13. If $\mathcal{M} \preccurlyeq \mathcal{U}$ is a model such that $|\mathcal{M}| < |\mathcal{U}|$, then by [Proposition 7.13](#), \mathcal{M} is algebraically closed.

Theorem 8.14. Suppose that $\mathcal{M}, \mathcal{N} \preccurlyeq \mathcal{U}$ are such that $\dim(\mathcal{M}) = \dim(\mathcal{N})$, then $\mathcal{M} \simeq \mathcal{N}$.

Proof. Let A, B be bases of \mathcal{M}, \mathcal{N} respectively. Then a bijection $f : A \rightarrow B$ is elementary (by Corollary 8.12). Then there is $\alpha \in \text{Aut}(\mathcal{U})$ such that $f \subseteq \alpha$ by homogeneity of the monster. Then by Proposition 7.14,

$$\alpha(\mathcal{M}) = \alpha(\text{acl}(\mathcal{M})) = \text{acl}(\alpha(A)) = \text{acl}(B) = \mathcal{N}. \quad \square$$

Corollary 8.15. Let T be strongly minimal, let $\lambda > |L|$. Then T is λ -categorical.

Proof. If $A \subseteq \mathcal{U}$, then $|\text{acl}(A)| \leq |L(A)| + \omega$ (there are at most $|L(A)| + \omega$ formulas, each element m in $\text{acl}(A)$ is one of finitely many solutions of one of those formulas). If $|\mathcal{M}| = \lambda$, then a basis of \mathcal{M} must have cardinality λ . By Theorem 8.14, any two models with equal dimension are isomorphic. \square

In T_{VSK} , if K is infinite countable, the vector space can have finite dimension (ω -categoricity fails). If K is finite, the vector space must have dimension $\geq \omega$.

9 Countable Models

Any fool can realise a type but it takes a model theorist to omit one. —
Gerald Sacks

Let T be a complete countable theory with a monster model \mathcal{U} .

Definition 9.1. An L -formula $\varphi(\bar{x})$ is said to **isolate** a type $p(\bar{x})$ in L if

- (i) $\varphi(\bar{x}) \rightarrow p(\bar{x})$, i.e. $T \vdash \forall \bar{x} (\varphi(\bar{x}) \rightarrow \psi(\bar{x}))$ for all $\psi(\bar{x}) \in p(\bar{x})$, and
- (ii) $\varphi(\bar{x})$ is consistent.

A set of formulas Δ with variables in \bar{x} **isolates** $p(\bar{x})$ if there is $\delta(\bar{x}) \in \Delta$ that isolates $p(\bar{x})$. When Δ contains all formulas in $L(A)$ with free variables in \bar{x} , we say that A **isolates** $p(\bar{x})$. If A is clear from the context, we say that $p(\bar{x})$ is **isolated** or **principal**.

A model \mathcal{M} is said to **omit** $p(\bar{x})$ if $p(\bar{x})$ is not realized in \mathcal{M} .

Remark 9.2. If \mathcal{M} is a model and $p(\bar{x})$ is a type in $L(M)$, then \mathcal{M} realises $p(\bar{x})$ if and only if \mathcal{M} isolates $p(\bar{x})$.

Proof. \Leftarrow Let $\varphi(\bar{x})$ isolate $p(\bar{x})$, so $\mathcal{M} \models \varphi(\bar{a})$ for some \bar{a} , so $\bar{a} \models p(\bar{x})$.

\Rightarrow Let $\bar{a} \models p(\bar{x})$. Then $\varphi(\bar{x}) := (\bar{x} = \bar{a})$ isolates $p(\bar{x})$. □

Lemma 9.3. Let $|L(A)| = \omega$. Let $p(\bar{x})$ be a type in $L(A)$ and suppose that A does not isolate $p(\bar{x})$. Let $\psi(z)$ be a consistent $L(A)$ -formula in one free variable. Then there is $a \in U$ such that

- (i) $\mathcal{U} \models \psi(a)$,
- (ii) $A \cup \{a\}$ does not isolate $p(\bar{x})$.

Lemma 9.3 will be proven later.

Theorem 9.4 (Omitting Types). Let $|L(A)| = \omega$ and let $p(\bar{x})$ be a consistent type in $L(A)$ with variables in \bar{x} , $|\bar{x}| < \omega$. Then the following are equivalent:

- (i) all models \mathcal{M} containing A realise $p(\bar{x})$,
- (ii) A isolates $p(\bar{x})$.

Proof. (ii) implies (i): Let $\varphi(\bar{x})$ be an $L(A)$ -formula that isolates $p(\bar{x})$. Then $\models \exists \bar{x} \varphi(\bar{x})$, so if \mathcal{M} contains A , then there is $\bar{a} \in M$ such that $\mathcal{M} \models \varphi(\bar{a})$ and \bar{a} realizes $p(\bar{x})$. This follows from **Remark 9.2**.

(i) implies (ii): Argue by contraposition and assume A does not isolate $p(\bar{x})$. We build a chain $\langle A_i : i < \omega \rangle$ such that

- (i) $A_0 = A$,
- (ii) $|A_i| = \omega$ for all $i < \omega$,
- (iii) A_i does not isolate $p(\bar{x})$ for any $i < \omega$.

At stage $i + 1$, enumerate all consistent $L(A_i)$ -formulas with one free variable, say $\langle \psi_k(z) : k < \omega \rangle$. For $k \in \omega$, we find $a_k^i \in U$ such that $\models \psi_k(a_k^i)$, and such that $A_i \cup \{a_0^i, \dots, a_k^i\}$ does not isolate $p(\bar{x})$. This is possible by **Lemma 9.3**. Let $A_{i+1} := A_i \cup \{a_k^i \mid k < \omega\}$. Let $M := \bigcup A_i$. We claim that

- (a) $\mathcal{M} \preceq \mathcal{U}$,
- (b) \mathcal{M} omits $p(\bar{x})$.

For (a), use Tarski-Vaught Test (Lemma 3.8): if $\psi(z)$ is a consistent $L(M)$ -formula, then it has parameters in A_i for some i , so by Remark 9.2, \mathcal{M} contains a witness. Condition (b) is satisfied by construction: none of the A_i isolates $p(\bar{x})$, so \mathcal{M} does not isolate $p(\bar{x})$, so since \mathcal{M} is a model, by Remark 9.2 it does not realise $p(\bar{x})$. \square

Remark. We need $|L(A)| = \omega$. There are known counterexamples in the uncountable case.

Proof of Lemma 9.3. Let $\psi(z)$ be a consistent $L(A)$ -formula. We build a sequence $\langle \psi_i(z) : i < \omega \rangle$ starting with $\psi_0 := \psi$ such that

- (i) $\psi_i(z)$ is consistent,
- (ii) $\psi_{i+1}(z) \rightarrow \psi_i(z)$ for all $i < \omega$,
- (iii) a realisation of the type $\{\psi_i(z) \mid i < \omega\}$ is the required solution of $\psi(z)$.

Let $\langle \chi_i(\bar{x}, z) : i < \omega \rangle$ be an enumeration of $L(A)$ -formula with free variables in $\bar{x} \cup \{z\}$. At stage $i + 1$, if $\chi_i(\bar{x}, z)$ is inconsistent, set $\psi_{i+1}(z) = \psi_i(z)$. If otherwise $\chi_i(\bar{x}, z)$ is consistent, let $\varphi(\bar{x}) \in p(\bar{x})$ such that

$$\psi_i(z) \wedge \exists \bar{x} (\chi_i(\bar{x}, z) \wedge \neg \varphi(\bar{x}))$$

is consistent. Let $\psi_{i+1}(z)$ be this conjunction. These conditions guarantee that a realisation of the type $\{\psi_i(z) \mid i < \omega\}$ does not isolate $p(\bar{x})$. We must show that it is possible to find such $\varphi(\bar{x})$. If no such $\varphi(\bar{x})$ exists, then for all $\varphi(\bar{x}) \in p(\bar{x})$,

$$\chi_i(\bar{x}, z) \wedge \psi_i(z) \rightarrow \varphi(\bar{x}).$$

But this implies that

$$\exists z (\chi_i(\bar{x}, z) \wedge \chi_i(z)) \rightarrow p(\bar{x}).$$

This is an $L(A)$ -formula which yields a contradiction to the assumption that A does not isolate $p(\bar{x})$. \square

Definition 9.5. Let \mathcal{M} be a model, $A \subseteq M$. Then

- (i) \mathcal{M} is **prime over** A if for every $\mathcal{N} \supseteq A$ there is an elementary embedding $f : \mathcal{M} \rightarrow \mathcal{N}$ that fixes A pointwise. If $A = \emptyset$, then \mathcal{M} is a **prime model**.
- (ii) \mathcal{M} is **atomic over** A if for all $n \in \omega$ and $\bar{a} \in M^n$, the type $\text{tp}(\bar{a}/A)$ is isolated. When $A = \emptyset$, then \mathcal{M} is said to be **atomic**.

Fact 9.6. Let $\bar{a}, \bar{b} \in U^n$ and $A \subseteq U$. Suppose that $\text{tp}(\bar{b}\bar{a}/A)$ is isolated, then $\text{tp}(\bar{b}/A\bar{a})$ and $\text{tp}(\bar{a}/A)$ are isolated.

Proof (sketch). Let $p(\bar{x}, \bar{z}) = \text{tp}(\bar{b}\bar{a}/A)$. Then $\text{tp}(\bar{b}/A\bar{a}) = p(\bar{x}, \bar{a})$ and $\text{tp}(\bar{a}/A) = \{\exists \bar{x} \varphi(\bar{x}, \bar{z}) \mid \varphi(\bar{x}, \bar{z}) \in p(\bar{x}, \bar{z})\}$. Suppose $\varphi(\bar{x}, \bar{z})$ isolates $p(\bar{x}, \bar{z})$. Then

- (i) $\varphi(\bar{x}, \bar{a})$ isolates $\text{tp}(\bar{b}/A\bar{a})$,
- (ii) $\exists \bar{x} \varphi(\bar{x}, \bar{z})$ isolates $\text{tp}(\bar{a}/A)$.

\square

Proposition 9.7. If \mathcal{M} is atomic over A and $\bar{a} \in M^n$, then \mathcal{M} is atomic over $A \cup \bar{a}$.

Proof. Let $\bar{b} \in M^m$. Then $\text{tp}(\bar{b}\bar{a}/A)$ is isolated, so $\text{tp}(\bar{b}/A\bar{a})$ is isolated by [Fact 9.6](#). \square

Proposition 9.8 (Extension Lemma). Let $f : \mathcal{M} \rightarrow \mathcal{N}$ be elementary and \mathcal{M} atomic over $\text{dom}(f)$. Then for every $b \in M$ there is $c \in N$ such that $f \cup \{\langle b, c \rangle\}$ is elementary.

Proof. Let \bar{a} enumerate $\text{dom}(f)$ and let $p(x, \bar{z}) = \text{tp}(b\bar{a}/\emptyset)$. Let $\varphi(x, \bar{a})$ isolate $p(x, \bar{a})$. Then by elementarity, $\varphi(x, f(\bar{a}))$ isolates $p(x, f(\bar{a}))$. We can find $c \in N$ such that $\mathcal{N} \models \varphi(c, f(\bar{a}))$ and this c is the required element. \square

Proposition 9.9. Any two countable atomic models are isomorphic.

Proof. By a back-and-forth argument using [Propositions 9.7](#) and [9.8](#). \square

Theorem 9.10. Let $|L(A)| = \omega$. Then for any model $\mathcal{M} \supseteq A$, the following are equivalent:

- (i) \mathcal{M} is countable and atomic over A ,
- (ii) \mathcal{M} is prime over A .

Proof. (i) implies (ii): Let $\mathcal{N} \supseteq A$ be a model. Then $\text{id}_A : \mathcal{M} \rightarrow \mathcal{N}$ is elementary and by [Propositions 9.7](#) and [9.8](#), id_A can be extended to a elementary embedding $g : \mathcal{M} \rightarrow \mathcal{N}$.

(ii) implies (i): By Downward Löwenheim-Skolem ([Theorem 3.11](#)), we know that there is a countable model that contains A . Then \mathcal{M} embeds into this model and so $|M| = \omega$. Suppose that \mathcal{M} is not atomic over A , i.e. that there is $\bar{b} \in M^n$ such that $\text{tp}(\bar{b}/A)$ is not isolated. By the Omitting Type Theorem ([Theorem 9.4](#)), there is a countable model \mathcal{N} that omits $\text{tp}(\bar{b}/A)$. But then \mathcal{M} does not embed into \mathcal{N} , a contradiction to \mathcal{M} being prime. \square

Definition 9.11. For $n \in \omega$, $A \subseteq U$, let $S_n(A)$ denote the collection of complete consistent types in $L(A)$ with n free variables. When $A = \emptyset$, we write $S_n(T)$ for $S_n(\emptyset)$.

Theorem 9.12 (Ryll–Nardzewski–Engeler–Svenonins). For a countable theory T , the following are equivalent:

- (i) T is ω -categorical,
- (ii) for all n , every type $p(\bar{x}) \in S_n(T)$ is isolated,
- (iii) for all n , $|S_n(T)| < \omega$,
- (iv) $\text{Aut}(U)$ has finitely many n -orbits (i.e., orbits when acting on n -tuples) for all $n \in \omega$.

Proof. (ii) implies (iii): We have $U^n = \bigcup_{p(\bar{x}) \in S_n(T)} p(\mathcal{U})$. But $p(\bar{x}) \in S_n(T)$ is isolated by a formula $\varphi_p(\bar{x})$, say. And so $U^n = \bigcup_{p(\bar{x}) \in S_n(T)} \varphi_p(\mathcal{U})$. By compactness, $U^n = \bigcup_{i=1}^k \varphi_{p_i}(\mathcal{U})$ for k finite and certain p_1, \dots, p_k . This implies that $|S_n(T)| < \omega$.

(iii) implies (ii): Let $p(\bar{x}) \in S_n(T)$. If $|S_n(T)| < \omega$, then $\mathcal{U} \setminus p(\mathcal{U})$ is a union of finitely many type-definable sets, so there it is type-definable by $q(\bar{x})$, not necessarily complete. By an argument similar to [Fact 7.2](#), there are formulas $\varphi(\bar{x})$ and $\chi(\bar{x})$ such that $\varphi(\mathcal{U}) = p(\mathcal{U})$ and $\chi(\mathcal{U}) = \mathcal{U} \setminus p(\mathcal{U})$. But then $\varphi(\bar{x})$ isolates $p(\bar{x})$.

(iii) and (iv) are equivalent: This follows from the fact that for $\bar{a}, \bar{b} \in U$,

$$\text{tp}(\bar{a}) = \text{tp}(\bar{b}) \iff O(\bar{a}/\emptyset) = O(\bar{b}/\emptyset).$$

(i) and (ii) are equivalent: This is an exercise. It follows from atomicity. \square

10 Bonus Lecture: Existence of saturated models

If \mathcal{M} is [saturated](#), then

- \mathcal{M} is [homogeneous](#).
- \mathcal{M} is [universal](#).

If \mathcal{M} is λ -[saturated](#), then:

- \mathcal{M} is weakly λ -homogeneous, i.e. for all $f : \mathcal{M} \rightarrow \mathcal{M}$ (partial) [elementary](#) such that $|f| < \lambda$, for every $b \in \mathcal{M}$, then $\exists \hat{f} \supseteq f$ elementary and such that $b \in \text{dom } \hat{f}$.

Can prove: λ -homogeneous is equivalent to homogeneity when $|\mathcal{M}| = \lambda$.

Definition (Cofinality). If α is a limit ordinal $\geq \omega$, $\text{cof}(\alpha)$ (**cofinality** of α) is the least λ such that there is $f : \lambda \rightarrow \alpha$ such that $\text{img}(f)$ is unbounded in α .

Example.

$$\text{cof}(\omega) = \aleph_0 \quad \text{cof}(\omega_\omega) = \aleph_0.$$

Definition (Regular). A cardinal κ is **regular** if $\text{cof}(\kappa) = \kappa$.

Example. \aleph_0 is [regular](#). Also, every successor cardinal is regular.

Are there any limit cardinals other than \aleph_0 that are [regular](#)?

Definition ($S_1^{\mathcal{M}}$). If $\mathcal{M} \models T$, $A \subseteq \mathcal{M}$, then define

$$S_1^{\mathcal{M}}(A) := \{p(x) \mid p(x) \text{ is a complete type in a single variable with parameters in } A\}$$

Lemma. If \mathcal{M} is such that $|\mathcal{M}| \geq |L| + \omega$, let $\kappa > \aleph_0$. Then there is $\mathcal{M}' \succ \mathcal{M}$ such that for all $A \subseteq \mathcal{M}$ with $|A| < \kappa$, if $p(x) \in S_1^{\mathcal{M}}(A)$, then $p(x)$ is [realized](#) in \mathcal{M}' , $|\mathcal{M}'| \leq |\mathcal{M}|^\kappa$.

Proof. First, note

$$\begin{aligned} |\{A \subseteq \mathcal{M} \mid |A| \leq \kappa\}| &\leq |\mathcal{M}|^\kappa \\ |S_1^{\mathcal{M}}(A)| &\leq 2^\kappa. \end{aligned}$$

Enumerate $S_1^{\mathcal{M}}(A)$ as $\langle p_\alpha : \alpha < |\mathcal{M}|^\kappa \rangle$. Build $\langle \mathcal{M}_\alpha : \alpha < |\mathcal{M}|^\kappa \rangle$ as follows:

- $\mathcal{M}_0 = \mathcal{M}$
- $\mathcal{M}_\alpha = \bigcup_{\beta < \alpha} \mathcal{M}_\beta$ when α is a limit.
- $\mathcal{M}_\alpha \preceq \mathcal{M}_{\alpha+1}$ such that $\mathcal{M}_{\alpha+1}$ realizes $p_\alpha(x)$ and $|\mathcal{M}_{\alpha+1}| = |\mathcal{M}_\alpha|$. Then $\bigcup_{\alpha < |\mathcal{M}|^\kappa} \mathcal{M}_\alpha$ realizes all types in $S_1^{\mathcal{M}}(A)$ and

$$\left| \bigcup_{\alpha < |\mathcal{M}|^\kappa} \mathcal{M}_\alpha \right| \leq |\mathcal{M}|^\kappa. \quad \square$$

Theorem. Let $\kappa > \aleph_0$, let $\mathcal{M} \models T$. Then there is a κ^+ -saturated $\mathcal{N} \succ \mathcal{M}$ such that $|\mathcal{N}| \leq |\mathcal{M}|^\kappa$.

Proof. Build an elementary chain $\langle \mathcal{N} : \alpha < \kappa^+ \rangle$ such that

- $\mathcal{N}_0 = \mathcal{M}$

- take unions at limit stages
- Given \mathcal{N}_α , find $\mathcal{N}_{\alpha+1} \succ \mathcal{N}_\alpha$ such that all types in $S_1^{\mathcal{N}_\alpha}(A)$ with $|A| \leq \kappa$ are realized.

Moreover, $|\mathcal{N}_\alpha| \leq |\mathcal{M}|^\kappa$ (follows from previous result). Let $\mathcal{N} = \bigcup_{\alpha < \kappa^+} \mathcal{N}_\alpha$. Since $\kappa^+ \leq |\mathcal{M}|^\kappa$, \mathcal{N} is the union of at most $|\mathcal{M}|^\kappa$ sets each of size at most $|\mathcal{M}|^\kappa$, hence $|\mathcal{N}| \leq |\mathcal{M}|^\kappa$.

To see that \mathcal{N} is κ^+ saturated, pick $A \subseteq \mathcal{N}$ such that $|A| \leq \kappa$. By the regularity of κ^+ , there is α such that $A \subseteq \mathcal{N}_\alpha$, hence all types $/A$ with one free variable are realized in \mathcal{N} . \square

Recap: For arbitrarily large κ , there is a κ^+ saturated $\mathcal{N} \succ \mathcal{M}$ with $|\mathcal{N}| \leq |\mathcal{M}|^\kappa$. If $\kappa, |\mathcal{M}|$ are such that $|\mathcal{M}| \leq 2^\kappa$, then $|\mathcal{M}|^\kappa = 2^\kappa$ so you get a κ^+ -saturated $\mathcal{N} \succ \mathcal{M}$ such that $|\mathcal{N}| = 2^\kappa$. So GCH implies saturated models exist.

Alternatively, suppose there are arbitrarily large cardinals κ such that

$$\kappa^{<\kappa} = \bigcup \{ \kappa^\alpha \mid \alpha < \kappa \} = \kappa$$

(strongly inaccessible cardinals). Then the chain stabilises, giving the required structure.

Definition. Take T a complete theory in a countable language, $\kappa \geq \aleph_0$ a cardinal. Then T is κ -**stable** if for all $\mathcal{M} \models T$, $A \subseteq \mathcal{M}$, $|A| \leq \kappa$, $\forall n \leq \omega$, we have

$$|S_n^{\mathcal{M}}(A)| \leq \kappa$$

where $S_n^{\mathcal{M}}(A)$ is the set of complete types with n variables and parameters in A .

Theorem. Let κ be a regular cardinal, and T κ -stable. Then there is a $\mathcal{M} \models T$, $|\mathcal{M}| = \kappa$, \mathcal{M} saturated.

Proof. We build an elementary chain $\langle \mathcal{M}_\alpha : \alpha < \kappa \rangle$ where $|\mathcal{M}_\alpha| < \kappa$ as follows:

- $\mathcal{M}_0 \models T$
- unions at limit stages
- given \mathcal{M}_α , $|\mathcal{M}_\alpha| = \kappa \Rightarrow S_1^{\mathcal{M}_\alpha}(\mathcal{M}_\alpha) = \kappa$, there is $\mathcal{M}_{\alpha+1} \succ \mathcal{M}_\alpha$ that realizes all types in $S_1^{\mathcal{M}_\alpha}(\mathcal{M}_\alpha)$ and $|\mathcal{M}_{\alpha+1}| = |\mathcal{M}_\alpha|$. Let $\bigcup_{\alpha < \kappa} \mathcal{M}_\alpha$, then $|\bigcup \mathcal{M}_\alpha| = \kappa$ and $\bigcup \mathcal{M}_\alpha$ is κ -saturated by construction.

Now, \mathcal{M} κ -saturated, κ -strongly homogeneous, $|\mathcal{M}| \gg \kappa$. \square

11 Bonus Material: An Alternative Proof of Compactness

Definition 11.1. Take an L -theory T .

- (i) T is **finitely satisfiable** if every finite subset of **sentences** in T has a **model**.
- (ii) T is **maximal** if for all L -sentences σ , either $\sigma \in T$ or $\neg\sigma \in T$.
- (iii) T has the **witness property** if for all $\varphi(x)$ (L -formula with one **free** variable) there is a constant $c \in \mathcal{C}$ such that

$$((\exists x \varphi(x)) \rightarrow \varphi(c)) \in T.$$

Lemma 11.2. If T is **maximal** and **finitely satisfiable** and φ is an L -sentence, and $\Delta \subseteq^{\text{finite}} T$ with $\Delta \vdash \varphi$, then $\varphi \in T$.

Proof. If $\varphi \notin T$ then $\neg\varphi \in T$ (by maximality). But then $\Delta \cup \{\neg\varphi\}$ is a finite subset of T which does not have a model. \square

Lemma 11.3. Let T be a **maximal**, **finitely satisfiable** theory with the **witness property**. Then T has a **model**. Moreover, if λ is a cardinal and $|\mathcal{C}| \leq \lambda$, then T has a model of size at most λ .

Proof. Let $c, d \in \mathcal{C}$, define $c \sim d$ iff $c = d \in T$.

Claim: \sim is an equivalence relation. **Proof:** For transitivity, let $c \sim d$ and $d \sim e$. Then $c = d \in T$ and $d = e \in T$, so $c = e \in T$ (by [Lemma 11.2](#)), and so $c \sim e$. Reflexivity follows from **maximality**, and symmetry is immediate. \blacksquare

We denote $[c] \in \mathcal{C} / \sim$ by c^* . Now, define a **structure** \mathcal{M} whose domain is $\mathcal{C} / \sim = M$. Clearly, $|M| \leq \lambda$ if $|\mathcal{C}| \leq \lambda$. We must define **interpretations** in \mathcal{M} for symbols of L .

- If $c \in \mathcal{C}$, then $c^{\mathcal{M}} = c^*$.
- If $R \in \mathcal{R}$, define

$$R^{\mathcal{M}} := \{ (c_1^*, \dots, c_{n_R}^*) \mid R(c_1, \dots, c_{n_R}) \in T \}.$$

Claim: $R^{\mathcal{M}}$ is well defined. **Proof:** Suppose $\bar{c}, \bar{d} \in \mathcal{C}^{n_R}$ and suppose $c_i \sim d_i$. That is, $c_i = d_i \in T$ for $i = 1, \dots, n_R$ so by [Lemma 11.2](#)

$$R(\bar{c}) \in T \iff R(\bar{d}) \in T. \quad \blacksquare$$

- If $f \in \mathcal{F}$, and $\bar{c} \in \mathcal{C}^{n_f}$, then $f\bar{c} = d \in T$ for some $d \in \mathcal{C}$. (This is because $\exists x (f(\bar{c}) = x) \in T$ so apply **witness property**.)

Then define $f^{\mathcal{M}}(\bar{c}^*) = d^*$. Exercise: Check $f^{\mathcal{M}}(\bar{c}^*)$ is well-defined!

Claim: if $t(x_1, \dots, x_n)$ is an L -term and $c_1, \dots, c_n, d \in \mathcal{C}$, then

$$t(c_1, \dots, c_n) = d \in T \iff t^{\mathcal{M}}(c_1^*, \dots, c_n^*) = d^*.$$

Proof:

(\Rightarrow) by induction on the complexity of t .

(\Leftarrow) Assume $t^{\mathcal{M}}(c_1^*, \dots, c_n^*) = d^*$. Then

$$t(c_1, \dots, c_n) = e \in T$$

for some constant e by [witness property](#) and [Lemma 11.2](#). Use (\Rightarrow) to get that $t^{\mathcal{M}}(c_1^*, \dots, c_n^*) = e^*$. But then $d^* = e^*$, i.e. $d = e \in T$. Then $t(c_1, \dots, c_n) = d \in T$. ■

Claim: For all L -formulas $\varphi(\bar{x})$, and $\bar{c} \in \mathcal{C}^{|\bar{x}|}$,

$$\mathcal{M} \models \varphi(\bar{c}) \iff \varphi(\bar{c}) \in T.$$

Proof: By induction on $\varphi(\bar{x})$. (Exercise: Fill in the details). ■ This shows $\mathcal{M} \models T$. □

Lecture 8 **Lemma 11.4.** Let T be a [finitely satisfiable \$L\$ -theory](#). Then there are $L^* \supseteq L$ and a finitely satisfiable L^* -theory $T^* \supseteq T$ such that

$$(i) \quad |L^*| = |L| + \omega.$$

(ii) any L^* -theory extending T^* has the [witness property](#).

Proof. We define $\langle L_i : i < \omega \rangle$ a [chain of languages](#) containing L and such that $|L_i| = |L| + \omega$, and $\langle T_i : i < \omega \rangle$ of [finitely satisfiable theories](#) such that $\forall i, T_i$ is an L_i -theory and $T_i \supseteq T$.

Set $L_0 = L$ and $T_0 = T$. At stage $i + 1$, L_i and T_i are given. List all L_i -formulas $\varphi(x)$ (one [free](#) variable) and let

$$L_{i+1} = L_i \cup \{c_\varphi \mid \varphi(x) \text{ an } L_i \text{ formula}\}.$$

For all $\varphi(x)$, an L_i formula in one free variable, let Φ_φ be the L_{i+1} -sentence

$$\exists x \varphi(x) \rightarrow \varphi(c_\varphi).$$

Then let

$$T_{i+1} = T_i \cup \{\Phi_\varphi \mid \varphi(x) \text{ is an } L_i \text{ formula}\}.$$

Claim: T_{i+1} is [finitely satisfiable](#).

Proof: Let $\Delta \subseteq T_{i+1}$ be finite. Then

$$\Delta = \Delta_0 \cup \{\Phi_{\varphi_1}, \dots, \Phi_{\varphi_n}\}$$

where $\Delta_0 \subseteq T_i$. Let $\mathcal{M} \models \Delta_0$ (\mathcal{M} is an L_i [structure](#); it exists because T_i is [finitely satisfiable](#)).

We define an L_{i+1} -structure \mathcal{M}' with domain M . Define the [interpretation](#) of new constants as follows: if $\mathcal{M} \models \exists x \varphi(x)$, then let a be such that $\mathcal{M} \models \varphi(a)$, and set $c_\varphi^{\mathcal{M}'} := a$. Otherwise, $c_\varphi^{\mathcal{M}'}$ is arbitrary. Then $\mathcal{M}' \models \Delta$. ■

Let

$$L^* = \bigcup_{i < \omega} L_i, \quad T^* = \bigcup_{i < \omega} T_i.$$

By construction, any extension of T^* has the [witness property](#) (check this!) and T^* is finitely satisfiable. (If $\Delta \subseteq T^*$ then $\Delta \subseteq T_i$ for some i). □

Lemma 11.5. If T is [finitely satisfiable](#), there exists a [maximal](#) finitely satisfiable $T' \supseteq T$.

Proof. Let

$$I := \{ S \mid S \text{ is a finitely satisfiable } L\text{-theory such that } T \subseteq S \}.$$

I is partially ordered by inclusion, and non-empty.

If $\langle C_i : i < \lambda \rangle$ is a chain in I , then $\bigcup_{i < \lambda} C_i$ is an upper bound for the chain - it is finitely satisfiable. Then by Zorn's lemma, I has a maximal element (with respect to \subseteq).

Claim: the maximal element T' of I is the required extension of T (check that for all L -sentences σ , $\sigma \in T'$ or $\neg\sigma \in T'$). \square

Theorem 11.6 (Compactness). If T is a finitely satisfiable L -theory and $\lambda \geq |L| + \omega$, then there is $\mathcal{M} \models T$ such that $|\mathcal{M}| \leq \lambda$.

Proof sketch. Extend T to T^* , an L^* -theory that is finitely satisfiable and such that any $S \supseteq T^*$ has the witness property (by Lemma 11.4).

By Lemma 11.5, there is $T' \supseteq T^*$, which is maximal and finitely satisfiable. Then T' has the witness property. Then by Lemma 11.3 there is $\mathcal{M} \models T'$ with $|\mathcal{M}| \leq \lambda$, and $\mathcal{M} \models T$. \square

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