

A Crèche Course in Model Theory

Domenico Zambella
Università di Torino

July 2018

Preface	4
1 Preliminaries and notation	5
1 Structures	5
2 Tuples	6
3 Terms	7
4 Substructures	8
5 Formulas	9
6 Yet more notation	11
2 Theories and elementarity	13
1 Logical consequences	13
2 Elementary equivalence	15
3 Embeddings and isomorphisms	17
4 Quotient structures	19
5 Completeness	20
6 The Tarski-Vaught test	21
7 Downward Löwenheim-Skolem	22
8 Elementary chains	23
3 Ultraproducts	25
1 Filters and ultrafilters	25
2 Direct products	26
3 Łoś's Theorem	27
4 Compactness	30
1 Compactness via syntax	30
2 Compactness via ultraproducts	31
3 Upward Löwenheim-Skolem	32
4 Finite axiomatizability	33
5 Types and morphisms	35
1 Semilattices and filters	35
2 Distributive lattices and prime filters	37
3 Types as filters	39
4 Morphisms	41

6	Some relational structures	44
1	Dense linear orders	44
2	Random graphs	46
3	Notes and references	49
7	Fraïssé limits	50
1	Rich models.	50
2	Weaker notions of universality and homogeneity	55
3	The amalgamation property	56
8	Some algebraic structures	59
1	Abelian groups	59
2	Torsion-free abelian groups	60
3	Divisible abelian groups	61
4	Commutative rings	63
5	Integral domains	64
6	Algebraically closed fields	65
7	Hilbert's Nullstellensatz	66
9	Saturation and homogeneity	69
1	Saturated structures	69
2	Homogeneous structures	71
3	The monster model	72
10	Preservation theorems	77
1	Lyndon-Robinson Lemma	77
2	Quantifier elimination by back-and-forth	79
3	Model-completeness	81
11	Geometry and dimension	83
1	Algebraic and definable elements	83
2	Strongly minimal theories	85
3	Independence and dimension	86
12	Countable models	89
1	The omitting types theorem	89
2	Prime and atomic models	91
3	Countable categoricity	92
4	Small theories	94
5	A toy version of a theorem of Zil'ber	96
6	Notes and references	97
13	Imaginaries	98
1	Many-sorted structures	98
2	The eq-expansion	99
3	The definable closure in the eq-expansion	101
4	The algebraic closure in the eq-expansion	102
5	Elimination of imaginaries	103

6	The true story of imaginaries	106
7	Uniform elimination of imaginaries	106
8	Notes and references	108
14	Invariant sets	109
1	Invariant sets and types	109
2	Invariance from the dual perspective	110
3	Heirs and coheirs	111
4	Morley sequences and indiscernibles	113
15	Ramsey theory	115
1	Ramsey theorem from coheir sequences	115
2	Ehrenfeucht-Mostowski construction of indiscernibles	116
3	Idempotent orbits in semigroups	117
4	Hindman theorem	118
5	Hales-Jewett theorem	119
16	Lascar invariant sets	122
1	Expansions	122
2	Lascar strong types	123
3	The Lascar graph and Newelski's theorem	125
4	Kim-Pillay types	128
5	Notes and references	130
17	Externally definable sets	131
1	Approximable sets	131
2	Ladders and definability	133
3	Vapnik-Chevronenkis dimension	135
4	Honest definitions	136
5	Stable theories	137
6	Stability and the number of types	139
7	Notes and references	140
18	Keisler measures	141
1	T.b.c.	141

Preface

*This book was written to answer one question
“Does a recursion theorist dare to write a book
on model theory?”*

Gerald E. Sacks
Saturated Model Theory (1972)



These are the notes of a course that I have given for a few years in Amsterdam and many more in Turin. A few chapters will be added soon. Find the most recent version in

<https://github.com/domenicozambella/creche>



A warning sign in the margin indicates that the notation is nonstandard. Occasionally, the whole exposition is substantially nonstandard. Below are a few examples.

- ▷ **Fraïssé limits** are presented in a general setting that accommodates a large variety of examples (and I'll add a few more). This setting is used, for example, to discuss saturation.
- ▷ **Quantifier elimination for ACF** and Hilbert's Nullstellensatz are presented in more detail than is usual. (This may annoy some readers, but I hope it will help others.)
- ▷ The proof of the **Omitting Types Theorem** uses a model theoretic construction.
- ▷ **Imaginaries and the eq-expansion** are introduced from the (equivalent) dual perspective that the canonical name of a definable set is the set itself.
- ▷ **Ramsey's Theorem** is derived from the existence of coheir sequences. This is not the shortest proof, but it should be interesting.
- ▷ Along the same lines we sketch a proof of **Hindman's Theorem** which based on coheir sequences and uniqueness of coheir extensions.
- ▷ **Lascar and Kim-Pillay types** are introduced in a slightly unconventional way.
- ▷ **Newelski's Theorem** on the diameter of Lascar types is proved in an elementary self-contained way.
- ▷ **Stability and NIP** are introduced very briefly. We only discuss the properties of externally definable sets, which we identify with *approximable sets*.

Chapter 1

Preliminaries and notation

This chapter introduces the syntax and semantic of first order logic. We assume that the reader has at least some familiarity with first order logic.

The definitions of terms and formulas we give in Section 3 and 5 are more formal than is required in subsequent chapters. Our main objective is to convince the reader that a rigorous definition of language and truth is possible. However, the actual details of such a definition are not relevant for our purposes.

1 Structures

A (first order) language L (also called signature) is a triple that consists of

1. a set L_{fun} whose elements are called function symbols;
2. a set L_{rel} whose elements are called relation symbols;
3. a function that assigns to every $f \in L_{\text{fun}}$, respectively $r \in L_{\text{rel}}$, non-negative integers n_f and n_r that we call arity of the function, respectively relation, symbol. We say that f is an n_f -ary function symbol, and similarly for r . A 0-ary function symbol is also called a constant.

Warning: it is customary to use the symbol L to denote both the language and the set of formulas (to be defined below) associated to it. The cardinality of $L_{\text{fun}} \cup L_{\text{rel}} \cup \omega$ is denoted by $|L|$.

A (first order) structure M of signature L (for short L -structure) consists of

1. a set that we call the domain or support and denote by the same symbol M used for the structure as a whole;
2. a function that assigns to every $f \in L_{\text{fun}}$ a total map $f^M : M^{n_f} \rightarrow M$;
3. a function that assigns to every $r \in L_{\text{rel}}$ a relation $r^M \subseteq M^{n_r}$.

We call f^M , respectively r^M , the interpretation of f , respectively r , in M .

Recall that, by definition, $M^0 = \{\emptyset\}$. Therefore the interpretation of a constant c is a function that maps the unique element of M^0 to an element of M . We identify c^M with $c^M(\emptyset)$.

We may use the word model as a synonym for structure. But beware that, in some contexts, the word is used to denote a particular kind of structure.

If M is an L -structure and $A \subseteq M$ is any subset, we write $L(A)$ for the language obtained by adding to L_{fun} the elements of A as constants. In this context, the elements of A are called parameters. There is a canonical expansion of M to an $L(A)$ -structure that is obtained by setting $a^M = a$ for every $a \in A$.

1.1 Example The language of additive groups consists of the following function sym-

bols:

1. a constant (that is, a function symbol of arity 0) 0
2. a unary function symbol (that is, of arity 1) $-$
3. a binary function symbol (that is, of arity 2) $+$.

In the **language of multiplicative groups** the three symbols above are replaced by 1 , $-^1$, and \cdot respectively. Any group is a structure in either of these two signatures with the obvious interpretation. Needless to say, not all structures with these signatures are groups.

The **language of (unitary) rings** contains all the function symbols above except $-^1$. The **language of ordered rings** also contains the binary relation symbol $<$. \square

The following example is less straightforward. The reason for the choice of the language of vector spaces will become clear in Example 1.9 below.

- 1.2 Example** Let F be a field. The **language of vector spaces over F** , which we denote by L_F , extends that of additive groups by a unary function symbol k for every $k \in F$. Recall that a vector space over F is an abelian group M together with a function $\mu : F \times M \rightarrow M$ satisfying some properties (that we assume well-known, see Example 2.4). To view a vector space over F as an L_F -structure, we interpret the group symbols in the obvious way and each $k \in F$ as the function $\mu(k, -)$. \square


The languages in Examples 1.1 and 1.2, with the exception of that of ordered rings, are **functional languages**, that is, $L_{\text{rel}} = \emptyset$. In what follows, we consider two important examples of **relational languages**, that is, languages where $L_{\text{fun}} = \emptyset$.


- 1.3 Example** The **language of strict orders** only contains the binary relation symbol $<$. The **language of graphs**, too, only contains a binary relation symbol (for which there is no standard notation). In combinatorics, a graph is a set of unordered pairs. To view a graph as a first order structure, we identify sets of unordered pairs with symmetric irreflexive relations. \square

2 Tuples

A **tuple of elements of A** is a function $a : \alpha \rightarrow A$ from an ordinal α to a set A . We call α the **length** of a and denote it by $|a|$. If a is surjective, it is said to be an **enumeration** of A . Occasionally, we may say **sequence** for tuple – a word that is also used when the domain is not necessarily an ordinal.

We write a_i for the i -th element of a , that is, the element $a(i)$, where $i < \alpha$. We may use the notation $a = \langle a_i : i < \alpha \rangle$ for a tuple; when α is finite, we may also write $a = a_0, \dots, a_{\alpha-1}$. We write $a_{\upharpoonright n}$ for the restriction of a to n .

 In general, note that $I \subseteq \alpha$ has a unique increasing enumeration, say $\langle i_k : k < \beta \rangle$. Then we write $a_{\upharpoonright I}$ for the tuple $\langle a_{i_k} : k < \beta \rangle$.

 We sometimes overline the symbol that denotes a tuple. For ease of notation, the elements of the tuple \bar{a} are denoted by a_i (without the bar). Similarly for $a_{\upharpoonright n}$ and $a_{\upharpoonright I}$.

The set of tuples of elements of length α is denoted by A^α . The set of tuples of length $< \alpha$ is denoted by $A^{<\alpha}$. For instance, $A^{<\omega}$ is the set of all finite tuples of elements of A . When α is finite we do not distinguish between A^α and the α -th Cartesian power of A . In particular, we do not distinguish between A^1 and A .

If $a, b \in A^{|\alpha|}$ and h is a function defined on A , we write $h(a) = b$ for $h(a_i) = b_i$. We often do not distinguish between the pair $\langle a, b \rangle$ and the tuple of pairs $\langle a_i, b_i \rangle$. The context will resolve the ambiguity.

Note that there is a unique tuple of length 0, the empty set \emptyset , which in this context is called **empty tuple**. Recall that by definition $A^0 = \{\emptyset\}$ for every set A . Therefore, even when A is empty, A^0 contains the empty string.

We often concatenate tuples. If a and b are tuples, we write ab or, equivalently, a, b .

3 Terms

Let V be an infinite set whose elements we call **variables**. We use the letters x, y, z , etc. to denote variables or tuples of variables. We rarely refer to V explicitly, and we always assume that V is large enough for our needs.

We fix a signature L for the whole section.

1.4 Definition A **term** is a finite sequence of elements of $L_{\text{fun}} \cup V$ that are obtained inductively as follows:

- o.* every variable, intended as a tuple of length 1, is a term;
- i.* if $f \in L_{\text{fun}}$ and t is a tuple obtained by concatenating n_f terms, then ft is a term. We write ft for the tuple obtained by prefixing t by f .

We say **L-term** when we need to specify the language L . □

Note that any constant f , intended as a tuple of length 1, is a term (by *i*, the term f is obtained concatenating $n_f = 0$ terms and prefixing by f). Terms that do not contain variables are called **closed terms**.

The intended meaning of, for instance, the term $++xyz$ is $(x+y)+z$. The first expression uses **prefix notation**; the second uses **infix notation**. When convenient, we informally use infix notation and add parentheses to improve legibility and avoid ambiguity.

The following lemma shows that prefix notation allows to write terms unambiguously without using parentheses.

1.5 Lemma (unique legibility of terms) Let a be a sequence of terms. Suppose a can be obtained both by concatenating the terms t_1, \dots, t_n and by concatenating the terms s_1, \dots, s_m . Then $n = m$ and $s_i = t_i$.

Proof By induction on $|a|$. If $|a| = 0$ then $n = m = 0$ and there is nothing to prove. Suppose the claim holds for tuples of length k and let $a = a_1, \dots, a_{k+1}$. Then a_1 is the first element of both t_1 and s_1 . If a_1 is a variable, say x , then t_1 and s_1 are the term x and $n = m = 1$. Otherwise a_1 is a function symbol, say f . Then $t_1 = f\bar{t}$ and $s_1 = f\bar{s}$, where \bar{t} and \bar{s} are obtained by concatenating the terms t'_1, \dots, t'_p and

s'_1, \dots, s'_p . Now apply the induction hypothesis to a_2, \dots, a_{k+1} and to the terms $t'_1, \dots, t'_p, t_2, \dots, t_n$ and $s'_1, \dots, s'_p, s_2, \dots, s_m$. \square

If $x = x_1, \dots, x_n$ is a tuple of distinct variables and $s = s_1, \dots, s_n$ is a tuple of terms, we write $t[x/s]$ for the sequence obtained by replacing x by s coordinatewise. Proving that $t[x/s]$ is indeed a term is a tedious task that can be safely skipped.

If t is a term and x_1, \dots, x_n are (tuples of) variables, we write $t(x_1, \dots, x_n)$ to declare that the variables occurring in t are among those that occur in x_1, \dots, x_n . When a term has been presented as $t(x, y)$, we write $t(s, y)$ for $t[x/s]$.

Finally, we define the interpretation of a term in a structure M . We begin with closed terms. These are interpreted as 0-ary functions, i.e. as elements of the structure.

1.6 Definition Let t be a closed $L(M)$ term. The *interpretation of t* , denoted by t^M , is defined by induction of the syntax of t as follows.

- i. if $t = f \bar{t}$, where $f \in L_{\text{fun}}$ and \bar{t} is a tuple obtained by concatenating the terms t_1, \dots, t_{n_f} , then $t^M = f^M(t_1^M, \dots, t_{n_f}^M)$.

Note that in i we have used Lemma 1.5 in an essential way. In fact this ensures that the sequence \bar{t} uniquely determines the terms t_1, \dots, t_{n_f} . \square

The inductive definition above is based on the case $n_f = 0$, that is, the case where f a constant, or a parameter. When $t = c$, a constant, \bar{t} is the empty tuple, and so $t^M = c^M(\emptyset)$, which we abbreviate as c^M . In particular, if $t = a$, a parameter, then $t^M = a^M = a$.

Now we generalize the interpretation to all (not necessarily closed) terms. If $t(x)$ is a term, we define $t^M(x) : M^{|x|} \rightarrow M$ to be the function that maps a to $t(a)^M$.

4 Substructures

In the working practice, a *substructure* is a subset of a structure that is closed under the interpretation of the functions in the language. But there are a few cases when we need the following formal definition.

1.7 Definition Fix a signature L and let M and N be two L -structures. We say that M is a *substructure* of N , and write $M \subseteq N$, if

1. the domain of M is a subset of the domain of N
2. $f^M = f^N \upharpoonright M^{n_f}$ for every $f \in L_{\text{fun}}$
3. $r^M = r^N \cap M^{n_r}$ for every $f \in L_{\text{rel}}$.

Note that when f is a constant 2 becomes $f^M = f^N$, in particular the substructures of N contains at least all the constants of N .

If a set $A \subseteq N$ is such that

1. $f^N[A^{n_f}] \subseteq A$ for every $f \in L_{\text{fun}}$

then there is a unique substructure $M \subseteq N$ with domain A , namely, the structure with the following interpretation

2. $f^M = f^N \upharpoonright A^{n_f}$ (which is a good definition by the assumption on A);

$$3. \quad r^M = r^N \cap A^{n_r}.$$

It is usual to confuse subsets of N that satisfy 1 with the unique substructure they support.

It is immediate to verify that the intersection of an arbitrary family of substructures of N is a substructure of N . Therefore, for any given $A \subseteq N$ we may define the **substructure of N generated A** as the intersection of all substructures of N that contain A . We write $\langle A \rangle_N$. The following easy proposition gives more concrete representation of $\langle A \rangle_N$

1.8 Lemma *The following hold for every $A \subseteq N$*

1. $\langle A \rangle_N = \left\{ t^N : t \text{ a closed } L(A)\text{-term} \right\}$
2. $\langle A \rangle_N = \left\{ t^N(a) : t(x) \text{ an } L\text{-term and } a \in A^{|x|} \right\}$
3. $\langle A \rangle_N = \bigcup_{n \in \omega} A_n$, where $A_0 = A$
 $A_{n+1} = A_n \cup \left\{ f^N(a) : f \in L_{\text{fun}}, a \in A_n^{n_f} \right\}.$ \square

1.9 Example Let L be the language of groups. Let N be a group, which we consider as an L -structure in the natural way. Then the substructures of N are exactly the subgroups of N and $\langle A \rangle_N$ is the group generated by $A \subseteq N$. A similar claim is true when L_F is the signature of vector spaces over some fixed field F . The choice of the language is more or less fixed if we want that the algebraic and the model theoretic notion of substructure coincide. \square

5 Formulas

Fix a language L and a set of variables V as in Section 3. A **formula** is a finite sequence of symbols in $L_{\text{fun}} \cup L_{\text{rel}} \cup V \cup \{\doteq, \perp, \neg, \vee, \exists\}$. The last set contains the logical symbols that are called respectively

\doteq	equality	\perp	contradiction	\neg	negation
\vee	disjunction	\exists	existential quantifier.		

Syntactically, \doteq behaves like a binary relation symbol. So, for convenience set $n_{\doteq} = 2$. However \doteq is considered as a logic symbol because its semantic is fixed (it is always interpreted in the diagonal).

The definition below uses the prefix notation which simplifies the proof of the unique legibility lemma. However, in practice we always use the infix notation: $t \doteq s$, $\varphi \vee \psi$, etc.

1.10 Definition A **formula** is any finite sequence is obtained with the following inductive procedure

- o. if $r \in L_{\text{rel}} \cup \{\doteq\}$ and t is a tuple obtained concatenating n_r terms then $r t$ is a formula. Formulas of this form are called **atomic**;
- i. if φ e ψ are formulas then the following are formulas: \perp , $\neg \varphi$, $\varphi \vee \psi$, and $\exists x \varphi$, for any $x \in V$. \square

We use L to denote both the language and the set of formulas. We write L_{at} for the set of atomic formulas and L_{qf} for the set of **quantifier-free formulas** i.e. formulas where \exists does not occur.

The proof of the following is similar to the analogous lemma for terms.

1.11 Lemma (unique legibility of formulas) *Let a be a sequence of formulas. Suppose a can be obtained both by the concatenation of the formulas $\varphi_1, \dots, \varphi_n$ or by the concatenation of the formulas ψ_1, \dots, ψ_m . Then $n = m$ and $\varphi_i = \psi_i$.* \square

A formula is **closed** if all its variables occur under the scope of a quantifier. Closed formulas are also called **sentences**. We will do without a formal definition of *occurs under the scope of a quantifier* which is too lengthy. An example suffices: all occurrences of x are under the scope a quantifiers in the formula $\exists x \varphi$. These occurrences are called **bonded**. The formula $x \doteq y \wedge \exists x \varphi$ has **free** (i.e., not bond) occurrences of x and y .

Let x is a tuple of variables and t is a tuple of terms such that $|x| = |t|$. We write $\varphi[x/t]$ for the formula obtained substituting t for all free occurrences of x , coordinatewise.

We write $\varphi(x)$ to declare that the free variables in the formula φ are all among those of the tuple x . In this case we write $\varphi(t)$ for $\varphi[x/t]$.

We will often use without explicit mention the following useful syntactic decomposition of formulas with parameters.

1.12 Lemma *For every formula $\varphi(x) \in L(A)$ there is a formula $\psi(x; z) \in L$ and a tuple of parameters $a \in A^{|z|}$ such that $\varphi(x) = \psi(x; a)$.* \square

Just as a term $t(x)$ is a name for a function $t(x)^M : M^{|x|} \rightarrow M$, a formula $\varphi(x)$ is a name for a subset $\varphi(x)^M \subseteq M^{|x|}$ which we call **the subset of M defined by $\varphi(x)$** . It is also very common to write $\varphi(M)$ for the set defined by $\varphi(x)$. In general sets of the form $\varphi(M)$ for some $\varphi(x) \in M$ are called **definable**.

1.13 Definition of truth *For every formula φ with variables among those of the tuple x we define $\varphi(x)^M$ by induction as follows*

$$o1. \quad (\doteq t s)(x)^M = \{a \in M^{|x|} : t^M(a) = s^M(a)\}$$

$$o2. \quad (r t_1 \dots t_n)(x)^M = \{a \in M^{|x|} : \langle t_1^M(a), \dots, t_n^M(a) \rangle \in r^M\}$$

$$i0. \quad \perp(x)^M = \emptyset$$

$$i1. \quad (\neg \xi)(x)^M = M^{|x|} \setminus \xi(x)^M$$

$$i2. \quad (\vee \xi \psi)(x)^M = \xi(x)^M \cup \psi(x)^M$$

$$i3. \quad (\exists y \varphi)(x)^M = \bigcup_{a \in M} (\varphi[y/a])(x)^M$$

Condition i2 assumes that ξ and ψ are uniquely determined by $\vee \xi \psi$. This is guaranteed by the unique legibility of formulas, Lemma 1.11. Analogously, o1 and o2 assume Lemma 1.5.

The case when x is the empty tuple is far from trivial. Note that $\varphi(\emptyset)^M$ is a subset of $M^0 = \{\emptyset\}$. Then there are two possibilities either $\{\emptyset\}$ or \emptyset . We will read them as two **truth values**: **True** and **False**, respectively. If $\varphi^M = \{\emptyset\}$ we say that **φ is true in M** , if $\varphi^M = \emptyset$, we say that **φ is false in M** . We write **$M \models \varphi$** , respectively **$M \not\models \varphi$** . Or we may say that **M models φ** , respectively **M does not model φ** . It is immediate to verify at

$$\varphi(M) = \{a \in M^{|x|} : M \models \varphi(a)\}.$$

Note that usually, we say *formula* when, strictly speaking, we mean *pair* that consists of a formula and a tuple of variables. Such pairs are interpreted in definable sets (cfr. Definition 1.13). In fact, if the tuple of variables were not given, the arity of the corresponding set is not determined.

In some contexts we also want to distinguish between two sorts of variables that play different roles. Some are placeholder for parameters, some are used to define a set. In the first chapters this distinction is only a clue for the reader, in the last chapters it is an essential part of the definitions.

1.14 Definition A **partitioned formula** (strictly speaking, we should say a **2-partitioned formula**) is a triple $\varphi(x; z)$ consisting of a formula and two tuples of variables such that the variables occurring in φ are all among x, z . □

We use a semicolon to separate the two tuples of variables. Typically, z is the placeholder for parameters and x runs over the elements of the set defined by the formula.

6 Yet more notation

Now we abandon the prefix notation in favor of the infix notation. We also use the following logical connectives as abbreviations

\top	stands for	$\neg \perp$	tautology
$\varphi \wedge \psi$	stands for	$\neg[\neg\varphi \vee \neg\psi]$	conjunction
$\varphi \rightarrow \psi$	stands for	$\neg\varphi \vee \psi$	implication
$\varphi \leftrightarrow \psi$	stands for	$[\varphi \rightarrow \psi] \wedge [\psi \rightarrow \varphi]$	bi-implication
$\varphi \nleftrightarrow \psi$	stands for	$\neg[\varphi \leftrightarrow \psi]$	exclusive disjunction
$\forall x \varphi$	stands for	$\neg \exists x \neg \varphi$	universal quantifier

We agree that \rightarrow and \leftrightarrow bind less than \wedge and \vee . Unary connectives (quantifiers and negation) bind stronger than binary connectives. For example

$$\exists x \varphi \wedge \psi \rightarrow \neg \xi \vee \vartheta \quad \text{reads as} \quad [(\exists x \varphi) \wedge \psi] \rightarrow [(\neg \xi) \vee \vartheta]$$

We say that $\forall x \varphi(x)$ and $\exists x \varphi(x)$ are the **universal**, respectively, **existential closure** of $\varphi(x)$. We say that $\varphi(x)$ **holds in M** when its universal closure is true in M . We say that $\varphi(x)$ is **consistent in M** when its existential closure is true in M .

The semantic of conjunction and disjunction is associative. Then for any finite set of formulas $\{\varphi_i : i \in I\}$ we can write without ambiguities

$$\bigwedge_{i \in I} \varphi_i$$

$$\bigvee_{i \in I} \varphi_i$$

When $x = x_1, \dots, x_n$ is a tuple of variables we write $\exists x \varphi$ or $\exists x_1, \dots, x_n \varphi$ for $\exists x_1 \dots \exists x_n \varphi$. With first order sentences we are able to say that $\varphi(M)$ has at least n elements (also, no more than, or exactly n). It is convenient to use the following abbreviations.

$$\exists^{\geq n} x \varphi(x) \quad \text{stands for} \quad \exists x_1, \dots, x_n \left[\bigwedge_{1 \leq i \leq n} \varphi(x_i) \wedge \bigwedge_{1 \leq i < j \leq n} x_i \neq x_j \right].$$

$$\exists^{\leq n} x \varphi(x) \quad \text{stands for} \quad \neg \exists^{\geq n+1} x \varphi(x)$$

$$\exists^=n x \varphi(x) \quad \text{stands for} \quad \exists^{\geq n} x \varphi(x) \wedge \exists^{\leq n} x \varphi(x)$$

1.15 Exercise Let M be an L -structure and let $\psi(x), \varphi(x, y) \in L$. For each of the following conditions, write a sentence true in M exactly when

- a. $\psi(M) \in \{\varphi(a, M) : a \in M\}$;
- b. $\{\varphi(a, M) : a \in M\}$ contains at least two sets;
- c. $\{\varphi(a, M) : a \in M\}$ contains only sets that are pairwise disjoint. □

1.16 Exercise Let M be a structure in the signature of graphs as defined in Example 1.3 (but not necessarily a graph). Write a sentence φ such that,

- a. $M \models \varphi$ if and only if there is an $A \subseteq M$ such that $r^M \subseteq A \times \neg A$.

Remark: φ assert an asymmetric version of the property below

- b. $M \models \psi$ if and only if there is an $A \subseteq M$ such that $r^M \subseteq (A \times \neg A) \cup (\neg A \times A)$.

Assume M is a graph, what required in b is equivalent to saying that M is a *bipartite graph*, or equivalently that it has *chromatic number* 2 i.e., we can color the vertices with 2 colors so that no two adjacent vertices share the same color. □

Chapter 2

Theories and elementarity

1 Logical consequences

A **theory** is a set $T \subseteq L$ of sentences. We write $M \models T$ if $M \models \varphi$ for every $\varphi \in T$. If $\varphi \in L$ is a sentence we write $T \vdash \varphi$ when

$$M \models T \Rightarrow M \models \varphi \quad \text{for every } M.$$

In words, we say that φ is a **logical consequence** of T or that φ **follows from** T . If S is a theory $T \vdash S$ has a similar meaning. If $T \vdash S$ and $S \vdash T$ we say that T and S are **logically equivalent**. We may say that T **axiomatizes** S (or vice versa).

We say that a theory is **consistent** if it has a model. With the notation above, T is consistent if and only if $T \not\vdash \perp$.

The **closure of T under logical consequence** is the set $\text{ccl}(T)$ which is defined as follows:

$$\text{ccl}(T) = \{ \varphi \in L : \text{sentence such that } T \vdash \varphi \}$$

If T is a finite set, say $T = \{ \varphi_1, \dots, \varphi_n \}$ we write $\text{ccl}(\varphi_1, \dots, \varphi_n)$ for $\text{ccl}(T)$. If $T = \text{ccl}(T)$ we say that T is **closed under logical consequences**.

The **theory of M** is the set of sentences that hold in M and is denoted by $\text{Th}(M)$. More generally, if \mathcal{K} is a class of structures, $\text{Th}(\mathcal{K})$ is the set of sentences that hold in every model in \mathcal{K} . That is

$$\text{Th}(\mathcal{K}) = \bigcap_{M \in \mathcal{K}} \text{Th}(M)$$

The class of all models of T is denoted by $\text{Mod}(T)$. We say that \mathcal{K} is **axiomatizable** if $\text{Mod}(T) = \mathcal{K}$ for some theory T . If T is finite we say that \mathcal{K} is **finitely axiomatizable**. To sum up

$$\text{Th}(M) = \{ \varphi : M \models \varphi \}$$

$$\text{Th}(\mathcal{K}) = \{ \varphi : M \models \varphi \text{ for all } M \in \mathcal{K} \}$$

$$\text{Mod}(T) = \{ M : M \models T \}$$

2.1 Example Let L be the language of multiplicative groups. Let T_g be the set containing the universal closure of following three formulas

1. $(x \cdot y) \cdot z = x \cdot (y \cdot z);$
2. $x \cdot x^{-1} = x^{-1} \cdot x = 1;$
3. $x \cdot 1 = 1 \cdot x = x.$

Then T_g axiomatizes the theory of groups, i.e. $\text{Th}(\mathcal{K})$ for \mathcal{K} the class of all groups. Let φ be the universal closure of the following formula

$$z \cdot x = z \cdot y \rightarrow x = y.$$

As φ formalizes the cancellation property then $T_g \vdash \varphi$, that is, φ is a logical consequence of T_g . Now consider the sentence ψ which is the universal closure of

$$4. \quad x \cdot y = y \cdot x.$$

So, commutative groups model ψ and non commutative groups model $\neg\psi$. Hence neither $T_g \vdash \psi$ nor $T_g \vdash \neg\psi$. We say that T_g **does not decide** ψ . \square

Note that even when T is a very concrete set, $\text{ccl}(T)$ may be more difficult to grasp. In the example above T_g contains three sentences but $\text{ccl}(T_g)$ is an infinite set containing sentences that code theorems of group theory yet to be proved.

2.2 Remark The following properties say that ccl is a finitary closure operator.

1. $T \subseteq \text{ccl}(T)$ (extensive)
2. $\text{ccl}(T) = \text{ccl}(\text{ccl}(T))$ (increasing)
3. $T \subseteq S \Rightarrow \text{ccl}(T) \subseteq \text{ccl}(S)$ (idempotent)
4. $\text{ccl}(T) = \bigcup \{ \text{ccl}(S) : S \text{ finite subset of } T \}$. (finitary)

Properties 1-3 are easy to verify while 4 requires the compactness theorem. \square

In the next example we list a few algebraic theories with straightforward axiomatization.

2.3 Example We write T_{ag} for the theory of abelian groups which contains the universal closure of following

- a1. $(x + y) + z = y + (x + z);$
- a2. $x + (-x) = 0;$
- a3. $x + 0 = x;$
- a4. $x + y = y + x.$

The theory T_r of (unitary) rings extends T_{ag} with

- a5. $(x \cdot y) \cdot z = x \cdot (y \cdot z);$
- a6. $1 \cdot x = x \cdot 1 = x;$
- a7. $(x + y) \cdot z = x \cdot z + y \cdot z;$
- a8. $z \cdot (x + y) = z \cdot x + z \cdot y.$

The theory of commutative rings T_{cg} contains also com of examples 2.1. The theory of ordered rings T_{or} extends T_{cr} with

- o1. $x < z \rightarrow x + y < z + y;$
- o2. $0 < x \wedge 0 < z \rightarrow 0 < x \cdot z.$

\square

The axiomatization of the **theory of vector spaces** is less straightforward.

2.4 Example Fix a field F . The language L_F extends the language of additive groups with a unary function for every element of F . The theory of vector fields over F extends T_{ag} with the following axioms (for all $h, k, l \in F$)

$$\text{m1. } h(x + y) = hx + hy$$

$$\text{m2. } lx = hx + kx, \quad \text{where } l = h +_F k$$

$$\text{m3. } lx = h(kx), \quad \text{where } l = h \cdot_F k$$

$$\text{m4. } 0_F x = 0$$

$$\text{m5. } 1_F x = x$$

The symbols 0_F and 1_F denote the zero and the unit of F . The symbols $+_F$ and \cdot_F denote the sum and the product in F . These are not part of L_F , they are symbols we use in the metalanguage. \square

2.5 Example Recall from Example 1.3 that we represent a graph with a symmetric irreflexive relation. Therefore **theory of graphs** contains the following two axioms

$$1. \neg r(x, x);$$

$$2. r(x, y) \rightarrow r(y, x).$$

\square

Our last example is a trivial one.

2.6 Example Let L be the empty language The **theory of infinite sets** is axiomatized by the sentences $\exists^{\geq n} x (x = x)$ for all positive integer n . \square

2.7 Exercise Prove that $\text{ccl}(\varphi \vee \psi) = \text{ccl}(\varphi) \cap \text{ccl}(\psi)$. \square

2.8 Exercise Prove that $T \cup \{\varphi\} \vdash \psi$ then $T \vdash \varphi \rightarrow \psi$. \square

2.9 Exercise Prove that $\text{Th}(\text{Mod}(T)) = \text{ccl}(T)$. \square

2 Elementary equivalence

The following is a fundamental notion in model theory.

2.10 Definition We say that M and N are **elementarily equivalent** if

$$ee. N \models \varphi \Leftrightarrow M \models \varphi, \quad \text{for every } \varphi \in L.$$

In this case we write $M \equiv N$. More generally, we write $M \equiv_A N$ and say that M and N are **elementarily equivalent over A** if the following hold

$$a. A \subseteq M \cap N$$

$$ee'. \text{ equivalence } ee \text{ above holds for every sentence } \varphi \in L(A).$$

\square

The case when A is the whole domain of M is particularly important.

2.11 Definition When $M \equiv_M N$ we write $M \preceq N$ and say that M is an **elementary substructure** of N . \square

In the definition above the use of the term *substructure* is appropriate by the following lemma.

2.12 Lemma If M and N are such that $M \equiv_A N$ and A is the domain of a substructure of M then A is also the domain a substructure of N and the two substructures coincide.

Proof Let f be a function symbol and let r be a relation symbol. It suffices to prove that $f^M(a) = f^N(a)$ for every $a \in A^{n_f}$ and that $r^M \cap A^{n_r} = r^N \cap A^{n_r}$.

If $b \in A$ is such that $b = f^M a$ then $M \models fa = b$. So, from $M \equiv_A N$, we obtain $N \models fa = b$, hence $f^N a = b$. This proves $f^M(a) = f^N(a)$.

Now let $a \in A^{n_r}$ and suppose $a \in r^M$. Then $M \models ra$ and, by elementarity, $N \models ra$, hence $a \in r^N$. By symmetry $r^M \cap A^{n_r} = r^N \cap A^{n_r}$ follows. \square

It is not easy to prove that two structures are elementary equivalent. A direct verification is unfeasible even for the most simple structures. It will take a few chapters before we are able to discuss concrete examples.

We generalize the definition of $\text{Th}(M)$ to include parameters

$$\text{Th}(M/A) = \left\{ \varphi : \text{sentence in } L(A) \text{ such that } M \models \varphi \right\}.$$

The following proposition is immediate

2.13 Proposition For every pair of structures M and N and every $A \subseteq M \cap N$ the following are equivalent

- a. $M \equiv_A N$;
- b. $\text{Th}(M/A) = \text{Th}(N/A)$;
- c. $N \models \varphi(a) \Leftrightarrow M \models \varphi(a)$ for every $\varphi(x) \in L$ and every $a \in A^{|x|}$.
- d. $\varphi(M) \cap A^{|x|} = \varphi(N) \cap A^{|x|}$ for every $\varphi(x) \in L$.

\square

If we restate a and c of the proposition above when $A = M$ we obtain that the following are equivalent

- a'. $M \preceq N$;
- c'. $\varphi(M) = \varphi(N) \cap M^{|x|}$ for every $\varphi(x) \in L$.

Note that c' extends to all definable sets what Definition 1.7 requires for a few basic definable sets.

2.14 Example Let G be a group which we consider as a structure in the multiplicative language of groups. We show that if G is simple and $H \preceq G$ then also H is simple. Recall that G is simple if all its normal subgroups are trivial, equivalently, if for every $a \in G \setminus \{1\}$ the set $\{gag^{-1} : g \in G\}$ generates the whole group G .

Assume H is not simple then there $a, b \in H$ be such that b is not product of elements of $\{hah^{-1} : h \in H\}$, hence for every n

$$H \models \neg \exists x_1, \dots, x_n (b = x_1 a x_1^{-1} \cdots x_n a x_n^{-1})$$

By elementarity the same hold in G . Hence G is not simple. \square

2.15 Exercise Let $A \subseteq M \cap N$. Prove that $M \equiv_A N$ if and only if $M \equiv_B N$ for every finite $B \subseteq A$. \square

2.16 Exercise Let $M \preceq N$ and let $\varphi(x) \in L(M)$. Prove that $\varphi(M)$ is finite if and only if

$\varphi(N)$ is finite and in this case $\varphi(N) = \varphi(M)$. \square

2.17 Exercise Let $M \preceq N$ and let $\varphi(x, z) \in L$. Suppose there are finitely many sets of the form $\varphi(a, N)$ for some $a \in N^{|x|}$. Prove that all these sets are definable over M . \square

2.18 Exercise Consider \mathbb{Z}^n as a structure in the additive language of groups with the natural interpretation. Prove that $\mathbb{Z}^n \not\cong \mathbb{Z}^m$ for every positive integers $n \neq m$. Hint: in \mathbb{Z}^n there are at most $2^n - 1$ elements that are not congruent modulo 2. \square

3 Embeddings and isomorphisms

Here we prove that isomorphic structures are elementary equivalent and a few related results.

2.19 Definition An **embedding** of M into N is an injective map $h : M \rightarrow N$ such that

1. $a \in r^M \Leftrightarrow ha \in r^N$ for every $r \in L_{\text{rel}}$ and $a \in M^{n_r}$;
2. $h f^M(a) = f^N(h a)$ for every $f \in L_{\text{fun}}$ and $a \in M^{n_f}$.

Note that when $c \in L_{\text{fun}}$ is a constant 2 reads $h c^M = c^N$. Therefore that $M \subseteq N$ if and only if $\text{id}_M : M \rightarrow N$ is an embedding.

An **surjective embedding** is an **isomorphism** or, when domain and codomain coincide, an **automorphism**. \square

Condition 1 above and the assumption that h is injective can be summarized in the following

- 1'. $M \models r(a) \Leftrightarrow N \models r(ha)$ for every $r \in L_{\text{rel}} \cup \{=\}$ and every $a \in M^{n_r}$.

Note also that, by straightforward induction on syntax, from 2 we obtain

- 2' $h t^M(a) = t^N(h a)$ for every term $t(x)$ and every $a \in M^{|x|}$.

Combining these two properties, and by straightforward induction on the syntax, we obtain

3. $M \models \varphi(a) \Leftrightarrow N \models \varphi(ha)$ for every $\varphi(x) \in L_{\text{qf}}$ and every $a \in M^{|x|}$.

Recall that we write L_{qf} for the set of quantifier-free formulas. It is worth noting that when $M \subseteq N$ and $h = \text{id}_M$ then 3 becomes

- 3' $M \models \varphi(a) \Leftrightarrow N \models \varphi(a)$ for every $\varphi(x) \in L_{\text{qf}}$ and for every $a \in M^{|x|}$.

In words this is summarized by saying that the truth of quantifier-free formulas is preserved under sub- and superstructure.

Finally we prove that first order truth is preserved under isomorphism. We say that a map $h : M \rightarrow N$ **fixes** $A \subseteq M$ (pointwise) if $\text{id}_A \subseteq h$. An isomorphism that fixes A is also called an **A-isomorphism**.

2.20 Theorem If $h : M \rightarrow N$ is an isomorphism then for every $\varphi(x) \in L$

$$\# \quad M \models \varphi(a) \Leftrightarrow N \models \varphi(ha) \text{ for every } a \in M^{|x|}$$

In particular, if h is an A-isomorphism then $M \equiv_A N$.

Proof We proceed by induction of the syntax of $\varphi(x)$. When $\varphi(x)$ is atomic # holds by 3 above. Induction for the Boolean connectives is straightforward so we only need to consider the existential quantifier. Assume as induction hypothesis that

$$M \models \varphi(a, b) \Leftrightarrow N \models \varphi(ha, hb) \quad \text{for every tupla } a \in M^{|x|} \text{ and } b \in M.$$

We prove that # holds for the formula $\exists y \varphi(x, y)$.

$$\begin{aligned} M \models \exists y \varphi(a, y) &\Leftrightarrow M \models \varphi(a, b) \quad \text{for some } b \in M \\ &\Leftrightarrow N \models \varphi(ha, hb) \text{ for some } b \in M \quad (\text{by induction hypothesis}) \\ &\Leftrightarrow N \models \varphi(ha, c) \quad \text{for some } c \in N \quad (\Leftarrow \text{by surjectivity}) \\ &\Leftrightarrow N \models \exists y \varphi(ha, y). \end{aligned} \quad \square$$

2.21 Corollary If $h : M \rightarrow N$ is an isomorphism then $h[\varphi(M)] = \varphi(N)$ for every $\varphi(x) \in L$. \square

We can now give a few very simple examples of elementarily equivalent structures.

2.22 Example Let L be the language of strict orders. Consider intervals of \mathbb{R} (or in \mathbb{Q}) as structures in the natural way. The intervals $[0, 1]$ and $[0, 2]$ are isomorphic, hence $[0, 1] \equiv [0, 2]$ follows from Theorem 2.20. Clearly, $[0, 1]$ is a substructure of $[0, 2]$. However $[0, 1] \not\preceq [0, 2]$, in fact the formula $\forall x (x \leq 1)$ holds in $[0, 1]$ but is false in $[0, 2]$. This shows that $M \subseteq N$ and $M \equiv N$ does not imply $M \preceq N$.

Now we prove that $(0, 1) \preceq (0, 2)$. By Exercise 2.15 above, it suffices to verify that $(0, 1) \equiv_B (0, 2)$ for every finite $B \subseteq (0, 1)$. This follows again by Theorem 2.20 as $(0, 1)$ and $(0, 2)$ are B -isomorphic for every finite $B \subseteq (0, 1)$. \square

For the sake of completeness we also give the definition of homomorphism.

2.23 Definition A **homomorphism** is a total map $h : M \rightarrow N$ such that

1. $a \in r^M \Rightarrow ha \in r^N \quad \text{for every } r \in L_{\text{rel}} \text{ and } a \in M^{n_r};$
2. $h f^M(a) = f^N(h a) \quad \text{for every } f \in L_{\text{fun}} \text{ and } a \in M^{n_f}.$

Note that only one implication is required in 1. \square

2.24 Exercise Prove that if $h : N \rightarrow N$ is an automorphism and $M \preceq N$ then $h[M] \preceq N$. \square

2.25 Exercise Let L be the empty language. Let $A, D \subseteq M$. Prove that the following are equivalent

1. D is definable over A ;
2. either D is finite and $D \subseteq A$ or $\neg D$ is finite and $\neg D \subseteq A$.

Hint: as L -structures are plain sets, every bijection $f : M \rightarrow M$ is an automorphism. \square

2.26 Exercise Prove that if $\varphi(x)$ is an existential formula and $h : M \rightarrow N$ is an embedding then

$$M \models \varphi(a) \Rightarrow N \models \varphi(ha) \quad \text{for every } a \in M^{|x|}.$$

Recall that existential formulas are those of the form $\exists y \psi(x, y)$ for $\psi(x, y) \in L_{\text{qf}}$. Note that Theorem 10.6 proves that the property above characterizes existential formulas. \square

2.27 Exercise Assume that the language L contains only the symbol $+$. Consider \mathbb{Z} as a structure of signature L with the usual interpretation of $+$. Prove that there is no existential formula that defines the set of even integers. Hint: use Exercise 2.26. \square

2.28 Exercise Let N be the multiplicative group of \mathbb{Q} . Let M be the subgroup of those rational numbers that are of the form n/m for some odd integers m and n . Prove that $M \preceq N$. Hint: use the fundamental theorem of arithmetic and reason as in Example 2.22. \square

4 Quotient structures

The content of this section is mainly technical and only required later in the course. Its reading may be postponed.

If E is an equivalence relation on N we write $[c]_E$ for the equivalence class of $c \in N$. We use the same symbol for the equivalence relation on N^n defined as follow: if $a = a_1, \dots, a_n$ and $b = b_1, \dots, b_n$ are n -tuples of elements of N then $a E b$ means that $a_i E b_i$ holds for all i . It is easy to see that $b_1, \dots, b_n \in [a, \dots, a_n]_E$ if and only if $b_i \in [a_i]_E$ for all i . Therefore we use the notation $[a]_E$ for both the equivalence class of $a \in N^n$ and the tuple of equivalence classes $[a_1]_E, \dots, [a_n]_E$.

2.29 Definition We say that the equivalence relation E on a structure N is a **congruence** if for every $f \in L_{\text{fun}}$

$$c1. \quad a E b \Rightarrow f^N a E f^N b;$$

When E is a congruence on N we write N/E for the a structure that has as domain the set of E -equivalence classes in N and the following interpretation of $f \in L_{\text{fun}}$ and $r \in L_{\text{rel}}$:

$$c2. \quad f^{N/E}[a]_E = [f^N a]_E;$$

$$c3. \quad [a]_E \in r^{N/E} \Leftrightarrow [a]_E \cap r^N \neq \emptyset.$$

We call N/E the **quotient structure**. \square

By c1 the quotient structure is well defined. The reader will recognize it as a familiar notion by the following proposition (which is not required in the following and requires the notion of homomorphism, see Definition 2.23. Recall that the **kernel** of a total map $h : N \rightarrow M$ is the equivalence relation E such that

$$a E b \Leftrightarrow ha = hb$$

for every $a, b \in N$.

2.30 Proposition Let $h : N \rightarrow M$ be a surjective homomorphism and let E be the kernel of h . Then there is an isomorphism k that makes the following diagram commute

$$\begin{array}{ccc} N & \xrightarrow{h} & M \\ \downarrow \pi & \nearrow k & \\ N/E & & \end{array}$$

where $\pi : a \mapsto [a]_E$ is the projection map. □



Quotients clutter the notation with brackets. To avoid the mess, we prefer to reason in N and tweak the satisfaction relation. Warning: this is not standard.

Essentially, we work in N while thinking of N/E . So, we replace equality with E and adapt the interpretation of relation symbols according to c3 above. The proposition below shows that the definition does what is intended to do.

2.31 Definition For t_1, t_2 closed terms of $L(N)$ define

$$1^* \quad N/E \models^* t_1 = t_2 \Leftrightarrow t_1^N E t_2^N$$

For t a tuple of closed terms of $L(N)$ and $r \in L_{\text{rel}}$ a relation symbol

$$2^* \quad N/E \models^* rt \Leftrightarrow t^N E a \in r^N \text{ for some } a \in M^{|t|}$$

Finally the definition is extended to all sentences $\varphi \in L(N)$ by induction in the usual way

$$3^* \quad N/E \models^* \neg \varphi \Leftrightarrow \text{not } N/E \models^* \varphi$$

$$4^* \quad N/E \models^* \varphi \wedge \psi \Leftrightarrow N/E \models^* \varphi \text{ and } N/E \models^* \psi$$

$$5^* \quad N/E \models^* \exists x \varphi(x) \Leftrightarrow N/E \models^* \varphi(\hat{a}) \text{ for some } a \in N. \quad \square$$

Now, by induction on the syntax of formulas one can prove \models^* does what required. In particular, $N/E \models^* \varphi(a) \Leftrightarrow \varphi(b)$ for every $a E b$.

2.32 Proposition Let E be a congruence relation of N . Then the following are equivalent for every $\varphi(x) \in L$

$$1. \quad N/E \models^* \varphi(a);$$

$$2. \quad N/E \models \varphi([a]_E). \quad \square$$

5 Completeness

A theory T is **maximal consistent** if it is consistent and there is no consistent theory S such that $S \subset T$. Equivalently, T contains every sentence φ **consistent with** T , that is, such that $T \cup \{\varphi\}$ is consistent. Clearly a maximal consistent theory is closed under logical consequences.

A theory T is **complete** if $\text{ccl}T$ is maximal consistent. Concrete examples will be given in the next chapters as it is not easy to prove that a theory is complete.

2.33 Proposition The following are equivalent

- a. T is maximal consistent;
- b. $T = \text{Th}(M)$ for some structure M ;
- c. T is consistent and $\varphi \in T$ or $\neg \varphi \in T$ for every sentence φ .

Proof To prove a \Rightarrow b, assume that T is consistent. Then there is $M \models T$. Therefore $T \subseteq \text{Th}(M)$. As T is maximal consistent $T = \text{Th}(M)$. Implication b \Rightarrow c is immediate. As for c \Rightarrow a note that if $T \cup \{\varphi\}$ is consistent then $\neg \varphi \notin T$ therefore $\varphi \in T$ follows from c. □

The proof of the proposition below is left as an exercise for the reader.

2.34 Proposition *The following are equivalent*

- a. T is complete;
- b. there is a unique maximal consistent theory S such that $T \subseteq S$;
- c. T is consistent and $T \vdash \text{Th}(M)$ for every $M \models T$;
- d. T is consistent and $T \vdash \varphi \leftrightarrow T \vdash \neg\varphi$ for every sentence φ ;
- e. T is consistent and $M \equiv N$ for every pair of models of T . □

2.35 Exercise Prove that the following are equivalent

- a. T is complete;
- b. for every sentence φ , $T \vdash \varphi \leftrightarrow T \vdash \neg\varphi$ but not both.

By contrast prove that the following are *not* equivalent

- a. T is maximal consistent;
- b. for every sentence φ , $\varphi \in T \leftrightarrow \neg\varphi \in T$ but not both.

Hint: consider the theory containing all sentences where the symbol \neg occurs an even number of times. This theory is not consistent as it contains \perp . □

2.36 Exercise Prove that if T has exactly 2 maximal consistent extensions T_1 and T_2 then there is a sentence φ such that $T, \varphi \vdash T_1$ and $T, \neg\varphi \vdash T_2$. State and prove the generalization to finitely many maximally consistent extensions. □

6 The Tarski-Vaught test

There is no natural notion of *smallest* elementary substructure containing a set of parameters A . The downward Löwenheim-Skolem, which we prove in the next section, is the best result that holds in full generality. Given an arbitrary $A \subseteq N$ we shall construct a model $M \preceq N$ containing A that is small in the sense of cardinality. The construction selects one by one the elements of M that are required to realise the condition $M \preceq N$. Unfortunately, Definition 2.11 supposes full knowledge of the truth in M and it may not be applied during the construction. The following lemma comes to our rescue with a property equivalent to $M \preceq N$ that only mention the truth in N .

2.37 Lemma (Tarski-Vaught test) *For every $A \subseteq N$ the following are equivalent*

- 1. A is the domain of a structure $M \preceq N$;
- 2. for every formula $\varphi(x) \in L(A)$, with $|x| = 1$,
 $N \models \exists x \varphi(x) \Rightarrow N \models \varphi(b)$ for some $b \in A$.

Proof $1 \Rightarrow 2$

$$\begin{aligned} N \models \exists x \varphi(x) &\Rightarrow M \models \exists x \varphi(x) \\ &\Rightarrow M \models \varphi(b) \quad \text{for some } b \in M \end{aligned}$$

$$\Rightarrow N \models \varphi(b) \quad \text{for some } b \in M.$$

$2 \Rightarrow 1$ Firstly, note that A is the domain of a substructure of N , that is, $f^N a \in A$ for every $f \in L_{\text{fun}}$ and every $a \in A^{n_f}$. In fact, this follows from 2 with $fa = x$ for $\varphi(x)$.

Write M for the substructure of N with domain A . By induction on the syntax we prove

$$M \models \varphi(a) \Leftrightarrow N \models \varphi(a) \quad \text{for every } a \in M^{|x|}.$$

If $\varphi(x)$ is atomic the claim follows from $M \subseteq N$ and the remarks underneath Definition 2.19. The case of Boolean connectives is straightforward, so only the existential quantifier requires a proof

$$\begin{aligned} M \models \exists x \varphi(a, x) &\Leftrightarrow M \models \varphi(a, b) && \text{for some } b \in M \\ &\Leftrightarrow N \models \varphi(a, b) && \text{for some } b \in M \\ &\Leftrightarrow N \models \exists x \varphi(a, x). \end{aligned}$$

The second equivalence holds by induction hypothesis, in the last equivalence we use 2 for the implication \Leftarrow . □

2.38 Exercise Prove that, in the language of strict orders, $\mathbb{R} \setminus \{0\} \preceq \mathbb{R}$ and $\mathbb{R} \setminus \{0\} \not\preceq \mathbb{R}$. □

7 Downward Löwenheim-Skolem

The main theorem of this section was proved by Löwenheim at the beginning of the last century. Skolem gave a simpler proof immediately afterwards. At the time, the result was perceived as paradoxical.

A few years earlier, the works of Zermelo and Fraenkel had convinced the mathematical community that the whole of set theory could be formalised in a first order language.

The downward Löwenheim-Skolem theorem implies the existence of an infinite countable model M of set theory: this is the so-called **Skolem paradox**.

The existence of M seems paradoxical because, in particular, a sentence that formalises the axiom of power set holds in M .

Therefore M contains an element b which, in M , is the set of subsets of the natural numbers.

But the set of elements of b is a subset of M , and therefore it is countable.

In fact, this is not a contradiction, because the expression *all subsets of the natural numbers* does not have the same meaning in M as it has in the real world.

The notion of cardinality, too, acquires a different meaning.

In the language of set theory, there is a first order sentence that formalises the fact that b is uncountable: the sentence says that there is no bijection between b and the natural numbers.

Therefore the bijection between the elements of b and the natural numbers (which exists in the real world) does not belong to M .

The notion of equinumerosity has a different meaning in M and in the real world,

but those who live in M cannot realise this.

2.39 Downward Löwenheim-Skolem Theorem *Let N be an infinite L -structure and let $A \subseteq N$. Then there is a structure M of cardinality $\leq |L(A)|$ such that $A \subseteq M \preceq N$.*

Proof Set $\lambda = |L(A)|$. Below we construct a chain $\langle A_i : i < \lambda \rangle$ of subsets of N . The chain begins at $A_0 = A$ and is continuous at limit ordinals. Finally we set $M = \bigcup_{i < \lambda} A_i$. All A_i will have cardinality $\leq \lambda$ so $|M| \leq \lambda$ follows.

Now we construct A_{i+1} given A_i . Assume as induction hypothesis that $|A_i| \leq \lambda$. Then $|L(A_i)| \leq \lambda$. For some fixed variable x let $\langle \varphi_k(x) : k < \lambda \rangle$ be an enumeration of the formulas in $L(A_i)$ that are consistent in N . For every k pick $a_k \in N$ such that $N \models \varphi_k(a_k)$. Define $A_{i+1} = A_i \cup \{a_k : k < \lambda\}$. Then $|A_{i+1}| \leq \lambda$ is clear.

Now use Tarski-Vaught test to prove $M \preceq N$. Suppose $\varphi(x) \in L(M)$ is consistent in N . As finitely many parameters occur in formulas, $\varphi(x) \in L(A_i)$ for some i . Then $\varphi(x)$ is among the formulas enumerated above and $A_{i+1} \subseteq M$ contains a solution of $\varphi(x)$. \square

We will need to adapt the construction above to meet more requirements on the model M . To better control the elements that enters M it is convenient to add one element at the time (above we add λ elements at each stage). We need to enumerate formulas with care if we want to complete the construction by stage λ .

2.40 Second proof of the downward Löwenheim-Skolem Theorem From set theory we know there is a bijection $\pi : \lambda \rightarrow \lambda^2$ such that $\pi_1(i)$ and $\pi_2(i)$, the two components of $\pi(i)$, are both $\leq i$. Suppose we have defined the set A_j for every $j \leq i$. Let $\langle \varphi_k(x) : k < \lambda \rangle$ be an enumeration of the formulas in $L(A_{\pi_1(i)})$. Let b be a solution of the $\varphi_k(x)$ for $k = \pi_2(i)$ and define $A_{i+1} = A_i \cup \{b\}$.

We use Tarski-Vaught test to prove $M \preceq N$. Let $\varphi(x) \in L(M)$ be consistent in N . As π is a bijection, there is an i such that $\varphi(x)$ is the $\pi_2(i)$ -th formula enumerated in $L(A_{\pi_1(i)})$. Hence a witness of $\varphi(x)$ is enumerated in M at stage $i + 1$. \square

2.41 Exercise Assume L is countable and let $M \preceq N$ have arbitrary (large) cardinality. Let $A \subseteq N$ be countable. Prove there is a countable model K such that $A \subseteq K \preceq N$ and $K \cap M \preceq N$ (in particular, $K \cap M$ is a model). Hint: adapt the construction used to prove the downward Löwenheim-Skolem Theorem. \square

8 Elementary chains

An **elementary chain** is a chain $\langle M_i : i < \lambda \rangle$ of structures such that $M_i \preceq M_j$ for every $i < j < \lambda$. The **union** (or **limit**) of the chain is the structure with as domain the set $\bigcup_{i < \lambda} M_i$ and as relations and functions the union of the relations and functions of M_i . It is plain that all structures in the chain are substructures of the limit.

2.42 Lemma *Let $\langle M_i : i \in \lambda \rangle$ be an elementary chain of structures. Let N be the union of the chain. Then $M_i \preceq N$ for every i .*

Proof By induction on the syntax of $\varphi(x) \in L$ we prove

$$M_i \models \varphi(a) \Leftrightarrow N \models \varphi(a) \quad \text{for every } i < \lambda \text{ and every } a \in M_i^{|x|}$$

As remarked in 3' of Section 3, the claim holds for quantifier-free formulas. Induction for Boolean connectives is straightforward so we only need to consider the existential quantifier

$$\begin{aligned} M_i \models \exists y \varphi(a, y) &\Rightarrow M_i \models \varphi(a, b) && \text{for some } b \in M_i. \\ &\Rightarrow N \models \varphi(a, b) && \text{for some } b \in M_i \subseteq N \end{aligned}$$

where the second implication follows from the induction hypothesis. Vice versa

$$N \models \exists y \varphi(a, y) \Rightarrow N \models \varphi(a, b) \quad \text{for some } b \in N$$

Without loss of generality we can assume that $b \in M_j$ for some $j \geq i$ and obtain

$$\Rightarrow M_j \models \varphi(a, b) \quad \text{for some } b \in M_j$$

Now apply the induction hypothesis to $\varphi(x, y)$ and M_j

$$\begin{aligned} &\Rightarrow M_j \models \exists y \varphi(a, y) \\ &\Rightarrow M_i \models \exists y \varphi(a, y) \end{aligned}$$

where the last implication holds because $M_i \preceq M_j$. □

2.43 Exercise Let $\langle M_i : i \in \lambda \rangle$ be an elementary chain of substructures of N . Let M be the union of the chain. Prove that $M \preceq N$. □

2.44 Exercise Give an alternative proof of Exercise 2.41 using the downward Löwenheim-Skolem Theorem (instead of its proof). Hint: construct two countable chains of countable models such that $K_i \cap M \subseteq M_i \preceq N$ and $A \cup M_i \subseteq K_{i+1} \preceq N$. The required model is $K = \bigcup_{i \in \omega} K_i$. In fact it is easy to check that $K \cap M = \bigcup_{i \in \omega} M_i$. □

Chapter 3

Ultraproducts

In these notes we only use ultraproducts to prove the compactness theorem. Since a syntactic proof of the compactness theorem is also given, this chapter is, strictly speaking, not required. However, the importance of ultraproducts transcends its application to model theory.

1 Filters and ultrafilters

The material in this section will appear again in a more general setting in Chapter 5.

Let I be any set. A **filter on I** (or a **filter of $\mathcal{P}(I)$**), is a non empty set $F \subseteq \mathcal{P}(I)$ such that for every $a, b \in \mathcal{P}(I)$:

$$f1 \quad a \in F \text{ and } a \subseteq b \Rightarrow b \in F$$

$$f2 \quad a \in F \text{ and } b \in F \Rightarrow a \cap b \in F$$

A filter F is **proper** if $F \neq \mathcal{P}(I)$, equivalently if $\emptyset \notin F$. Otherwise it is **improper**. By f1 above, F is proper if and only if $\emptyset \notin F$. A filter F is **principal** if $F = \{a \subseteq I : b \subseteq a\}$ for some set $b \subseteq I$. When this happens, we say that $\{b\}$ **generates** F . When I is finite every filter F is principal and generated by $\{\cap F\}$. Non-principal filters on I exist as soon as I is infinite. In fact, if I is infinite it is easy to check that the following is a filter:

$$F = \{a \subseteq I : a \text{ is cofinite in } I\}.$$

where **cofinite (in I)** means that $I \setminus a$ is finite. This is called the **Fréchet filter on I** . The Fréchet filter is the minimal non-principal filter.

A proper filter F is **maximal** if there is no proper filter H such that $F \subset H$. A proper filter F is an **ultrafilter** if for every $a \subseteq I$

$$a \notin F \Rightarrow \neg a \in F \quad \text{where } \neg a = I \setminus a.$$

Below we prove that the ultrafilters are exactly the maximal filters.

3.1 Exercise Let I be infinite. Prove that every non-principal ultrafilter on I contains Fréchet's filter. Show that this does not hold for plain filters. \square

Let $B \subseteq \mathcal{P}(I)$. Then the **filter generated by B** is the intersection of all the filters that contain B . It is easy to check that the intersection of a family of filters is a filter, so the notion is well defined. The following easy proposition gives a workable characterization of the filter generated by a set.

3.2 Proposition The filter generated by B is $\{a \subseteq I : \cap C \subseteq a \text{ for some finite } C \subseteq B\}$. \square

We say that B has the **finite intersection property** if $\cap C \neq \emptyset$ for every finite $C \subseteq B$. The following proposition is immediate.

3.3 Proposition *The following are equivalent:*

1. *the filter generated by B is non principal;*
2. *B has the finite intersection property.*

□

A proper filter F is **prime** if for every $a, b \subseteq I$.

$$a \cup b \in F \Rightarrow a \in F \text{ or } b \in F$$

Prime filters coincide with maximal filters. However, in Chapter 5, we introduce a more general context where primality is distinct from maximality.

3.4 Proposition *For every filter F on I , the following are equivalent:*

1. *F is a maximal filter;*
2. *F is a prime filter;*
3. *F is an ultrafilter.*

Proof $1 \Rightarrow 2$. Suppose $a, b \notin F$, where F is maximal. We claim that $a \cup b \notin F$. By maximality, there is a $c \in F$ such that $a \cap c = b \cap c = \emptyset$. Therefore $(a \cup b) \cap c = \emptyset$. Hence $a \cup b \notin F$.

$2 \Rightarrow 3$. It suffices to note that $I = a \cup \neg a \in F$.

$3 \Rightarrow 1$. If $a \notin F$, where F is an ultrafilter, then $\neg a \in F$ and no proper filter contains $F \cup \{a\}$. □

3.5 Proposition *Let $B \subseteq \mathcal{P}(I)$ have the finite intersection property. Then B is contained in a maximal filter.*

Proof First we prove that the union of a chain of subsets of $\mathcal{P}(I)$ with the finite intersection property has the finite intersection property. Let \mathcal{B} be such a chain and suppose for a contradiction that $\bigcup \mathcal{B}$ does not have the finite intersection property. Fix a finite $C \subseteq \bigcap \mathcal{B}$ such that $\bigcap C = \emptyset$. As C is finite, we have $C \subseteq B$ for some $B \in \mathcal{B}$. Hence B does not have the finite intersection property, which is a contradiction.

Now apply Zorn's lemma to obtain a $B \subseteq \mathcal{P}(I)$ which is maximal among the sets with the finite intersection property. It is immediate that B is a filter. □

3.6 Exercise Prove that all principal ultrafilters are generated by a singleton. □

2 Direct products

In this and in the next section $\langle M_i : i \in I \rangle$ is a sequence of L -structures. (We are abusing of the word sequence, since I is only a set.) The **direct product** of this sequence is a structure denoted by

$$\prod_{i \in I} M_i \quad (\text{below this product is denoted by } N).$$

and defined by conditions 1-3 below. If $M_i = M$ for all $i \in I$, we say that N is a **direct power** of M and denote it by M^I .

The domain of N is the set containing all functions

$$\begin{aligned}
1. \quad \hat{a} &: I \rightarrow \bigcup_{i \in I} M_i \\
\hat{a} &: i \mapsto \hat{a}i \in M_i
\end{aligned}$$

We do not distinguish between tuples of elements of N and tuple-valued functions. For instance, the tuple $\hat{a} = \langle \hat{a}_1 \dots \hat{a}_n \rangle$ is identified with the function $\hat{a} : i \mapsto \hat{a}i = \langle \hat{a}_1 i, \dots, \hat{a}_n i \rangle$. On a first reading of what follows, it may help to pretend that all functions and relations are unary.

The interpretation of $f \in L_{\text{fun}}$ is defined as follows:

$$2. \quad (f^N \hat{a})i = f^{M_i}(\hat{a}i) \quad \text{for all } i \in I.$$

The interpretation of $r \in L_{\text{rel}}$ is the product of the relations r^{M_i} , that is, we define

$$3. \quad \hat{a} \in r^N \Leftrightarrow \hat{a}i \in r^{M_i} \quad \text{for all } i \in I.$$

The following proposition is immediate.

3.7 Proposition *If \wedge is the only connective and \forall, \exists the only quantifiers that occur in $\varphi(x) \in L$, then for every $\hat{a} \in N^{|x|}$*

$$\# \quad N \models \varphi(\hat{a}) \Leftrightarrow M_i \models \varphi(\hat{a}i) \quad \text{for all } i \in I.$$

Proof By induction on syntax. First note that we can extend 2 to all terms $t(x)$ as follows:

$$2'. \quad (t^N \hat{a})i = t^{M_i}(\hat{a}i) \quad \text{for all } i \in I.$$

Combining 3 and 2' gives that for every $r \in L_{\text{rel}} \cup \{=\}$ and every L -term $t(x)$

$$3'. \quad N \models rt\hat{a} \Leftrightarrow M_i \models rt\hat{a}i \quad \text{for all } i \in I.$$

This shows that $\#$ holds for $\varphi(x)$ atomic. Induction for the connectives \wedge, \forall and \exists is immediate. \square

A consequence of Proposition 3.7 is that a direct product of groups, rings or vector spaces is a structure of the same sort. However, a product of fields is not a field.

3 Łoś's Theorem

Assume the notation of the previous sections. In particular, $\langle M_i : i \in I \rangle$ is a sequence of structures and N is the direct product of this sequence.

Let F be a filter on I . We define the following congruence on N (see Definition 2.29):

$$\hat{a} \sim_F \hat{c} \Leftrightarrow \{ i \in I : \hat{a}i = \hat{c}i \} \in F.$$

To check that \sim_F is indeed a congruence, first we need to check that it is an equivalence relation. Reflexivity and symmetry are immediate, and transitivity follows from f2 in Section 1. Then we check that \sim_F is compatible with the functions of L , that is, that c1 of Definition 2.29 is satisfied. This follows from f1 in Section 1.

For brevity, we write N/F for N/\sim_F and $[\hat{a}]_F$ for $[\hat{a}]_{\sim_F}$. Then c3 of Section 2.4 gives

$$c3'. \quad [\hat{a}]_F \in r^{N/F} \Leftrightarrow \{ i : \hat{a}i = \hat{b}i \in r^{M_i} \} \in F \quad \text{for some } \hat{b} \in N.$$

The structure N/F is called the **reduced product** of the structures $\langle M_i : i \in I \rangle$ or, when $M_i = M$ for all $i \in I$, the **reduced power** of M . When F is an ultrafilter we say **ultraproduct**, respectively **ultrapower**.

3.8 Łoś's Theorem Let $\varphi(x) \in L$ and let F be an ultrafilter on I . Then for every $\hat{a} \in N^{|x|}$ the following are equivalent:

1. $N/F \models^* \varphi(\hat{a})$ (see Definition 2.31);
2. $\{i : M_i \models \varphi(\hat{a}i)\} \in F$.

Proof We proceed by induction on the syntax of $\varphi(x)$. Suppose $\varphi(x)$ is of the form $rt(x)$ for some tuple of terms $t(x)$ and $r \in L_{\text{rel}} \cup \{=\}$. Then $1 \Leftrightarrow 2$ is clear.

We prove the inductive step for the connectives \neg , \wedge , and the quantifier \exists . We begin with \neg . This is the only place in the proof where the assumption that F is an ultrafilter is required. By the inductive hypothesis,

$$N/F \models^* \neg\varphi(\hat{a}) \Leftrightarrow \{i : M_i \models \varphi(\hat{a}i)\} \notin F$$

So, as F is an ultrafilter

$$\Leftrightarrow \{i : M_i \models \neg\varphi(\hat{a}i)\} \in F.$$

Now consider \wedge . Assume inductively that the equivalence $1 \Leftrightarrow 2$ holds for $\varphi(x)$ and $\psi(x)$. Then

$$N/F \models^* \varphi(\hat{a}) \wedge \psi(\hat{a}) \Leftrightarrow \{i : M_i \models \varphi(\hat{a}i)\} \in F \text{ and } \{i : M_i \models \psi(\hat{a}i)\} \in F.$$

As filters are closed under intersection, we obtain

$$\Leftrightarrow \{i : M_i \models \varphi(\hat{a}i) \wedge \psi(\hat{a}i)\} \in F.$$

Finally, consider $\exists y$. Assume inductively that the equivalence $1 \Leftrightarrow 2$ holds for $\varphi(x, y)$. Then

$$\begin{aligned} N/F \models^* \exists y \varphi(\hat{a}, y) &\Leftrightarrow N/F \models^* \varphi(\hat{a}, \hat{b}) && \text{for some } \hat{b} \in N \\ &\Leftrightarrow \{i : M_i \models \varphi(\hat{a}i, \hat{b}i)\} \in F && \text{for some } \hat{b} \in N. \end{aligned}$$

We claim this is equivalent to

$$\Leftrightarrow \{i : M_i \models \exists y \varphi(\hat{a}i, y)\} \in F.$$

The \Rightarrow direction is trivial. For \Leftarrow , we choose as \hat{b} a sequence that picks a witness of $M_i \models \exists y \varphi(\hat{a}i, y)$ if it exists, and some arbitrary element of M_i otherwise. \square

Let a^I denote the element of M^I that has constant value a . The following is an immediate consequence of Łoś's theorem.

3.9 Corollary For every $a \in M$

$$M^I/F \models^* \varphi(a^I) \Leftrightarrow M \models \varphi(a). \quad \square$$

We often identify M with its image under the embedding $h : a \mapsto [a^I]_F$, and say that M^I/F is an elementary extension of M .

The following corollary is an immediate consequence of the compactness theorem that we prove in the next chapter. The construction in the proof uses ultrapowers.

3.10 Corollary Every infinite structure has a proper elementary extension.

Proof Let M be an infinite structure and let F be a non-principal ultrafilter on ω . It suffices to show that $h[M]$, the image of the embedding defined above, is a proper substructure of M^ω/F . As M is infinite, there is an injective function $\hat{d} \in M^\omega$. Then for every $a \in M$ the set $\{i : \hat{d}i = a\}$ is either empty or a singleton and, as F is non

principal, it does not belong to F . So, by Łoś Theorem, we have $M^\omega / F \models \hat{d} \neq a^I$ for every $a \in M$, that is, $[\hat{d}]_F \notin h[M]$. \square

3.11 Exercise Consider \mathbb{N} as a structure in the language of strict orders. Let F be a non-principal ultrafilter on ω . Prove that in \mathbb{N}^ω / F there is a sequence $\langle \hat{a}_i : i \in \omega \rangle$ such that $\hat{a}_{i+1} < \hat{a}_i$. \square

3.12 Exercise Let I be the set of integers $i > 1$. For $i \in I$, let \mathbb{Z}_i denote the additive group of integers modulo i , and let N denote the product $\prod_{i \in I} \mathbb{Z}_i$. Prove that, if F is a non-principal ultrafilter on I ,

1. for some F , N/F does not contain any element of finite order;
2. for some F , N/F has some elements of order 2;
3. for all F , N/F contains an element of infinite order;
4. for some F , $N/F \models \forall x \exists y \, my = x$ for every integer $m > 0$;
5. for some F , N/F contains an element \hat{a} such that $N/F \models \forall x \, mx \neq \hat{a}$ for every positive integer m . \square

Chapter 4

Compactness

We present two proofs of the compactness theorem. The first is syntactic, the second uses ultrapowers.

Somewhat surprisingly, the compactness theorem is not strictly required for the next few chapters (only from Chapter 9). So the reading of this chapter may be postponed.

1 Compactness via syntax

Here we prove the compactness theorem using the so-called Henkin method. We divide the proof in two steps. Firstly, we observe that when the language is rich enough to name witnesses for all existential statements of the theory, these witnesses (*Henkin constants*) form a canonical model. Secondly, we show that we can add the required Henkin constants to any finitely consistent theory.

4.1 Definition Fix a language L . Assume for simplicity that formulas use only the connectives \wedge, \neg and \exists . We say that T is a **Henkin theory** if for every formulas φ and ψ

0. $\varphi \in T \Rightarrow \neg\varphi \notin T$
1. $\neg\neg\varphi \in T \Rightarrow \varphi \in T$
2. $\varphi \wedge \psi \in T \Rightarrow \varphi \in T \text{ and } \psi \in T$
3. $\neg(\varphi \wedge \psi) \in T \Rightarrow \neg\varphi \in T \text{ or } \neg\psi \in T$
4. $\exists x \varphi \in T \Rightarrow \varphi[x/a] \in T \text{ for some closed term } a$
5. $\neg\exists x \varphi \in T \Rightarrow \neg\varphi[x/a] \in T \text{ for all closed terms } a.$

Moreover, the following holds for all closed terms t and all closed terms a, b, c

- a. $a \doteq a \in T$
- b. $a \doteq b \in T \Rightarrow b \doteq a \in T$
- c. $a \doteq b, b \doteq c \in T \Rightarrow a \doteq c \in T$
- d. $a \doteq b, \varphi[x/a] \in T \Rightarrow \varphi[x/b] \in T.$

□

Fix a theory T and let M be the structure that has as domain the set of closed terms. Define for every relation symbol

$$r^M = \{ \langle a_1, \dots, a_n \rangle : r(a_1, \dots, a_n) \in T \}.$$

Define for every function symbol f

$$f^M = \{ \langle a_1, \dots, a_n, t \rangle : a_1, \dots, a_n \in M, t = f a_1 \dots a_n \}.$$

An easy proof by induction shows that $t^M = t$ for all closed terms t .

Finally, let E be the relation on M that holds when $a \doteq b \in T$.

4.2 Lemma *The relation E is a congruence on M (as defined in Section 2.4).*

Proof Axioms a-c ensure that E is an equivalence. Axiom e that it is a congruence. \square

4.3 Theorem *If T is Henkin theory then $M/E \models T$.*

Proof By induction on the complexity of the formula φ in T we prove that

1. $\varphi \in T \Rightarrow M/E \models^* \varphi$ for the notation cf. Definition 2.31
2. $\neg\varphi \in T \Rightarrow M/E \models^* \neg\varphi$

Induction is immediate by 1-5 of Definition 4.1. We verify the claim for atomic formulas. Consider first the formula $\varphi = (t \doteq s)$ where t and s are closed terms. Recall that $t^M = t$ and $s^M = s$, so claim 1 is clear. As for 2, suppose $M/E \models^* t \doteq s$, that is tEs . Then $t \doteq s \in T$ and $\neg t \doteq s \notin T$ follows from axiom 0.

Now assume $\varphi = rt$ for a relation r and a tuple of closed terms t . The argument is similar: 1 is immediate; to prove 2 suppose that $M/E \models^* rt$. Then $tEs \in r^M$ for some tuple of closed terms s . Then $rs \in T$, and by d $rt \in T$. Finally from 0 we obtain $\neg rt \notin T$. \square

4.4 Proposition *If every finite subset of T has a model then there is a Henkin theory T' containing T . (The theory T' may be in an expanded language.)*

Proof Set $\lambda = |L|$. Let $\langle c_i : i < \lambda \rangle$ be some constants not in L . Write L_i be the language L expanded with the constants $c_{\upharpoonright i}$ and fix an enumeration of all sentences in L_λ .

If α is 0 or a limit ordinal define

$$T'_\alpha = T_\alpha = T \cup \bigcup_{i < \alpha} T'_i$$

As for successor ordinals, let T_{i+1} be a maximal finitely consistent set of L_i -formulas containing T'_i . It is immediate that T'_i satisfy Definition 4.1 but possibly for 3.

Let $\exists x \varphi$ be the least sentence in L_λ contradicting 3 and set $T_{i+1} = T_i \cup \{\varphi[x/c_i]\}$. It is immediate that T_{i+1} is finitely consistent.

At stage λ all possible counterexamples to 3 have been ruled out, then $T' = T_\lambda$ is the required Henkin theory. \square

A theory is **finitely consistent** if all its finite subsets are consistent. The following theorem is an immediate corollary of the proposition above.

4.5 Compactness Theorem *If every finite subset of T is consistent then T is consistent.* \square

2 Compactness via ultraproducts

We repeat, a theory is **finitely consistent** if all its finite subsets are consistent. The following theorem is the *fiat lux* of model theory.

4.6 Compactness Theorem *Every finitely consistent theory is consistent.*

Proof Let T be a finitely consistent theory. We claim that the structure N/F which we define below is a model of T . Let I be the set of consistent sentences I in the

language L . For every $\zeta \in I$ pick some $M_\zeta \models \zeta$. For any sentence $\varphi \in L$ we write X_φ for the following subset of I

$$X_\varphi = \{ \zeta \in I : \zeta \vdash \varphi \}$$

Clearly φ is consistent if and only if $X_\varphi \neq \emptyset$. Moreover $X_{\varphi \wedge \psi} = X_\varphi \cap X_\psi$. hence, as T is finitely consistent, the set $B = \{X_\varphi : \varphi \in T\}$ has the finite intersection property. Therefore B extends to an ultrafilter F on I . Define

$$N = \prod_{\zeta \in I} M_\zeta.$$

We claim that $N/F \models T$. By Łoś Theorem, for every sentence $\varphi \in L$

$$N/F \models \varphi \Leftrightarrow \{ \zeta : M_\zeta \models \varphi \} \in F.$$

By the definition of F , for every $\varphi \in T$, the set $X_\varphi \subseteq \{ \zeta : M_\zeta \models \varphi \}$ belongs to F . Therefore $N/F \models T$, *et lux fuit*. \square

The compactness theorem can be formulated in the following apparently stronger way.

4.7 Corollary *If $T \vdash \varphi$ then there is some finite $S \subseteq T$ such that $S \vdash \varphi$.*

Proof Suppose $S \not\vdash \varphi$ for every finite $S \subseteq T$. Then for every finite $S \subseteq T$ there is a model $M \models S \cup \{\neg\varphi\}$. In other words, $T \cup \{\neg\varphi\}$ is finitely consistent. By compactness $T \cup \{\neg\varphi\}$ hence $T \not\vdash \varphi$. \square

4.8 Exercise Let $\Phi \subseteq L$ be a set of sentences and suppose that $\vdash \psi \leftrightarrow \bigvee \Phi$ for some sentence ψ . Prove that there is a finite $\Phi_0 \subseteq \Phi$ such that $\vdash \psi \leftrightarrow \bigvee \Phi_0$. \square

3 Upward Löwenheim-Skolem

Recall that a **type** is a set of formulas. When we present types we usually declare the variables that may occur in it – we write $p(x)$, $q(x)$, etc. where x is a tuple of variables. Clearly, when x is the empty tuple, $p(x)$ is just a theory. We identify a finite types with the conjunction of the formulas contained in it.

We write $M \models p(a)$ if $M \models \varphi(a)$ for every $\varphi(x) \in p$. We say that a is a **solution** or a **realization** of $p(x)$. An equivalent notation is $M, a \models p(x)$ or, when M is clear from the context, $a \models p(x)$. We say that $p(x)$ is **consistent in M** if it has a solution in M . In this case we may write $M \models \exists x p(x)$. We say that $p(x)$ is **consistent** if it is consistent in some model.

We say that a type $p(x)$ is **finitely consistent** if all its finite subsets are consistent. If they are all consistent in the same model M , we say that $p(x)$ is **finitely consistent in M** . The following theorem shows that the latter notion, which is trivial for theories, is very interesting for types.

4.9 Compactness Theorem for types *Every finitely consistent type $p(x) \subseteq L$ is consistent. Moreover, if $p(x) \subseteq L(M)$ is finitely consistent in M then it is realised in some elementary extension of M .*

Proof Let L' be the expansion of L obtained by adding the fresh symbols c , a tuple of constants of the same length as x . Then $p(c)$ is a finitely consistent theory in the

language L' . By the compactness theorem there is an L' -structure $N' \models p(c)$. Let N be the reduced of N' to L . That is the L -structure with the same domain and the same interpretation of N' on the symbols of L . Note that, though the constants c are not in L , the elements $c^{N'}$ remain in N . Then $N, c^{N'} \models p(x)$.

As for the second claim, let a be an enumeration of M . We can assume that $p(x)$ has the form $p'(x; a)$ for some $p'(x; z) \in L$. Define

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

Clearly, $p'(x; z) \cup q(z)$ is finitely consistent in M . By the first part of the proof there is a model N such that $N \models p'(c'; a')$ for some $c', a' \in N^{|x, z|}$. Let $h = \{\langle a, a' \rangle\}$. We claim that $h : M \rightarrow N$ is an embedding and that $h[M] \preceq N$. So the theorem follows by identifying M with $h[M]$.

For any $\varphi(z) \in L$ we have

$$h[M] \models \varphi(ha) \Leftrightarrow M \models \varphi(a) \Leftrightarrow \varphi(z) \in q(z) \Rightarrow N \models \varphi(a').$$

Then $h[M] \preceq N$ follows because all sentences in $L(M)$ have the form $\varphi(a)$ for some $\varphi(z) \in L$. (Using a term that will be introduced only in Section 5.4, we have proved that $h : M \rightarrow N$ is an elementary embedding.) \square

The following corollary is historically important.

4.10 Upward Löwenheim-Skolem Theorem *Every infinite structure has arbitrarily large elementary extensions.*

Proof Let $x = \langle x_i : i < \lambda \rangle$ be a tuple distinct variables, where λ is an arbitrary cardinal. The type $p(x) = \{x_i \neq x_j : i < j < \lambda\}$ is finitely consistent in every infinite structure and every structure that realises p has cardinality $\geq \lambda$. Hence the claim follows from Theorem 4.9. \square

4 Finite axiomatizability

A theory T is **finitely axiomatizable** if $\text{ccl}(S) = \text{ccl}(T)$ for some finite S . The following theorem shows that we can restrict the search of S to the subsets of T .

4.11 Proposition *For every theory T the following are equivalent*

1. T is finitely axiomatizable;
2. there a finite $S \subseteq T$ such that $S \vdash T$.

Proof Only $1 \Rightarrow 2$ requires a proof. If T is finitely axiomatizable, there is a sentence φ such that $\text{ccl}(\varphi) = \text{ccl}(T)$. Then $T \vdash \varphi \vdash T$. By Proposition 4.7 there is a finite $S \subseteq T$ such that $S \vdash \varphi$. Then also $S \vdash T$. \square

If L is empty, then every structure is a model. The **theory of infinite sets** is the set of sentences that hold in every infinite structure.

4.12 Example The theory of infinite sets is not finitely axiomatizable. Define

$$T_\infty = \{\exists^{\geq n} x (x = x) : n \in \omega\}$$

Every infinite set is a model of T_∞ and, vice versa, every model of T_∞ is an infinite set. Then $\text{ccl}(T_\infty)$ is the theory of infinite sets. Suppose for a contradiction that T_∞

is finitely axiomatizable. By Proposition 4.11, $\exists^{\geq n} x(x = x) \vdash T_\infty$ for some n . Any set of cardinality $n + 1$ proves that this is not the case. \square

The following is a less trivial example. It proves a claim we made in Exercise 1.16.

4.13 Example Write T_{gph} for the theory of graphs, see Example 2.5. Let \mathcal{K} be the following class of structures

$$\mathcal{K} = \left\{ M \models T_{\text{gph}} : r^M \subseteq (A \times \neg A) \cup (\neg A \times A) \text{ for some } A \subseteq M \right\}$$

We prove that \mathcal{K} is axiomatizable but not finitely axiomatizable, i.e. $\mathcal{K} = \text{Mod}(T)$ for some theory T , but T cannot be chosen finite.

A *path of length n* in M is a sequence $c_0, \dots, c_n \in M$ such that $M \models r(c_i, c_{i+1})$ for every $0 \leq i < n$. A path is *closed* if $c_0 = c_n$. We claim that the following theory axiomatizes \mathcal{K} .

$$T = \left\{ \neg \exists x_0, \dots, x_{2n+1} \left[\bigwedge_{i=0}^{2n} r(x_i, x_{i+1}) \wedge x_0 = x_{2n+1} \right] : n \in \omega \right\}$$

In words, T says that all closed paths have even length. Inclusion $\mathcal{K} \subseteq \text{Mod}(T)$ is clear, we prove $\text{Mod}(T) \subseteq \mathcal{K}$. Let $M \models T$ and let $A_o \subseteq M$ contain exactly one point for every connected component of M . Define

$$A = \left\{ b : M \models \exists x_0, \dots, x_{2n} \left[\bigwedge_{i=1}^{2n-1} r(x_i, x_{i+1}) \wedge a = x_0 \wedge x_{2n} = b \right], a \in A_o, n \in \omega \right\}$$

We claim that $r^M \subseteq (A \times \neg A) \cup (\neg A \times A)$, hence $M \in \mathcal{K}$. We need to verify that if $r(b, c)$ then neither $b, c \in A$ nor $b, c \in \neg A$. Suppose for a contradiction that $r(b, c)$ and $b, c \in A$ (the case $b, c \in \neg A$ is similar). As b and c belong to the same connected component, there are two paths b_0, \dots, b_{2n} and c_0, \dots, c_{2m} that connect $a = b_0 = c_0 \in A_o$ to $b = b_{2n}$ and $c = c_{2m}$. Then $a, b_1, \dots, b_{2n}, c_{2m}, \dots, c_1, a$ is a closed path of odd length. A contradiction.

We now prove that \mathcal{K} is not finitely axiomatizable. By Proposition 4.11 it suffices to note that no finite $S \subseteq T$ axiomatizes \mathcal{K} . \square

Chapter 5

Types and morphisms

In Section 1 and 2 we introduce distributive lattices and prime filters and prove Stone's representation theorem for distributive lattices. In Section 3 we discuss lattices that arise from sets of formulas and their prime filters (prime types). These sections are mainly required for the discussion of Hilbert's Nullstellensatz in Section 8.7 below.

There is a lot of notation in this chapter. The reader may skim through and return to it when we refer to it.

1 Semilattices and filters

A **preorder** is a set \mathbb{P} with a transitive and symmetric relation which we usually denote by \leq . If $A, B \subseteq \mathbb{P}$ we write $A \leq B$ if $a \leq b$ for every $a \in A$ and $b \in B$. We write $a \leq B$ and $A \leq b$ for $\{a\} \leq B$ and $A \leq \{b\}$ respectively.

Quotienting a preorder by the equivalence relation

$$a \sim b \Leftrightarrow a \leq b \text{ and } b \leq a$$

gives a **(partial) order**. We often do not distinguish between a preorder and the partial order associated to it. Preorders are very common; here we are interested in the one induced by the relation of logical consequence

$$\varphi \leq \psi \Leftrightarrow \varphi \vdash \psi,$$

or, more generally, by the relation of **logical consequence over a theory T** , that is

$$\varphi \leq \psi \Leftrightarrow T \cup \{\varphi\} \vdash \psi.$$

A partial order \mathbb{P} is a **lower semilattice** if for each pair $a, b \in \mathbb{P}$ there is a maximal element c such that $c \leq \{a, b\}$. We call c the **meet** of a and b . The meet is unique and is denoted by $a \wedge b$. Dually, a partial order is an **upper semilattice** if for each pair of elements a and b there is a minimal element c such that $\{a, b\} \leq c$. This c is called the **join** of a and b . The join is unique and is denoted by $a \vee b$. A **lattice** is simultaneously a lower and an upper semilattice.

An element c such that $c \leq \mathbb{P}$ is called a **lower bound** or a **bottom**. An element such that $\mathbb{P} \leq c$ is called an **upper bound** or a **top**. Lower and upper bounds are unique and will be denoted by 0 , respectively 1 . Other symbols common in the literature are \perp , respectively \top . A semilattice is **bounded** if it has both an upper and a lower bound.

For the rest of this section we assume that \mathbb{P} is a bounded lower semilattice.

The meet is associative and commutative

$$\begin{aligned} (a \wedge b) \wedge c &= a \wedge (b \wedge c) \\ a \wedge b &= b \wedge a. \end{aligned}$$

Hence we may unambiguously write $a_1 \wedge \cdots \wedge a_n$. When $C \subseteq \mathbb{P}$ is finite, we write $\wedge C$ for the meet of all the elements of C . We agree that $\wedge \emptyset = 1$.

In an upper semilattice, the dual properties hold for the join. We write $\vee C$ for the join of all elements in C and we agree that $\vee \emptyset = 0$.

A **filter** of \mathbb{P} is a non-empty set $F \subseteq \mathbb{P}$ that satisfies the following for all $a, b \in \mathbb{P}$

- f1. $a \in F$ and $a \leq b \Rightarrow b \in F$
- f2. $a, b \in F \Rightarrow a \wedge b \in F$.

We say that F is a **proper filter** if $F \neq \mathbb{P}$, equivalently if $0 \notin F$. We say that F is **principal** if $F = \{b : a \leq b\}$ for some $a \in \mathbb{P}$. More precisely, we say that F is the **principal filter generated by a** . A proper filter F is **maximal** if there is no filter H such that $F \subset H \subset \mathbb{P}$.

We say that a filter F is **maximal relative to c** if $c \notin F$ and $c \in H$ for every $H \supset F$. So, a filter F is maximal if it is maximal relative to 0. We say that F is **relatively maximal** when it is maximal relative to some c .

For $B \subseteq \mathbb{P}$ we define the **filter generated by B** to be the intersection of all the filters containing B . It is easy to verify that this is indeed a filter. When B is a finite set, the filter generated by B is the principal filter generated by $\wedge B$. In general we have the following.

5.1 Proposition *For every $B \subseteq \mathbb{P}$, the filter generated by B is the set*

$$\{a : \wedge C \leq a \text{ for some finite non-empty } C \subseteq B\}.$$

□

This has the following important consequence.

5.2 Proposition *Let $B \subseteq \mathbb{P}$ and let $c \in \mathbb{P}$. If $\wedge C \not\leq c$ for every finite non-empty $C \subseteq B$, then B is contained in a maximal filter relative to c .*

Proof Let \mathcal{F} be the set of filters F such that $B \subseteq F$ and $c \notin F$. By Proposition 5.1, \mathcal{F} is non-empty. It is immediate that \mathcal{F} is closed under unions of arbitrary chains. Then, by Zorn's lemma, \mathcal{F} has a maximal element. □

5.3 Exercise Prove that the following are equivalent

- 1. F is maximal relative to c ;
- 2. for every $a \notin F$ there is $d \in F$ such that $d \wedge a \leq c$.

□

5.4 Exercise (A generalization of the exercise above.) Let $B \subseteq \mathbb{P}$ and let $c \in \mathbb{P}$ be such that $\wedge C \not\leq c$ for every finite non-empty $C \subseteq B$. Prove that the following are equivalent

- 1. B is a maximal filter relative to c ;
- 2. $a \notin B \Rightarrow b \wedge a \leq c$ for some $b \in B$.

□

5.5 Exercise Let $F \subseteq \mathbb{P}$ be a non-principal filter. Is F always contained in a maximal non-principal filter? □

2 Distributive lattices and prime filters

Let \mathbb{P} be a lattice. We say that \mathbb{P} is **distributive** if for every $a, b, c \in \mathbb{P}$

$$a \wedge (b \vee c) = (a \wedge b) \vee (a \wedge c)$$

$$a \vee (b \wedge c) = (a \vee b) \wedge (a \vee c)$$

Throughout this section we assume that \mathbb{P} is a bounded distributive lattice.

A proper filter F is **prime** if for every $a, b \in \mathbb{P}$

$$a \vee b \in F \Rightarrow a \in F \text{ or } b \in F.$$

5.6 Proposition *Every relatively maximal filter of \mathbb{P} is prime.*

Proof Let F be maximal relative to c and assume that $a \notin F$ and $b \notin F$. Then, by Exercise 5.3, there are $d_1, d_2 \in F$ such that $d_1 \wedge a \leq c$ and $d_2 \wedge b \leq c$. Let $d = d_1 \wedge d_2$. Then $d \wedge a \leq c$ and $d \wedge b \leq c$ and therefore $(d \wedge a) \vee (d \wedge b) \leq c$. Hence, by distributivity, $d \wedge (a \vee b) \leq c$. Then $a \vee b \notin F$. \square

The **Stone space** of \mathbb{P} is a topological space that we denote by $S(\mathbb{P})$. The points of $S(\mathbb{P})$ are the prime filters of \mathbb{P} . The closed sets of the **Stone topology** are arbitrary intersections of sets of the form

$$[a]_{\mathbb{P}} = \{ F : \text{prime filter such that } a \in F \}.$$

for $a \in \mathbb{P}$. In other words, the sets above form a base of closed sets of the Stone topology. Using 1 and 3 in the following proposition the reader can easily check that this is indeed a base for a topology.

5.7 Proposition *For every $a, b \in \mathbb{P}$ we have*

1. $[0]_{\mathbb{P}} = \emptyset$;
2. $[1]_{\mathbb{P}} = S(\mathbb{P})$;
3. $[a]_{\mathbb{P}} \cup [b]_{\mathbb{P}} = [a \vee b]_{\mathbb{P}}$;
4. $[a]_{\mathbb{P}} \cap [b]_{\mathbb{P}} = [a \wedge b]_{\mathbb{P}}$.

Proof The verification is immediate. Only 3 requires that the filters in $S(\mathbb{P})$ are prime. \square

The closed subsets of $S(\mathbb{P})$ ordered by inclusion form a distributive lattice. The following is a representation theorem for distributive lattices.

5.8 Theorem *The map $a \mapsto [a]_{\mathbb{P}}$ is an embedding of \mathbb{P} in the lattice of the closed subsets of $S(\mathbb{P})$. In particular*

1. $0 \mapsto \emptyset$;
2. $1 \mapsto S(\mathbb{P})$;
3. $a \vee b \mapsto [a]_{\mathbb{P}} \cup [b]_{\mathbb{P}}$;
4. $a \wedge b \mapsto [a]_{\mathbb{P}} \cap [b]_{\mathbb{P}}$.

Proof It is immediate that the map above preserves the order and Proposition 5.7 shows that it preserves the lattice operations. We prove that the map is injective. Let $a \neq b$, say $a \not\leq b$. We claim that $[a]_{\mathbb{P}} \not\subseteq [b]_{\mathbb{P}}$. There is a filter F that contains a and is

maximal relative to b . By Proposition 5.6 such an F is prime. Then $F \in [a]_{\mathbb{P}} \setminus [b]_{\mathbb{P}}$. \square

5.9 Theorem *With the Stone topology, $S(\mathbb{P})$ is a compact space.*

Proof Let $\langle [a_i]_{\mathbb{P}} : i \in I \rangle$ be basic closed sets such that for every finite $J \subseteq I$

$$\bigcap_{i \in J} [a_i]_{\mathbb{P}} \neq \emptyset.$$

We claim that

$$\bigcap_{i \in I} [a_i]_{\mathbb{P}} \neq \emptyset.$$

By 4 of Proposition 5.7 and a we obtain that $\wedge C \not\leq 0$ for every finite $C \subseteq \{a_i : i \in I\}$. By Proposition 5.2, there is a maximal (relative to 0) filter containing $\{a_i : i \in I\}$. By Proposition 5.6, such filter is prime and it belongs to the intersection in b. \square

Let $a, b \in \mathbb{P}$. If $a \wedge b = 0$ and $a \vee b = 1$, we say that b is the **complement** of a (and vice versa). The complement of an element need not exist. If the complement exists it is unique, the complement of a is denoted by $\neg a$.

5.10 Lemma *Let $U \subseteq S(\mathbb{P})$ be a clopen set. Then $U = [a]_{\mathbb{P}}$ for some $a \in \mathbb{P}$, and $\neg a$ exists.*

Proof As both U and $S(\mathbb{P}) \setminus U$ are closed, for some sets $A, B \subseteq \mathbb{P}$

$$\begin{aligned} \bigcap_{x \in A} [x]_{\mathbb{P}} &= U \\ \bigcap_{y \in B} [y]_{\mathbb{P}} &= S(\mathbb{P}) \setminus U. \end{aligned}$$

By compactness, that is Theorem 5.9, there are some finite $A_0 \subseteq A$ and $B_0 \subseteq B$ such that

$$\bigcap_{x \in A_0} [x]_{\mathbb{P}} \cap \bigcap_{y \in B_0} [y]_{\mathbb{P}} = \emptyset$$

Let $a = \wedge A_0$ and $b = \wedge B_0$. From claim 4 of Proposition 5.7 we obtain $[a]_{\mathbb{P}} \cap [b]_{\mathbb{P}} = \emptyset$. Therefore $U \subseteq [a]_{\mathbb{P}} \subseteq S(\mathbb{P}) \setminus [b]_{\mathbb{P}} \subseteq U$. Hence $U = [a]_{\mathbb{P}}$ and $b = \neg a$. \square

A **Boolean algebra** is a bounded distributive lattice where every element has a complement. In a Boolean algebra, the sets $[a]_{\mathbb{P}}$ are clopen and they form also a base of open set of the topology of $S(\mathbb{P})$. A topology that has a base of clopen sets is called **zero-dimensional**. By the following proposition the Stone topology of a Boolean algebra is Hausdorff.

A proper filter of a Boolean algebra is an **ultrafilter** if either $a \in F$ or $\neg a \in F$ for every a .

5.11 Proposition *Let \mathbb{P} be a Boolean algebra. Then the following are equivalent*

1. F is maximal;
2. F is prime;
3. F is an ultrafilter.

Proof Implication $2 \Rightarrow 3$ is obtained observing that $a \vee \neg a \in F$. The rest is immediate. \square

5.12 Exercise Prove that the stone topology on $S(\mathbb{P})$ has a base of open compact sets. \square

5.13 Exercise Suppose we had defined $S(\mathbb{P})$ as the set of relatively maximal filters. What could possibly go wrong? \square

3 Types as filters

This section we work with a fixed set of formulas Δ all with free variables among those of some fixed tuple x . In this section we do not display x in the notation. Subsets of Δ are called Δ -types.

We associate to Δ a bounded lattice $\mathbb{P}(\Delta)$. This is the closure under conjunction and disjunction of the formulas in $\Delta \cup \{\perp, \top\}$. The (pre)order relation in $\mathbb{P}(\Delta)$ is given by

$$\psi \leq \varphi \Leftrightarrow T \cup \{\psi\} \vdash \varphi,$$

for some fixed theory T . In this section, to lighten notation, we absorb T in the symbol \vdash . If p is a Δ -type we denote by $\langle p \rangle_{\mathbb{P}}$ the filter in $\mathbb{P}(\Delta)$ generated by p .

5.14 Lemma For every Δ -type p

$$\langle p \rangle_{\mathbb{P}} = \left\{ \varphi \in \mathbb{P}(\Delta) : p \vdash \varphi \right\}.$$

In particular p is consistent if and only if $\langle p \rangle_{\mathbb{P}}$ is a proper filter.

Proof Inclusion \subseteq is clear. Inclusion \supseteq is a consequence of the Compactness Theorem. In fact $p \vdash \varphi$ implies that $\psi \vdash \varphi$ for some formula ψ that is conjunction of formulas in p . Then $\varphi \in \langle p \rangle_{\mathbb{P}}$ follows from $\psi \in \langle p \rangle_{\mathbb{P}}$ and $\psi \leq \varphi$. \square

We say that $p \subseteq \Delta$ is a **principal Δ -type** if $\langle p \rangle_{\mathbb{P}}$ is a principal. The following lemma is an immediate consequence of the Compactness Theorem. Note that in 3 the formula φ is arbitrary, possibly not even in $\mathbb{P}(\Delta)$.

5.15 Lemma For every Δ -type p the following are equivalent

1. p is principal;
2. $\psi \vdash p \vdash \psi$ for some formula ψ (here ψ is any formula, it need not be in Δ);
3. $\varphi \vdash p$ where φ is conjunction of formulas in p . \square

Proof Implications $1 \Rightarrow 2$ is immediate by Lemma 5.14. To prove $2 \Rightarrow 3$ suppose $\psi \vdash p \vdash \psi$. Apply compactness to obtain a formula φ , conjunction of formulas in p , such that $\varphi \vdash \psi$. Implications $3 \Rightarrow 1$ is trivial. \square

5.16 Definition We say that $p \subseteq \Delta$ is a **prime Δ -type** if $\langle p \rangle_{\mathbb{P}}$ is a prime filter. We say that p is a **complete Δ -type** if $\langle p \rangle_{\mathbb{P}}$ is a maximal filter. \square

Though in general neither Δ nor $\mathbb{P}(\Delta)$ are closed under negation, Lemma 5.14 has the following consequence.

5.17 Proposition For every consistent Δ -type p the following are equivalent

1. p is complete;

2. p is consistent and either $p \vdash \varphi$ or $p \vdash \neg\varphi$ for every formula $\varphi \in \Delta$.

Proof $2 \Rightarrow 1$. Assume 2. As p is consistent, $\langle p \rangle_{\mathbb{P}}$ is a proper filter. To prove that it is maximal suppose $\varphi \notin \langle p \rangle_{\mathbb{P}}$. Then $p \not\vdash \varphi$ and from 2 it follows that $p \vdash \neg\varphi$. Hence no proper filter contains $p \cup \{\varphi\}$.

$1 \Rightarrow 2$. As $\langle p \rangle_{\mathbb{P}}$ is proper, p is consistent. Suppose $p \not\vdash \varphi$. Then $\varphi \notin \langle p \rangle_{\mathbb{P}}$ and, as $\langle p \rangle_{\mathbb{P}}$ is maximal, $p \cup \{\varphi\}$ generates the improper filter. Then $p \cup \{\varphi\}$ is inconsistent. Hence $p \vdash \neg\varphi$. \square

Given a model M and a tuple $c \in M^{|x|}$ the Δ -type of c in M is the sets

$$\Delta\text{-tp}_M(c) = \left\{ \varphi(x) \in \Delta : M \models \varphi(c) \right\}$$

When the model M is clear from the context we omit the subscript. When x and c are the empty tuple, we write $\text{Th}_{\Delta}(M)$ for $\Delta\text{-tp}_M(c)$.

5.18 Lemma *For every Δ -type p the following are equivalent*

1. p is prime;
2. $p \cup \{ \neg\varphi : \varphi \in \Delta \text{ such that } p \not\vdash \varphi \}$ is consistent;
3. $\{ \varphi \in \Delta : p \vdash \varphi \} = \Delta\text{-tp}_M(c)$ for some model M and some tuple $c \in M^{|x|}$.

Proof Implications $2 \Rightarrow 3 \Rightarrow 1$ are clear, we prove $1 \Rightarrow 2$. By compactness if the type in 2 is inconsistent then there are finitely many formulas $\varphi_1, \dots, \varphi_n \in \Delta$ such that $p \not\vdash \varphi_i$ and

$$p \vdash \bigvee_{i=1}^n \varphi_i.$$

hence p is not prime. \square

The following corollary is immediate. When it comes to verifying that a given Δ -type is prime, it simplifies the proof.

5.19 Corollary *For every Δ -type p the following are equivalent*

1. p is prime;
2. $p \vdash \bigvee_{i=1}^n \varphi_i \Rightarrow p \vdash \varphi_i$ for some $i \leq n$, for every n and every $\varphi_1, \dots, \varphi_n \in \Delta$. \square

The set Δ above contains only formulas with variables among those of the tuple x . In the following it is convenient to consider sets Δ that are closed under substitution of variables with any other variable. The set of prime Δ -types is denoted by $S(\Delta)$, and we write $S_x(\Delta)$ when we restrict to types in with variables among those of the tuple x .

The most common Δ used in the sequel is the set of all formulas in $L(A)$ and the underlying theory is $\text{Th}(M/A)$ for some given model M containing A . In this case we write $\text{tp}_M(c/A)$ for $\Delta\text{-tp}_M(c)$ or, when A is empty, $\text{tp}_M(c)$. The set $S_x(\Delta)$ is denoted by $S_x(A)$. The topology on $S_x(A)$ is generated by the clopen

$$[\varphi(x)] = \left\{ p \in S_x(A) : \varphi(x) \in p \right\}.$$

Sometimes Δ is the set of all formulas of a given syntactic form. Then we use some

more suggestive notation that we summarize below.

5.20 Notation The following are some of the most common Δ -types and Δ -theories

1. $\text{at-tp}(c)$, $\text{Th}_{\text{at}}(M)$ when $\Delta = L_{\text{at}}$
2. $\text{at}^{\pm}\text{-tp}(c)$, $\text{Th}_{\text{at}^{\pm}}(M)$ when $\Delta = L_{\text{at}^{\pm}}$
3. $\text{qf-tp}(c)$, $\text{Th}_{\text{qf}}(M)$ when $\Delta = L_{\text{qf}}$.

Clearly, the types/theories in 2 and 3 are equivalent. Most used is the theory $\text{Th}_{\text{at}^{\pm}}(M/M)$ which is called the **diagram of M** and has a dedicated symbol: $\text{Diag}(M)$. \square

5.21 Remark Let $A \subseteq M \cap N$. The following are equivalent

1. $N \models \text{Diag}\langle A \rangle_M$;
2. $\langle A \rangle_M$ is a substructure of N . \square

4 Morphisms

First we set the meaning that the word **map** has in these notes.

5.22 Definition A **map** consists a triple $f : M \rightarrow N$ where

1. M is a set (usually a structure) called the **domain of the map**;
2. N is a set (usually a structure) called the **codomain the map**;
3. f is a function with **domain of definition** $\text{dom } f \subseteq M$ and **image** $\text{img } f \subseteq N$.

By **cardinality of $f : M \rightarrow N$** we understand the cardinality of the function f . \square

If $\text{dom } f = M$ we say that the map is **total**; if $\text{img } f = N$ we say that it is **surjective**. The **composition** of two maps and the **inverse** of a map are defined in the obvious way.

5.23 Definition Let Δ be a set of formulas with free variables in the tuple $x = \langle x_i : i < \lambda \rangle$. The map $h : M \rightarrow N$ is a **Δ -morphism** if it **preserves the truth** of all formulas in Δ . By this we mean that

$$p. \quad M \models \varphi(a) \Rightarrow N \models \varphi(ha) \quad \text{for every } \varphi(x) \in \Delta \text{ and every } a \in (\text{dom } h)^{|x|}.$$

Notation: if a is the tuple $\langle a_i : i < \lambda \rangle$ then ha is the tuple $\langle ha_i : i < \lambda \rangle$. \square

When $\Delta = L$ we say **elementary map** for Δ -morphism. When $\Delta = L_{\text{at}}$ we say **partial homomorphism** and when $\Delta = L_{\text{at}^{\pm}}$ we say **partial embedding** or **partial isomorphism**. The reason for the latter name is explained in Remark 5.24.

It is immediate to verify that a partial embedding which is total is an embedding (so, there is not conflict with Definition 2.19 above). Similarly, a partial embedding which is a total and surjective is an isomorphism. The precise connection between partial and total homo/iso-morphisms is discussed in following remark.

5.24 Remark For every map $h : M \rightarrow N$ the following are equivalent

1. $h : M \rightarrow N$ is a partial isomorphism;

2. there is an isomorphism $k : \langle \text{dom } h \rangle_M \rightarrow \langle \text{img } h \rangle_N$ that extends h .

Moreover, k unique. The equivalence holds replacing isomorphism by homomorphism (in which case we in 2 we obtain an surjection). The extension k is obtained defining $k(t(a)) = t(ha)$.

A similar fact holds for partial homomorphisms with epimorphism (surjective homomorphism) for isomorphism. \square

We use Δ -morphisms to compare, locally, two structures. There are different ways to do this, in the proposition below we list a few synonymous expressions. But first some more notation. When x is a fixed tuple of variables, $a \in M^{|x|}$ and $b \in N^{|x|}$ we write

$$\begin{aligned} M, a &\Rightarrow_{\Delta} N, b && \text{if } M \models \varphi(a) \Rightarrow N \models \varphi(b) \text{ for every } \varphi(x) \in \Delta. \\ M, a &\equiv_{\Delta} N, b && \text{if } M \models \varphi(a) \Leftrightarrow N \models \varphi(b) \text{ for every } \varphi(x) \in \Delta. \end{aligned}$$

The following equivalences are immediate and will be used without explicit reference.

5.25 Proposition *For every given set of formulas Δ and every map $h : M \rightarrow N$ the following are equivalent*

1. $h : M \rightarrow N$ is a Δ -morphism;
2. $M, a \Rightarrow_{\Delta} N, ha$ for every $a \in (\text{dom } h)^{|x|}$;
3. $\Delta\text{-tp}_M(a) \subseteq \Delta\text{-tp}_N(ha)$ for every $a \in (\text{dom } h)^{|x|}$;
4. $N, ha \models p(x)$ for every $a \in (\text{dom } h)^{|x|}$ and $p(x) = \Delta\text{-tp}_M(a)$. \square

5.26 Remark Condition p in Definition 5.23 apply to tuples x of any length, in particular to the empty tuple. In this case $\varphi(x)$ is a sentence, $a \in (\text{dom } h)^0 = \{\emptyset\}$ is the empty tuple, and p asserts that $\text{Th}_{\Delta}(M) \subseteq \text{Th}_{\Delta}(N)$. When $h = \emptyset$ this is actually all that p says. In fact $\emptyset^{|x|} = \emptyset$ unless $|x| = 0$. Still, $\text{Th}_{\Delta}(M) \subseteq \text{Th}_{\Delta}(N)$ may be a non trivial requirement. \square

5.27 Definition We call $\text{Th}_{\Delta}(M)$ the Δ -characteristic of M . We say that T decides the Δ -characteristic if $\text{Th}_{\Delta}(M) = \text{Th}_{\Delta}(N)$ for all $M, N \models T$. In other words, for any pair of models of T , the empty map $\emptyset : M \rightarrow N$ is a Δ -morphism. When $\Delta = L_{\text{at}^{\pm}}$ we say simply characteristic, then T decides the characteristic $\langle \emptyset \rangle_M \simeq \langle \emptyset \rangle_N$ for all $M, N \models T$. \square

We conclude this section with a couple of propositions that break Theorem 2.20 into parts. More interestingly, in Chapter 10 we shall prove a sort of converse of Propositions 5.29 and 5.30.

Though the following is not immediately required, it is interesting to note that here is a relation between some properties of Δ -morphisms and the closure of Δ under logical connectives. When $C \subseteq \{\forall, \exists, \neg, \vee, \wedge\}$ is a set of connectives, we write $C\Delta$ for the closure of Δ with respect to all connectives in C . We write $\neg\Delta$ for the set containing the negation of the formulas in Δ . Warning: do not confuse $\neg\Delta$ with $\{\neg\}\Delta$.

It is clear that Δ -morphisms are $\{\wedge, \vee\}\Delta$ -morphisms.

5.28 Proposition For every given set of formulas Δ and every injective map $h : M \rightarrow N$ the following are equivalent

- a. $h : M \rightarrow N$ is a $\neg\Delta$ -morphism;
- b. $h^{-1} : M \rightarrow N$ is a Δ -morphism. □

5.29 Proposition For every set of formulas Δ , every Δ -embedding $h : M \rightarrow N$ is a $\{\exists\}\Delta$ -morphism.

Proof Formulas in $\{\exists\}\Delta$ have the form $\exists y \varphi(x, y)$ where y is a finite tuples of variables and $\varphi(x, y) \in \Delta$. For every tuple $a \in (\text{dom } h)^{|x|}$ we have:

$$\begin{aligned}
 M \models \exists y \varphi(a, y) &\Rightarrow M \models \varphi(a, b) \text{ for } b \in M^{|y|} \\
 &\Rightarrow N \models \varphi(ha, hb) \\
 &\Rightarrow N \models \varphi(ha, c) \text{ for } c \in N^{|y|} \\
 &\Rightarrow N \models \exists y \varphi(ha, y).
 \end{aligned}$$

Note that the second implication requires the totality of $h : M \rightarrow N$ which guarantees that $\varphi(a, y)$ has a solution in $\text{dom } h$. □

When $h : M \rightarrow N$ is injective the following is a corollary of Propositions 5.28 and 5.29. The general proof is the ‘dual’ of that of Propositions 5.29.

5.30 Proposition For every set of formulas Δ , every surjective Δ -morphism $h : M \rightarrow N$ is a $\{\forall\}\Delta$ -morphism. □

Chapter 6

Some relational structures

In the first section we prove that theory of *dense linear orders without endpoints* is ω -categorical. That is, any two such countable orders are isomorphic. This is an easy classical result of Cantor. In this chapter we examine Cantor's construction (a so-called *back-and-forth* construction) in great detail. In the second section we apply the same technique to prove that the theory of the *random graph* is ω -categorical.

1 Dense linear orders

The **language of strict orders**, which in this section we denote by L , contains only a binary relation symbol $<$. A structure M of signature L is a **strict order** if it models (the universal closure of) the following formulas

1. $x \not< x$ irreflexive;
2. $x < z < y \rightarrow x < y$ transitive.

Note that the following is an immediate consequence of 1 and 2.

$$x < y \rightarrow y \not< x \quad \text{antisymmetric.}$$

We say that the order is **total** or **linear** if

- li. $x < y \vee y < x \vee x = y$ linear or total.

An order is **dense** if

- nt. $\exists x, y (x < y)$ non trivial;
- d. $x < y \rightarrow \exists z (x < z < y)$ dense.

We need to require the existence of two comparable elements, then d implies that dense orders are in fact infinite. We say that the ordering has no **endpoints** if

- e. $\exists y (x < y) \wedge \exists y (y < x)$ without endpoints.

We denote by T_{lo} the theory strict linear orders and by T_{dlo} the theory of dense linear orders without endpoints. Clearly, these are consistent theories: \mathbb{Q} with the usual ordering is a model of T_{dlo} .

We introduce some notation to improve readability of the proof of the following theorem. Let A and B be subsets of an ordered set. We write $A < B$ if $a < b$ for every $a \in A$ and $b \in B$. We write $a < B$ e $A < b$ for $\{a\} < B$, respectively $A < \{b\}$. Let $M \models T_{lo}$. Then $M \models T_{dlo}$ if and only if for every finite $A, B \subseteq M$ such that $A < B$ there is a c such that $A < c < B$. In fact axiom d is evident and axioms nt and e are obtained taking replacing A and/or B by the empty set.

Now we prove the first of a series of lemmas that we call **extension lemmas**. Recall that in the language of strict orders an injective map $k : M \rightarrow N$ is a partial isomorphism if

$$M \models a < b \Leftrightarrow N \models ka < kb \quad \text{for every } a, b \in \text{dom } k.$$

(When $M, N \models T_{\text{lo}}$ direction \Rightarrow suffices.)

6.1 Lemma Fix $M \models T_{\text{lo}}$ and $N \models T_{\text{dlo}}$. Let $k : M \rightarrow N$ be a finite partial isomorphism and let $b \in M$. Then there is a partial isomorphism $h : M \rightarrow N$ that extends k and is defined in b .

Proof Given a finite partial isomorphism $k : M \rightarrow N$ define

$$A^- = \{a \in \text{dom}(k) : a < b\};$$

$$A^+ = \{a \in \text{dom}(k) : b < a\}.$$

The sets A^- and A^+ are finite and partition $\text{dom } k$, and $A^- < A^+$. As $k : M \rightarrow N$ is a partial isomorphism, $k[A^-] < k[A^+]$. Then in N there is an element c such that $k[A^-] < c < k[A^+]$. It is easy to check that setting $h = k \cup \{ \langle b, c \rangle \}$ we obtain the required extension. \square

The following is an equivalent version of Lemma 6.1.

6.2 Corollary Let $M \models T_{\text{lo}}$ be countable and let $N \models T_{\text{dlo}}$. Let $k : M \rightarrow N$ be a finite partial isomorphism. Then there is a (total) embedding $h : M \hookrightarrow N$ that extends k .

Proof Let $\langle a_i : i < \omega \rangle$ be an enumeration of M . Define by induction a chain of finite partial isomorphisms $h_i : M \rightarrow N$ such that $a_i \in \text{dom } h_{i+1}$. The construction starts with $h_0 = k$. At stage $i + 1$ we chose any finite partial isomorphism $h_{i+1} : M \rightarrow N$ that extends h_i and is defined in a_i . This is possible by Lemma 6.1. In the end we set

$$h = \bigcup_{i \in \omega} h_i.$$

It is immediate to verify that $h : M \hookrightarrow N$ is the required embedding. \square

6.3 Exercise Prove that the extension Lemma 6.1 characterizes models of T_{dlo} among models of T_{lo} . That is, if N is a model of T_{lo} such that the conclusion of Lemma 6.1 holds, then $M \models T_{\text{dlo}}$. \square

We are now ready to prove that any two countable models of T_{dlo} are isomorphic which is a classical result of Cantor's. Actually what we prove is slightly more general than that. In fact Cantor's theorem is obtained from the theorem below by setting $k = \emptyset$, which we are allowed to, because all models have the same empty characteristic (cfr. Remark 5.26).

6.4 Theorem Every finite partial isomorphism $k : M \rightarrow N$ between countable models of T_{dlo} extends to an isomorphism $g : M \xrightarrow{\sim} N$.

The following is the archetypal **back-and-forth** construction. It is important to note that it does not mention linear orders at all. It only uses the extension Lemma 6.1. In many other contexts, as soon as we have an extension lemma, we can apply verbatim the same construction (cfr. Theorem 7.6).

Proof Fix some enumerations of M and N , say $\langle a_i : i < \omega \rangle$, respectively $\langle b_i : i < \omega \rangle$. We define by induction a chain of finite partial isomorphisms $g_i : M \rightarrow N$ such that $a_i \in \text{dom } g_{i+1}$ and $b_i \in \text{img } g_{i+1}$. In the end we set

$$g = \bigcup_{i \in \omega} g_i$$

We begin by setting $g_0 = k$. The inductive step consists of two half-steps that we may call the *forth-step* and *back-step*. In the forth-step we define $g_{i+1/2}$ such that $a_i \in \text{dom } g_{i+1/2}$. In the back-step to define g_{i+1} such that $b_i \in \text{img } g_{i+1}$.

By the extension lemma 6.1 there is a finite partial isomorphism $g_{i+1/2} : M \rightarrow N$ that extends g_i and is defined in a_i . Now apply the same lemma to extend $(g_{i+1/2})^{-1} : N \rightarrow M$ to a finite partial isomorphism $(g_{i+1})^{-1} : N \rightarrow M$ defined in b_i . \square

Let λ be an infinite cardinal. We say that a theory is **λ -categorical** if any two models of T of cardinality λ are isomorphic. From Theorem 6.4, taking $k = \emptyset$, we obtain the following.

6.5 Corollary *The theory T_{dlo} is ω -categorical.* \square

We also obtain that T_{dlo} is a complete theory. This is consequence of the following general fact.

6.6 Proposition *If T is λ -categorical, for some $\lambda \geq |L|$, then T is complete.*

Proof Let M and N be any two models of T_{dlo} . Applying the upward and/or downward Löwenheim-Skolem theorem, we may assume they both have cardinality λ . (Here we use that $\lambda \geq |L|$.) Hence $M \simeq N$ and in particular $M \equiv N$. \square

6.7 Exercise Prove that T_{dlo} is not λ -categorical for any uncountable λ . \square

6.8 Exercise Prove that, in the language of strict orders, $\mathbb{Q} \preceq \mathbb{R}$. \square

6.9 Exercise Let L be the language of strict orders augmented with countably many constants $\{c_i : i \in \omega\}$. Let T be the theory that extends T_{dlo} with the axioms $c_i < c_{i+1}$ for all i . Prove that T is complete. Find three non isomorphic models of this theory. For N a rightly chosen model of T , prove the statement in Lemma 6.1, with M any model of T . \square

6.10 Exercise Show that in Theorem 6.6 the assumption $\lambda \geq |L|$ is necessary. (Hint. Let ν be an uncountable cardinal. The language contains only the ordinals $i < \nu$ as constants. The theory T says that there are infinitely many elements and either $i = 0$ for every $i < \nu$, or $i \neq j$ for every $i < j < \nu$. Prove that T is ω -categorical but incomplete.) \square

2 Random graphs

Recall that the **language of graphs**, which in this section we denote by L , contains only a binary relation r . A **graph** structure of signature L such that

1. $\neg r(x, x)$ irreflexive;
2. $r(x, y) \rightarrow r(y, x)$ symmetric.

An element of a graph M is called a **vertex** or a **node**. An **edge** is an unordered pair of vertices $\{a, b\} \subseteq M$ such that $M \models r(a, b)$. In words we may say that a is adjacent to b .

A **random graph** is a graph that also satisfies the following axioms for every n

nt. $\exists x, y, z \ (x \neq y \neq z \neq x)$ non trivial;

$r_n. \bigwedge_{i,j=1}^n x_i \neq y_j \rightarrow \exists z \bigwedge_{i=1}^n [r(x_i, z) \wedge \neg r(z, y_i)]$ for every $n \in \mathbb{Z}^+$.

The theory of graphs is denoted by T_{gph} and the theory of random graphs is denoted by T_{rg} . The scheme of axioms r_n plays the same role of density in the previous section. It says that given two non empty disjoint sets A^+ and A^- of cardinality $\leq n$ there is a vertex z that is adjacent to all vertices in A^+ and to no vertex in A^- . Note that it might well be that $z \in A^-$, however $z \in A^+$ would contradict 1.

Some readers may doubt if T_{rg} is consistent.

6.11 Proposition *There exists a random graph.*

Proof The domain of N is the set of natural numbers. Let $N \models r(n, m)$ hold if the n -th prime number divides m or vice versa m -th prime number divides n . \square

6.12 Proposition *Random graphs are infinite.*

Proof Suppose for a contradiction that M is a finite random graph. As M contains at least 3 elements, we can fix two distinct elements $a, b \in M$ and require a z adjacent to all elements of $M \setminus \{a, b\}$ and no element of $\{a, b\}$. As remarked above, $z \in \{a, b\}$, then a and b are not adjacent. Now let w be adjacent to all vertices in $M \setminus \{a\}$ but not to a . The only option is $w = b$, but this implies that a is adjacent to b . Contradiction. \square

The following is the analogous of Lemma 6.1 for random graphs. Recall that in the language of graphs a map $k : M \rightarrow N$ is a partial isomorphism if it is injective and

$$M \models r(a, b) \Leftrightarrow N \models r(ka, kb) \quad \text{for every } a, b \in \text{dom } k.$$

6.13 Lemma *Fix $M \models T_{\text{gph}}$ and $N \models T_{\text{rg}}$. Let $k : M \rightarrow N$ be a finite partial isomorphism and let $b \in M$. Then there is a partial isomorphism $h : M \rightarrow N$ that extends k and is defined in b .*

Proof The schema of the proof is the same as in Lemma 6.1, so we use the same notation. Assume $b \notin \text{dom } k$ and define

$$A^+ = \{x \in \text{dom } k : M \models r(x, b)\} \quad \text{e} \quad A^- = \{y \in \text{dom } k : M \models \neg r(y, b)\}.$$

These two sets are finite and disjoint, then so are $k[A^+]$ and $k[A^-]$. Then there is a c such that

$$\bigwedge_{a \in A^+} r(ka, c) \wedge \bigwedge_{a \in A^-} \neg r(ka, c).$$

As $k[A^+] \cup k[A^-] = \text{img } k$, it is immediate to verify that $h = k \cup \{\langle b, c \rangle\}$ is the required extension. \square

With the same proof of Corollary 6.2 obtain the following.

6.14 Corollary Let $M \models T_{\text{gph}}$ be countable and let $N \models T_{\text{rg}}$. Let $k : M \rightarrow N$ be a finite partial isomorphism. Then there is a (total) embedding $h : M \hookrightarrow N$ that extends k . \square

The proof of Theorem 6.4 gives the following theorem and its corollary.

6.15 Theorem Every finite partial isomorphism $k : M \rightarrow N$ between models of T_{rg} extends to an isomorphism $g : M \xrightarrow{\sim} N$. \square

6.16 Corollary The theory T_{rg} is ω -categorical (and therefore complete). \square

6.17 Exercise Let $a, b, c \in N \models T_{\text{rg}}$. Prove that $r(a, N) = r(b, N) \cap r(c, N)$ occurs only in the trivial case $a = b = c$. \square

6.18 Exercise Prove that for every $b \in N \models T_{\text{rg}}$ the set $r(b, N)$ is a random graph. Assume N is countable. Is every random graph $M \subseteq N$ of the form $r(b, N)$ for some $b \in N$? \square

6.19 Exercise Let N be free union of two random graphs N_1 and N_2 . That is, $N = N_1 \sqcup N_2$ and $r^N = r^{N_1} \sqcup r^{N_2}$. By \sqcup we denote the disjoint union. Prove that N is not a random graph. Show that N_1 is not definable without parameters (assume $|N_1| = |N_2| = \omega$, otherwise the proof is longer). Write a first order sentence $\psi(x, y)$ true if x and y belong to the same connected component of N . Axiomatize the class \mathcal{K} of graphs that are free union of two random graphs. \square

6.20 Exercise Prove that T_{rg} is not λ -categorical for any uncountable λ . Hint. Prove that there is a random graph N of cardinality λ where every vertex is adjacent to $< \lambda$ vertices. Compare it with its complement graph (the graph that has edges between pairs that are non adjacent in N). \square

6.21 Exercise Prove that T_{rg} is not finitely axiomatizable. Hint. Given a random graph N and a set P of cardinality $n + 1$ show that you can add edges to $M \sqcup P$ and make it satisfy axiom r_n but not r_{n+1} . \square

6.22 Exercise Let $A \subseteq N \models T_{\text{rg}}$ and let $\varphi(x) \in L(A)$, where $|x| = 1$. Prove that if $\varphi(N)$ is finite then $\varphi(N) \subseteq A$. \square

6.23 Exercise (Peter J. Cameron) Prove that for every infinite countable graph M the following are equivalent

1. M is either random, complete or empty (i.e. $r^M = \emptyset$);
2. if $M_1, M_2 \subseteq M$ are such that $M_1 \sqcup M_2 = M$, then $M_1 \simeq M$ or $M_2 \simeq M$.

Hint. For $2 \Rightarrow 1$ first show that if $r(a, M) = \emptyset$ for some $a \in M$ then the graph is null and if $\{b\} \cup r(b, M) = M$ for some b , then the graph is complete. Clearly, 2 implies that any finite partition of M contains an element isomorphic to M . Then the claim above generalizes as follows: if there is a finite A such that $\bigcap_{a \in A} r(a, M) = \emptyset$ then

M is the empty graph and if there is a finite B such that $\bigcup_{b \in B} r(b, M) = M$ then M is the complete graph.

Suppose M is not a random graph. Fix some finite, disjoint A and B such that no c satisfies both $r(A, c) = A$ and $r(B, c) = \emptyset$. Let $M_1 = \{c : r(A, c) \neq A\}$ and $M_2 = \neg M_1$. Now note that

$$\bigcap_{a \in A} r(a, M_1) = \emptyset \quad \text{and} \quad \bigcup_{b \in B} r(b, M_2) = M_2. \quad \square$$

3 Notes and references

The following is a well-written accessible survey on the amazing model theoretic properties of the random graph.

[1] Peter J. Cameron, *The random graph* (2013), [arXiv:1301.7544](#).

Chapter 7

Fraïssé limits

We introduce *Fraïssé limits*, also *homogeneous-universal* or *generic* structures, which here we call *rich* models, after Poizat. Rich models generalize the examples in Chapters 6 and the many more to come.

Elimination of quantifiers is briefly discussed at the end of Section 1. For the time being we identify quantifier elimination with the property that says that all partial isomorphisms are elementary maps. Proofs are easier with this notion in mind. The equivalence with its syntactic counterpart is only proved in Chapter 10, when the reader is more familiar with arguments of compactness.

1 Rich models.

We now define *categories of models and partial morphisms*. These are examples of concrete categories as intended in category theory. However, apart from the name, in what follows we dispense with all notions of category theory as they would make the exposition less basic than intended (without providing more technical instruments).

 **Warning:** the terminology introduced in this section is not standard. In the literature many details are left implicit. This is generally safe when the category used is fixed. Here we prefer to be more explicit because, when discussing saturation, quantifier elimination, and model completeness, it helps to compare different categories.

A **category (of models and partial morphisms)** is a class \mathcal{M} which is disjoint union of two classes: \mathcal{M}_{ob} and \mathcal{M}_{hom} . The first is the class of **objects** and contains structures with a common signature L which we call **models**. The second is the class of **morphisms** and contains (partial) maps between models. We require that the identity maps are morphisms and that composition of two morphisms is again a morphism. This makes \mathcal{M} a well-defined category.

For example, \mathcal{M} could consist of all models of some theory T_0 and of all partial isomorphisms between these. Alternatively, as morphisms we could take elementary maps between models. At a first reading the reader may assume \mathcal{M} is as in one of these two examples. In the general case we need to make some assumptions on \mathcal{M} .

7.1 Definition For ease of reference we list together all properties required below

- c1. the (partial) identity map $\text{id}_A : M \rightarrow M$ is a morphism, for any $A \subseteq M$;
- c2. if $k' : M \rightarrow N$ is a morphism for every finite $k' \subseteq k$, then $k : M \rightarrow N$ is a morphism.
- c3. morphisms are invertible maps and the inverse of a morphism is a morphism;
- c4. morphisms preserve the truth of L_{at} -formulas;
- c5. if M is a model and $N \equiv M$, then also N is a model;

c6. every elementary map between models is a morphism. \square

The **connected component** of a model M is the subclass of models N such that there is any morphism with domain M and codomain N (or vice versa, by c3). By axiom c1 the restriction of a morphism is a morphism, therefore M and N are in the same connected component if and only if the empty map $\emptyset : M \rightarrow N$ is a morphism. If the whole category \mathcal{M} consists of one connected component we say that \mathcal{M} is **connected**.

We call c2 the **finite character of morphisms**. Note that it implies the following

c7. if $k_i : M \rightarrow N$ is a chain of morphisms, then $\bigcup_{i < \lambda} k_i : M \rightarrow N$ is a morphism.

Notably, the following two definitions require c3. The generalization to non injective morphisms is not straightforward (in fact, there are two generalizations: *projective* and *inductive*). These generalizations are not very common and will not be considered here.

7.2 Definition Assume that \mathcal{M} satisfies c1-c3 of Definition 7.1. We say that a model N is **λ -rich** if for every model M , every $b \in M$ and every morphism $k : M \rightarrow N$ of cardinality $< \lambda$ there is a $c \in N$ such that $k \cup \{ \langle b, c \rangle \} : M \rightarrow N$ is a morphism. We say that N is **rich** if it is λ -rich for $\lambda = |N|$. When $\mathcal{M}_{\text{ob}} = \text{Mod}(T_0)$ for some theory T_0 and \mathcal{M}_{hom} is clear from the context, we say **rich model of T_0** . \square

Rich models are also called *Fraïssé limits* or *homogeneous-universal* for a reason that will soon be clear; they are also called *generic*. Unfortunately these names are either too long or too generic, so we opt for the less common term *rich* that was proposed by Poizat.

The following two notions are closely connected with richness.

7.3 Definition Assume that \mathcal{M} satisfies c1-c3 of Definition 7.1. We say that a model N is **λ -universal** if for every model M of cardinality $\leq \lambda$ in the same connected component of N there is an embedding $k : M \hookrightarrow N$. We say that a model N is **λ -homogeneous** if every $k : N \rightarrow N$ of cardinality $< \lambda$ extends to a bijective morphism $h : N \xrightarrow{\sim} N$ (an automorphism when c4 below holds).

Note that the larger \mathcal{M}_{hom} , the stronger notion of homogeneity. When \mathcal{M}_{hom} contains all partial isomorphisms between models (the largest class of morphisms considered here), it is common to say **λ -ultrahomogeneous** for λ -homogeneous.

As above, when $\lambda = |N|$ we say **universal**, **homogeneous** and **ultrahomogeneous**. \square

In Section 6.1 we implicitly used $\mathcal{M}_{\text{ob}} = \text{Mod}(T_{\text{lo}})$ and partial isomorphisms as \mathcal{M}_{hom} . In Section 6.2 we used $\mathcal{M}_{\text{ob}} = \text{Mod}(T_{\text{gph}})$ and again partial isomorphisms as \mathcal{M}_{hom} . Corollary 6.2 proves that every model of T_{dlo} is ω -rich. Corollary 6.14 claims the analogous fact for T_{rg} .

In the following we frequently work under the following assumption (even when not all properties are strictly necessary).

7.4 Assumption Assume $|L| \leq \lambda$ and suppose that \mathcal{M} satisfies c1-c6 of Definition 7.1

The assumption on the cardinality L is only necessary to apply the downward Löwenheim-Skolem Theorem when required.

7.5 Proposition (Assume 7.4) *The following are equivalent*

1. N is a λ -rich model;
2. for every model M of cardinality $\leq \lambda$ and every morphism $k : M \rightarrow N$ of cardinality $< \lambda$ there is a embedding $h : M \hookrightarrow N$ that extends k .

Proof Closure under union of chains of morphisms, which is ensured by c7, immediately yields $1 \Rightarrow 2$. As for implication $2 \Rightarrow 1$ we only need to consider the case $\lambda < |M|$. By the downward Löwenheim-Skolem theorem there is an $M' \preceq M$ of cardinality λ containing b . Let $h : M' \hookrightarrow N$ be the embedding obtained from 1. By c4, the map $h : M \rightarrow N$ is a composition of morphisms, hence a morphism. \square

The following theorem subsumes both Theorem 6.4 and Theorem 6.15.

7.6 Theorem (Assume 7.4) *Let M and N be two rich models of the same cardinality λ . Then every morphism $k : M \rightarrow N$ of cardinality $< \lambda$ extends to an isomorphism.*

Proof When $\lambda = \omega$, we can take the proof of Theorem 6.4 and replace *partial isomorphism* by *morphism* and the references to Lemma 6.1 by references to Proposition 7.5. As for uncountable λ , we only need to extend the construction through limit stages. By c7 we can simply take the union. \square

7.7 Corollary (Assume 7.4) *Then all rich models of cardinality λ in the same connected component are isomorphic.* \square

It is obvious that λ -rich models are λ -universals and, by Theorem 7.6, they are λ -homogeneous. These two notions are weaker than richness. For instance, when M is as in Section 6.2, the countable graph that has no arc is trivially ultrahomogeneous but it is not universal and a fortiori not rich. On the other hand if we add to a countable random graph an isolated point we obtain an universal graph which is not ultrahomogeneous. However, when taken together, these two properties are equivalent to richness.

7.8 Theorem (Assume 7.4) *The following are equivalent:*

1. N is rich;
2. N is homogeneous and universal.

Proof Implication $1 \Rightarrow 2$ is clear as noted above, so we prove $2 \Rightarrow 1$. We use the characterization of richness given in Proposition 7.5. Let $k : M \rightarrow N$ be a morphism such that $|k| < |N|$ and $|M| \leq |N|$. As N is universal, there is a total morphism $f : M \hookrightarrow N$. By c3 the map $k \circ f^{-1} : N \rightarrow N$ is a morphism of cardinality $< |N|$. By homogeneity it has an extension to an automorphism $h : N \xrightarrow{\sim} N$. It is immediate that $h \circ f : M \hookrightarrow N$ is the required extension of k . \square

7.9 Exercise Let N be the structure obtained by adding to a countable random graph an isolated point. Show that N is homogeneous if morphisms are elementary maps but it is not if morphisms are simply partial isomorphisms. \square

A consequence of Theorem 7.6 is that morphisms between rich models of the same cardinality are elementary maps. However, the theorem gives no information when the models have different cardinality nor when they are merely λ -rich. This case is dealt with by next theorem, arguably the main result of this section.

To test the theorem below in a simple case we propose the following exercise.

7.10 Exercise Every partial isomorphism $k : M \rightarrow N$ between models of T_{dlo} (or models of T_{rg}) is an elementary map. Hint: use downward Löwenheim-Skolem and Theorem 6.4. □

7.11 Theorem (Assume 7.4) *Every morphism between λ -rich models is elementary. In particular, λ -rich models in the same connected component are elementary equivalent.*

Proof Let $k : M \rightarrow N$ be a morphism between rich models. It suffices to prove that every finite restriction of k is elementary. By c2, we may as well assume that k itself is finite. It suffices to construct $M' \preceq M$ and $N' \preceq N$ together with a morphism $h : M \rightarrow N$ that extends k and maps M' bijectively to N' . Then by c6 the map $h : M' \xrightarrow{\sim} N'$ is the composition of morphisms, hence it is a morphism. Finally, by c4, it is an isomorphism, in particular an elementary map.

In general, richness is not preserved under elementary equivalence. Therefore M' and N' need to be constructed simultaneously with h . We define a chain of functions $\langle h_i : i < \lambda \rangle$ such that $h_i : M \rightarrow N$ are morphisms and in the end we set

$$h = \bigcup_{i < \lambda} h_i, \quad M' = \text{dom } h, \quad N' = \text{img } h.$$

We interweave the usual back-and-forth-argument with the Löwenheim-Skolem construction 2.40 in order to obtain $M' \preceq M$ and $N' \preceq N$.

The chains start with $h_0 = k$. At limit stages we take the union. Now assume we have h_i . Let $\varphi(x) \in L(\text{dom } h_i)$ some formula consistent in M and pick a solution $b \in M$. By λ -richness there is a $c \in N$ such that $h_i \cup \{\langle b, c \rangle\} : M \rightarrow N$ is a morphism. Let $h_{i+1/2} = h_i \cup \{\langle b, c \rangle\}$.

Finally, as in the proof of Theorem 6.4, we extend $h_{i+1/2}$ to obtain h_{i+1} . We use procedure with the roles of M and N inverted and with $h_{i+1/2}^{-1}$ for h_i .

In the end we obtain $M' \preceq M$ if all formulas $\varphi(x) \in L(M')$ are eventually considered. A similar consideration holds for N' . This is achieved using the same dovetail enumeration as in our second proof the downward Löwenheim-Skolem Theorem 2.40. □

The **theory of rich models** of \mathcal{M} is the set T_1 of sentences that hold in all rich models (or, equivalently, in any $|L|$ -rich model), assuming they exist. By the theorem above, T_1 is complete as soon as \mathcal{M} is connected.

Assume for simplicity that L is countable and that \mathcal{M} is connected. Then all ω -rich models belong to $\text{Mod}(T_1)$ for some complete theory T_1 . It is interesting to ask if the converse is true: if T_1 is the theory of the ω -rich models of \mathcal{M} , do all models in $\mathcal{M} \cap \text{Mod}(T_1)$ are rich? The answer is affirmative when T_1 is either T_{dlo} or T_{rg} , but this is not always the case, see Example 7.15 for an easy counterexample. An affirmative answer implies that the theory of rich models is ω -categorical. An interesting variant of this question is considered in Theorem 9.8.

For convenience of the reader, we instantiate Theorem 7.11 with the two categories used in Chapter 6.

7.12 Corollary *Partial isomorphisms between models of T_{dlo} and between models of T_{rg} are elementary maps.* □

When partial isomorphism between models of a given theory T coincide with elementary maps, it is always by a fundamental reason. Let us introduce some terminology. Let T be a consistent theory. We say that T has (or admits) elimination of quantifiers if for every $\varphi(x) \in L$ there is a quantifier-free formula $\psi(x) \in L_{\text{qf}}$ such that

$$T \vdash \psi(x) \leftrightarrow \varphi(x).$$

We will discuss general criteria for elimination of quantifiers in Chapter 10. Here we report without proof the following theorem.

7.13 Theorem *The following are equivalent*

1. T has elimination of quantifiers;
2. every partial isomorphism between models T is an elementary map.

□



For the time being when saying that T has quantifier elimination we intend 2 of the theorem above. The equivalence with 1 will be proved only in Corollary 10.11 and it is not required in the meanwhile (if you accept the theorem above as a definition). For instance we rephrase Corollary 7.12 above as follows.

7.14 Corollary *The theories T_{dlo} and T_{rg} have elimination of quantifiers.* □

In the next chapter we introduce important examples of ω -rich models that do not have an ω -categorical theory. These are algebraic structures (groups, fields etc.) hence more complex than pure relational structures. So, we conclude this section with an example of this phenomenon in almost trivial context.

7.15 Example Let L contain a unary predicate r_n for every positive integer n . The theory T_0 contains the axioms $\neg \exists x [r_n(x) \wedge r_m(x)]$ for $n \neq m$ and $\exists^{\leq n} x r_n(x)$ for every n . Work in the category of models of T_0 and partial isomorphisms. Let T_1 be the theory that extends T_0 with the axioms $\exists^=n x r_n(x)$ for every n . Let $q(x)$ be the type $\{\neg r_n(x) : n \in \omega\}$. There are models of T_1 that do not realize $q(x)$, hence T_1 is not ω -categorical. It is easy to verify that the following are equivalent.

1. N is an ω -rich model;
2. $N \models T_1$ and $q(N)$ is infinite.

The reader may use Theorem 7.11 and Compactness Theorem for Types 4.9 to prove that T_1 is complete and has elimination of quantifiers. It is also easy to verify that every uncountable model of T_1 is rich and consequently that T_1 is uncountably categorical. □

7.16 Exercise Let T_0 and \mathcal{M} be as in Example 7.15 except that we restrict the language to the relations r_0, \dots, r_n for a fixed n . Do ω -rich models of T_0 exist? Is their theory ω -categorical? What if we add to T_0 the axiom $r_0(x) \vee \dots \vee r_n(x)$? □

- 7.17 Exercise** The language contains only the binary relations $<$ and e . The theory T_0 says that $<$ is a strict linear order and that e is an equivalence relation. Let \mathcal{M} consists of models of T_0 and partial isomorphisms. Do rich models exist? Can we axiomatize their theory? If so, does it have elimination of quantifiers? Is it λ -categorical for some λ ? □
- 7.18 Exercise** The language contains only two binary relations. The theory T_0 says that they are equivalence relations. Let \mathcal{M} consists of models of T_0 and partial isomorphisms. Do rich models exist? Can we axiomatize their theory? If so, does it have elimination of quantifiers? Is it λ -categorical for some λ ? □
- 7.19 Exercise** In the language of graphs let T_0 say that there are no cycles (equivalently, there is at most one path between any two nodes). In combinatorics these graphs are called *forests*, and their connected components are called *trees*. Let \mathcal{M} consists of models of T_0 and partial isomorphisms. Do rich models exist? Can we axiomatize their theory? If so, does it have elimination of quantifiers? Is it λ -categorical for some λ ? □

2 Weaker notions of universality and homogeneity

We want to extend the equivalence in Theorem 7.8 to λ -rich models. For that we need to weaken the notions of λ -universality and λ -homogeneity. This section is more technical and could be skipped at a first reading.

- 7.20 Definition** We say that a structure N is *weakly λ -homogeneous* if for every $b \in N$ every morphism $k : N \rightarrow N$ of cardinality $< \lambda$ extends to one defined in b . The term *back-and-forth λ -homogeneous* is also used. □

The following easy exercise on back-and-forth is required in the sequel.

- 7.21 Exercise** (Assume 7.4) Prove that any weakly λ -homogeneous structure of cardinality λ is homogeneous. □
- 7.22 Definition** We say that a structure N is *weakly λ -universal* if for every model M in the connected component of N and every $A \subseteq M$ of cardinality $< \lambda$ there is a morphism $k : M \rightarrow N$ such that $A \subseteq \text{dom } k$. □

- 7.23 Lemma** (Assume 7.4) Let N be a weakly λ -homogeneous model. Let $A \subseteq N$ have cardinality $\leq \lambda$ and let $k : N \rightarrow N$ be a morphism of cardinality $< \lambda$. Then there is a model $M \preceq N$ containing A and an automorphism $h : M \xrightarrow{\sim} M$ that extends k .

Proof Similar to the proof of Theorem 7.11. We shall construct simultaneously a chain $\langle A_i : i < \lambda \rangle$ of subsets of N and a chain functions $\langle h_i : i < \lambda \rangle$, such that $h_i : N \rightarrow N$ are morphisms. In the end we will set

$$M = \bigcup_{i < \lambda} A_i \quad \text{and} \quad h = \bigcup_{i < \lambda} h_i$$

The chains start with $A_0 = A \cup \text{dom } k \cup \text{img } k$ and $h_0 = k$. As usual, at limit stages we take the union. Now we consider successor stages. At stage i we fix

some enumerations of A_i and of $L_x(A_i)$, where $|x| = 1$. Let $\langle i_1, i_2 \rangle$ be the i -th pair of ordinals $< \lambda$. If the i_2 -th formula in $L_x(A_{i_1})$ is consistent in N , let a be any of its solutions. Also let b be the i_2 -th element of A_{i_1} . Let $h_{i+1} : N \rightarrow N$ be a minimal morphism that extends h_i and is such that $b \in \text{dom } h_{i+1} \cap \text{img } h_{i+1}$. Define $A_{i+1} = A_i \cup \{a, h_{i+1}b, h_{i+1}^{-1}b\}$. \square

7.24 Theorem (Assume 7.4) *For every model N the following are equivalent*

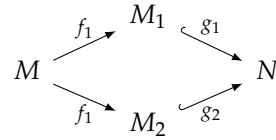
1. N is λ -rich;
2. N is weakly λ -universal and weakly λ -homogeneous.

Proof Implication $1 \Rightarrow 2$ is clear. To prove $2 \Rightarrow 1$ we generalize the proof of Theorem 7.8. We assume 2 fix some morphism $k : M \rightarrow N$ of cardinality $< \lambda$ and let $b \in M$. By weak λ -universality there is a morphism $f : M \rightarrow N$ with domain of definition $\text{dom } k \cup \{b\}$. The map $f \circ k^{-1} : N \rightarrow N$ has cardinality $< \lambda$ and, by Lemma 7.23, it has an extension to an automorphism $h : N' \xrightarrow{\sim} N'$ for some $N' \preceq N$ containing $\text{img } k \cup \text{img } f$. Then $h \circ f : M \rightarrow N$ extends k and is defined on b . \square

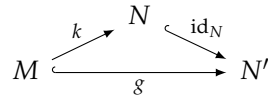
3 The amalgamation property

In this section we discuss conditions that ensure the existence of rich models.

We say that \mathcal{M} has the **amalgamation property** if for every pair of morphisms $f_1 : M \rightarrow M_1$ and $f_2 : M \rightarrow M_2$ there are two embeddings $g_1 : M_1 \hookrightarrow N$ and $g_2 : M_2 \hookrightarrow N$ such that $g_1 \circ f_1(a) = g_2 \circ f_2(a)$ for every a in the common domain of definition, $\text{dom}(f_1) \cap \text{dom}(f_2)$.



As we assume that morphisms are invertible, we may express the amalgamation property in a more concise form. Namely, for every morphism $k : M \rightarrow N$ there is morphism $g : M' \rightarrow N'$ such that the following diagram commutes



It is convenient to use the following terminology. We write $M \leq N$ for $M \subseteq N$ and $\text{id}_M : M \hookrightarrow N$ is a morphism. We say that $k : M \rightarrow N$ **extends to** $g : M' \rightarrow N'$ if $k \subseteq g$, $M \leq M'$, and $N \leq N'$.

7.25 Proposition *Assume c3, then the following are equivalent*

1. \mathcal{M} has the amalgamation property;
2. every morphism $k : M \rightarrow N$ extends to an embedding $g : M \hookrightarrow N'$.

Proof $1 \Rightarrow 2$ Given $k : M \rightarrow N$, the amalgamation property yields the following commutative diagram which can be simplified to the diagram at the right



Up to isomorphism we can assume $g_2 = \text{id}_M$, i.e. that $N \leq N'$. Hence $g_2 : M \hookrightarrow N'$ is the required extension of $k : M \rightarrow N$.

$2 \Rightarrow 1$ Let $f_1 : M \rightarrow M_1$ and $f_2 : M \rightarrow M_2$ be given. Let $k = f_2 \circ f_1^{-1} : M_1 \rightarrow M_2$ and let $g : M_1 \hookrightarrow N'$ be the extension ensured by 2. Then we obtain



as required. □

We say that $\langle M_i : i < \lambda \rangle$ is a **\leq -chain** if $M_i \leq M_j$ for all $i < j < \lambda$. For the next theorem to hold we need the following property:

7.26 Definition We say that \mathcal{M} is **closed under union of \leq -chains** if

c8. if $\langle M_i : i < \lambda \rangle$ is a \leq -chain, then $M_i \leq \bigcup_{j < \lambda} M_j$ for all $i < \lambda$. □

The following is a general existence theorem for rich models. This general form requires large cardinalities. We leave to the reader to verify that if the number of finite morphisms is countable (up to isomorphism) then countable rich models exist.

7.27 Theorem Assume 7.4. Assume further c8 and that \mathcal{M} has the amalgamation property. Let λ be such that $|L| < \lambda = \lambda^{<\lambda}$. Then there is a rich model N of cardinality λ .

Proof We construct N as union of a \leq -chain of models $\langle N_i : i < \lambda \rangle$ such that $|N_i| = \lambda$. Let N_0 be any model of cardinality λ . At stage $i + 1$, let $f : M \rightarrow N_i$ be the least morphism (in a well-ordering that we specify below) such that $|f| \leq |M| < \lambda$ and f has no extension to an embedding $f' : M \hookrightarrow N_i$. Apply the amalgamation property to obtain a total morphism $f' : M \hookrightarrow N'$ that extends $f : M \rightarrow N_i$. By the downward Löwenheim-Skolem Theorem we may assume $|N'| = \lambda$. Let $N_{i+1} = N'$. At limit stages take the union.

The well-ordering mentioned needs to be chosen so that in the end we forget nobody. So, first at each stage we well-order the isomorphism-type of the morphisms $f : M \rightarrow N_i$ such that $f \leq |M| < \lambda$. Then the required well-ordering is obtained by dovetailing all these well-orderings. The length of this enumeration is at most $\lambda^{<\lambda}$, which is λ by hypothesis.

We check that N is rich. Let $f : M \rightarrow N$ be a morphism and $|f| < |M| \leq \lambda$. As $|L| < \lambda$ we can approximate M with an elementary chain of structures of cardinality $< \lambda$. Hence we may as well assume that $|f| \leq |M| < \lambda$. The cofinality of λ is larger than $|f|$, hence $\text{img } f \subseteq N_i$ for some $i < \lambda$. So $f : M \rightarrow N_i$ is a morphism and at

some stage j we have ensured the existence of an embedding of $f' : M \hookrightarrow N_{j+1}$ that extends f . \square

7.28 Proposition *Let \mathcal{M} consist of all structures of some fixed signature and the elementary maps between these. Then \mathcal{M} has the amalgamation property.*

Proof Let $k : M \rightarrow N$ be an elementary map. Let a enumerate $\text{dom } k$ and let b enumerate M . Let $p(x; z) = \text{tp}_M(b; a)$. The type $p(x; a)$ is consistent in M , in particular, it is finitely consistent and, by elementarity, $p(x; ka)$ is finitely consistent in N . By the compactness theorem, there is $N' \succeq N$ such that $N' \models p(c; ka)$ for some $c \in N'^{|x|}$. Hence $g = \langle b, c \rangle : M \rightarrow N'$ is the required elementary map that extends $k : M \rightarrow N$. \square

Chapter 8

Some algebraic structures

The main result in this chapter is Corollary 8.26, the elimination of quantifiers in algebraically closed fields, which in algebra is called Chevalley's Theorem on constructible sets. From it we derive Hilbert's Nullstellensatz 8.26. Finally, we isolate the model theoretic properties of those types that correspond to the algebraic notions of prime and radical ideal of polynomials.

The first sections of this chapter are not a pre-requisite for Sections 4–7, at the cost of a few repetitions in the latter.

8.1 Notation Recall that when $A \subseteq M$ we denote by $\langle A \rangle_M$ the substructure of M generated by A . Then $\langle A \rangle_M \subseteq N$ is equivalent to $N \models \text{Diag} \langle A \rangle_M$. The diagram of a structure has been defined in Notation 5.20.

In this chapter, whenever some $A \subseteq M \models T$ are fixed, by *model* we mean superstructures of $\langle A \rangle_M$ that models T . The notions of *logical consequence*, *consistency*, *completeness*, etc. are modified accordingly, and we write \vdash for $T \cup \text{Diag} \langle A \rangle_M \vdash$.

We say that a type $p(x)$ is **trivial** if $\vdash p(x)$. □

1 Abelian groups

In this section the language L is that of additive groups. The theory T_{ag} of **abelian groups** is axiomatized by the universal closure of the following axioms

- a1 $(x + y) + z = y + (x + z)$;
- a2 $x + (-x) = (-x) + x = 0$;
- a3 $x + 0 = 0 + x = x$;
- a4 $x + y = y + x$.

Let x be a tuple of variables of length α , an ordinal. We write $L_{\text{ter},x}$ for the set of terms $t(x)$ with free variables among x . On this set we define the equivalence relation

$$t(x) \sim s(x) \quad = \quad T_{\text{ag}} \vdash t(x) = s(x).$$

We define the group operations on $L_{\text{ter},x}/\sim$ in the obvious way. We denote by $\mathbb{Z}^{\oplus \alpha}$ the set of tuples of integers of length α that are almost always 0. The group operations on $\mathbb{Z}^{\oplus \alpha}$ are defined coordinate-wise. The following immediate proposition implies in particular that $L_{\text{ter},x}/\sim$ is isomorphic to $\mathbb{Z}^{\oplus \alpha}$.

8.2 Proposition *Let $A \subseteq M \models T_{\text{ag}}$. Then for every formula $\varphi(x) \in L_{\text{at}}(A)$ there are $n \in \mathbb{Z}^{\oplus \alpha}$ and $c \in \langle A \rangle_M$ such that*

$$\vdash \varphi(x) \leftrightarrow \sum_{i < \alpha} n_i x_i = c.$$

where $n = \langle n_i : i < \alpha \rangle$ and $x = \langle x_i : i < \alpha \rangle$. \square

Proof Up to equivalence over T_{ag} the formula $\varphi(x)$ has the form $s(x) = t(a)$ for some parameter-free terms $s(x)$ and $t(z)$. Over $\text{Diag } \langle A \rangle_M$, we can replace $t(a)$ with a single $c \in \langle A \rangle_M$ and write $s(x)$ as the linear combination shown above. \square

8.3 Definition Let $M \models T_{\text{ag}}$. For $A \subseteq M$ and $c \in M$. We say that c is independent from A if $\langle A \rangle_M \cap \langle c \rangle_M = \{0\}$. Otherwise we say that c is dependent from A . The rank of M is the least cardinality of a subset $A \subseteq M$ such that all elements in M are dependent from A . We denote it by $\text{rank}(M)$. \square

Note that when M is a vector space the condition $\langle A \rangle_M \cap \langle c \rangle_M = \{0\}$ is equivalent to saying that c is not a linear combination of vectors in A . Then $\text{rank } M$ coincides with the dimension of M . In fact, what we do here for abelian groups could be easily generalized to D -modules, where D is any integral domain, and in particular to vector spaces.

The following proposition gives a convenient syntactic characterization of independence. An element c of a group is called **nilpotent**, or in abelian groups also a **torsion element**, if $c^n = 0$ for some n .

8.4 Proposition Let $A \subseteq M \models T_{\text{ag}}$. Let $c \in M$ be not a torsion element. Then the following are equivalent.

1. $\langle A \rangle_M \cap \langle c \rangle_M = \{0\}$;
2. $p(x) = \text{at-tp}_M(c/A)$ is trivial (see Notation 5.20 and 8.1).

Proof $1 \Rightarrow 2$ By Proposition 8.2, a non trivial formula in $p(x)$ may be assumed to have the form $nx = a$ for some n and some a . If such a formula is satisfied by c then $a \in \langle A \rangle_M \cap \langle c \rangle_M$. As c is not a torsion element, $n = 0$ and the equation is trivial.

$2 \Rightarrow 1$ If $\langle A \rangle_M \cap \langle c \rangle_M \neq \{0\}$ then $nc = a$ for some $a \in \langle A \rangle_M \setminus \{0\}$. Then c satisfies some non trivial equation $nx = a$. \square

8.5 Remark Let $k : M \rightarrow N$ be a partial embedding and let a be an enumeration of $\text{dom } k$. We claim that $k \cup \{ \langle b, c \rangle \} : M \rightarrow N$ is a partial embedding for every $b \in M$ and $c \in N$ that are independent from a , respectively ka . In fact, it suffices to check that $M, b, a \equiv_{\text{at}} N, c, ka$. Suppose $\varphi(x; z) \in L_{\text{at}}$ is such that $M \models \varphi(b; a)$. Then by independence $\varphi(x; a)$ is trivial, i.e.

$$T_{\text{ag}} \cup \text{Diag} \langle a \rangle_M \vdash \varphi(x; a).$$

As $\langle a \rangle_M$ and $\langle ka \rangle_N$ are isomorphic structures

$$T_{\text{ag}} \cup \text{Diag} \langle ka \rangle_N \vdash \varphi(x; ka).$$

Therefore $N \models \varphi(c; ka)$. The proof that $N \models \varphi(c; ka)$ implies $M \models \varphi(b; a)$ is similar. \square

2 Torsion-free abelian groups

The theory of **torsion-free abelian groups** extends T_{ag} with the following axioms for all positive integers n

st $nx = 0 \rightarrow x = 0$.

We denote this theory by T_{tfag} . It is not difficult to see that in a torsion-free abelian group every equation of the form $nx = a$ has at most one solution.

8.6 Proposition Let $M \models T_{\text{tfag}}$ be uncountable. Then $\text{rank } M = |M|$.

Proof Let $A \subseteq M$ have cardinality $< |M|$. We claim that M contains some element that is independent from A . It suffices to show that the number of elements that are dependent from A is $< |M|$. If $c \in M$ is dependent from A then, by Proposition 8.7, it is a solution of some formula $L_{\text{at}}(A)$. As there is no torsion, such a formula has at most one solution. Therefore the number of elements that are dependent from A is at most $|L_{\text{at}}(A)|$, that is $\max\{|A|, \omega\}$. If M is uncountable the claim follows. \square

8.7 Proposition Let $A \subseteq M \models T_{\text{tfag}}$. Let $p(x) = \text{at}^{\pm}\text{-tp}(b/A)$, where $b \in M$. Then one of the following holds:

1. b is independent from A ;
2. $M \models \varphi(b)$ for some $\varphi(x) \in L_{\text{at}}(A)$ such that $\vdash \varphi(x) \rightarrow p(x)$.

Note the similarity with Example 7.15, where the independent type is $q(x)$ and the isolating formulas are the $r_i(x)$.

It is important to observe that the set A above may be infinite. This is essential to obtain Corollary 8.11, and it is one of the main differences between this example and the examples encountered in Chapter 6.

Proof If b is dependent from A , then b satisfies a non trivial atomic formula $\varphi(x)$ which we claim is the formula required in 2. It suffices to show that $\varphi(x)$ implies a complete $L_{\text{at}^{\pm}}(A)$ -type. Clearly this type must be $p(x)$. Let $\varphi(x)$ have the form $nx = a$ for some $n \in \mathbb{Z} \setminus \{0\}$ and $a \in \langle A \rangle_M \setminus \{0\}$. We show that for every $m \in \mathbb{Z}$ and every $c \in \langle A \rangle_M$ one of the following holds

- a. $\vdash nx = a \rightarrow mx = c$;
- b. $\vdash nx = a \rightarrow mx \neq c$.

Suppose not for a contradiction that neither a nor b holds and fix models N_1, N_2 and some $b_i \in N_i$ such that

- a'. $N_1 \models nb_1 = a$ and $N_1 \models mb_1 \neq c$;
- b'. $N_2 \models nb_2 = a$ and $N_2 \models mb_2 = c$.

From b' we obtain $N_2 \models ma = nc$. As N_1 is torsion-free, from a' we obtain $N_1 \models ma \neq nc$. But $ma = nc$ is a formula with parameters in $\langle A \rangle_M$, so it should have the same truth value in all superstructures of $\langle A \rangle_M$, a contradiction. \square

3 Divisible abelian groups

The theory of **divisible abelian groups** extends T_{tfag} with the following axioms for all integers $n \neq 0$

$\text{div } y \neq 0 \rightarrow \exists x \, nx = y$.

We denote this theory by T_{dag} .

8.8 Proposition Let $A \subseteq M \models T_{\text{tfag}}$ and let $\varphi(\mathbf{x}) \in L_{\text{at}}(A)$, where $|\mathbf{x}| = 1$, be consistent. Then $N \models \exists \mathbf{x} \varphi(\mathbf{x})$ for every model $N \models T_{\text{dag}}$.

Note that in the proposition above *consistent* means satisfied in some M' such that $\langle A \rangle_M \subseteq M' \models T_{\text{tfag}}$.

The claim in the proposition holds more generally for all $\varphi(\mathbf{x}) \in L_{\text{qf}}$ and also when \mathbf{x} is a tuple of variables. This follows from Lemma 8.10, whose proof uses the proposition.

Proof We can assume that $\varphi(\mathbf{x})$ has the form $n\mathbf{x} = \mathbf{a}$ for some $n \in \mathbb{Z}$ and some $\mathbf{a} \in \langle A \rangle_M$. If $n = 0$, then $\mathbf{a} = 0$ since $\varphi(\mathbf{x})$ is consistent, and the claim is trivial. If $n \neq 0$ then by consistency $\mathbf{a} \neq 0$, hence a solution exist in N by axiom *div*. \square

8.9 Exercise Prove a converse of Proposition 8.8. Let $A \subseteq N \models T_{\text{ag}}$ and let \mathbf{x} be a single variable. Prove that if $N \models \exists \mathbf{x} \varphi(\mathbf{x})$ for every consistent $\varphi(\mathbf{x}) \in L_{\text{at}}(A)$, then $N \models T_{\text{dag}}$. \square

We are ready to prove that divisible abelian groups of infinite rank are ω -rich.

8.10 Lemma Let $k : M \rightarrow N$ be a partial isomorphism of cardinality $< \lambda$, where $M \models T_{\text{tfag}}$ and $N \models T_{\text{dag}}$ is a model of rank $\geq \lambda$. Then for every $\mathbf{b} \in M$ there is $\mathbf{c} \in N$ such that $k \cup \{ \langle \mathbf{b}; \mathbf{c} \rangle \} : M \rightarrow N$ is a partial isomorphism.

Proof Let \mathbf{a} be an enumeration of $\text{dom } k$ and let $p(\mathbf{x}; \mathbf{z}) = \text{at}^\pm\text{-tp}(\mathbf{b}; \mathbf{a})$. The required \mathbf{c} has to realize $p(\mathbf{x}; k\mathbf{a})$. We consider two cases. If \mathbf{b} is dependent from \mathbf{a} , then Proposition 8.7 yields a formula $\varphi(\mathbf{x}; \mathbf{z}) \in L_{\text{at}}$ such that

- i. $\vdash \varphi(\mathbf{x}; \mathbf{a}) \rightarrow p(\mathbf{x}; \mathbf{a})$
- ii. $\varphi(\mathbf{x}; \mathbf{a})$ is consistent.

By isomorphism, i and ii hold with \mathbf{a} replaced by $k\mathbf{a}$. Then by Proposition 8.8 the formula $\varphi(\mathbf{x}; k\mathbf{a})$ has a solution $\mathbf{c} \in N$.

The second case, which has no analogue in Lemma 6.1, is when \mathbf{b} is independent from \mathbf{a} . Then by Remark 8.5 we may choose \mathbf{c} to be any element of N independent from $k\mathbf{a}$. Such an element exists because N has rank at least λ . \square

8.11 Corollary Every uncountable model of T_{dag} is rich in the category of models of T_{tfag} and partial isomorphisms. In particular T_{dag} is uncountably categorical, complete, and has quantifier elimination.

Proof Any uncountable $N \models T_{\text{dag}}$ has rank $|N|$, therefore it is rich by Lemma 8.10; categoricity and completeness follow. As for quantifier elimination, let $k : M \rightarrow N$ is a partial isomorphism between models of T_{dag} . If $M \preceq M'$ and $M \preceq N'$ are elementary superstructures of uncountable cardinality then $k : M' \rightarrow N'$ is elementary by Theorem 7.11 and this suffices to conclude that $k : M \rightarrow N$ is elementary. \square

8.12 Exercise Prove that every model of T_{dag} is ω -ultraomogeneous (independently of cardinality and rank). \square

4 Commutative rings

In this section L is the **language of (unital) rings**. It contains two constants 0 and 1 the unary operation $-$ and two binary operations $+$ and \cdot . The theory of rings contains the following axioms

a1-a4 as for abelian groups

$$r1 \quad (x \cdot y) \cdot z = y \cdot (x \cdot z),$$

$$r2 \quad 1 \cdot x = x \cdot 1 = x,$$

$$r3 \quad (x + y) \cdot z = x \cdot z + y \cdot z,$$

$$r4 \quad z \cdot (x + y) = z \cdot x + z \cdot y.$$

All the rings we consider are **commutative**

$$c \quad x \cdot y = y \cdot x.$$

We denote the theory of commutative rings by T_{cr} .

In what follows the theory $T_{cr} \cup \text{Diag}\langle A \rangle_M$, for some M clear from the context, is implicit in the sense of Notation 8.1. So it is important to remember that $\text{Diag}\langle A \rangle_M$ is not trivial even when $A = \emptyset$. In fact, $\text{Diag}\langle \emptyset \rangle_M$ determines the characteristic of the models.

Let $A \subseteq M \models T_{cr}$ and let \mathbf{x} be a tuple of variables. We write $L_{\text{ter},\mathbf{x}}(A)$ for the set of terms $t(\mathbf{x})$ with free variables among \mathbf{x} and parameters in A . On this set we define the equivalence relation

$$t(\mathbf{x}) \sim s(\mathbf{x}) \quad = \quad \vdash \quad t(\mathbf{x}) = s(\mathbf{x}).$$

On $L_{\text{ter},\mathbf{x}}(A)/\sim$ we define the ring operations in the obvious way so that $L_{\text{ter},\mathbf{x}}(A)/\sim$ is a commutative ring. We denote by $A[\mathbf{x}]$ the set of polynomials with variables among \mathbf{x} and parameters in $\langle A \rangle_M$. The ring operations on $A[\mathbf{x}]$ are defined as usual. The following proposition (which is clear, but tedious to prove) implies in particular that $L_{\text{ter},\mathbf{x}}(A)/\sim$ is isomorphic to $A[\mathbf{x}]$. For simplicity we state it only for $|\mathbf{x}| = 1$.

8.13 Proposition *Let $A \subseteq M \models T_{cr}$ and let x be a single variable. Then for every formula $\varphi(x) \in L_{\text{at}}(A)$ there is a unique $n < \omega$ and a unique tuple $\langle a_i : i \leq n \rangle$ of elements of $\langle A \rangle_M$ such that $a_n \neq 0$ and*

$$\vdash \quad \varphi(x) \leftrightarrow \sum_{i \leq n} a_i x^i = 0. \quad \square$$

The integer n in the proposition above is called the **degree of $\varphi(x)$** .

8.14 Definition *Let $A \subseteq M \models T_{cr}$. We say that an element $b \in M$ is **transcendent over A** if the type $p(\mathbf{x}) = \text{at-tp}_M(b/A)$ is trivial (see Notation 5.20 and 8.1). Otherwise we say that b is **algebraic over A** . The **transcendence degree** of M is the least cardinality of a subset $A \subseteq M$ such that all elements of M are algebraic over A .* \square

8.15 Remark Remark 8.5 holds here with ‘independent’ replaced by ‘transcendent’ and T_{ag} replaced by T_{cr} . \square

5 Integral domains

Let $a \in M \models T$. We say that a is a **zero divisor** if $ab = 0$ for some $b \in M \setminus \{0\}$. An **integral domain** is a commutative ring without zero divisors. The theory of integral domains contains the axioms of commutative rings and the following

nt. $0 \neq 1$

id. $x \cdot y = 0 \rightarrow x = 0 \vee y = 0$.

We denote the theory of integral domains by T_{id} .

For a prime p , we define the theory T_{id}^p , which contains T_{id} and the axiom

ch $_p$. $1 + \dots (p \text{ times}) \dots + 1 = 0$.

The theory T_{id}^0 contains the negation of ch $_p$ for all p . Note that all models of T_{id}^p have the same characteristic in the model theoretic sense defined in 5.27. In the remaining section we work in the category of models of T_{id} with partial embeddings as morphisms. This category consists of countably many connected components each containing all models of T_{id}^p for some p .

8.16 Proposition *Let $M \models T_{\text{id}}$ be uncountable. Then M has transcendence degree $|M|$.*

Proof In an integral domain every polynomial has finitely many solutions and there are $|L(A)|$ polynomials over A . \square

8.17 Proposition *Let $A \subseteq M \models T_{\text{id}}$. For $b \in M$ let $p(x) = \text{at}^\pm\text{-tp}(b/A)$. Then one of the following holds*

1. b is transcendental over A ;
2. $M \models \varphi(b)$ for some $\varphi(x) \in L_{\text{at}}(A)$ such that $\vdash \varphi(x) \rightarrow p(x)$.

Note the similarity with Example 7.15, where the transcendental type is $q(x)$ and the isolating formulas are the $r_i(x)$.

As in Proposition 8.7, the set A may be infinite. This is essential to obtain Corollary 8.22.

Proof Suppose b is not transcendental, i.e. it satisfies a non trivial atomic formula. Let $\varphi(x) \in L_{\text{at}}(A)$ be a non trivial formula with minimal degree such that $\varphi(b)$. We prove that $\varphi(x)$ implies a complete $L_{\text{at}}^\pm(A)$ -type. Clearly this type must be $p(x)$. We prove that for any $\zeta(x) \in L_{\text{at}}(A)$ one of the following holds

1. $\vdash \varphi(x) \rightarrow \zeta(x)$
2. $\vdash \varphi(x) \rightarrow \neg\zeta(x)$.

Let us write $a(x) = 0$ and $a'(x) = 0$ for the formulas $\varphi(x)$ and $\zeta(x)$, respectively. Let n be the degree of the polynomial $a(x)$. If $\langle A \rangle_M$ is a field, choose a polynomial $d(x)$ of maximal degree such that

- a. $d(x)t(x) = a(x)$
- a'. $d(x)t'(x) = a'(x)$,

for some polynomials $t(x)$ and $t'(x)$.

If $\langle A \rangle_M$ is not a field, polynomials $d(x)$, $t(x)$ and $t'(x)$ as above exist with coeffi-

cients in the field of fractions of $\langle A \rangle_M$. Then a and a' hold up to a factor in $\langle A \rangle_M$ which we absorb in $a(x)$ and $a'(x)$.

From a we get $d(b) = 0$ or $t(b) = 0$. In the first case, as $a(x)$ has minimal degree, we conclude that $t(x)$ is constant. This implies that any zero of $a(x)$ is also a zero of $a'(x)$, that is, it implies 1.

Now suppose $t(b) = 0$. Then the minimality of the degree of $a(x)$ implies that $d(x) = d$, where d is a nonzero constant. If $\langle A \rangle_M$ is a field, apply Bézout's identity to obtain two polynomials $c(x)$ and $c'(x)$ such that $d = a(x)c(x) + a'(x)c'(x)$. Then $a(x)$ and $a'(x)$ have no common zeros, and 2 follows. If $\langle A \rangle_M$ is not a field, we use Bézout's identity in the field of fractions of $\langle A \rangle_M$ and, for some $d' \in \langle A \rangle_M \setminus \{0\}$, obtain $d'd = a(x)c(x) + a'(x)c'(x)$. Then we reach the same conclusion. \square

6 Algebraically closed fields

Let $a, b \in M \models T_{\text{id}}$. We say that b is the **inverse** of a if $a \cdot b = 1$. A field is a commutative ring where every non-zero element has an inverse. The **theory of fields** contains T_{id} and the axiom

$$\text{f. } \exists y [x \neq 0 \rightarrow x \cdot y = 1].$$

Fields are structures in the signature of rings: the language contains no symbol for the multiplicative inverse. So, substructures of fields are merely integral domains.

The theory of **algebraically closed field**, which we denote by T_{acf} , also contains the following axioms for every positive integer n

$$\text{ac. } \exists x (x^n + z_{n-1}x^{n-1} + \dots + z_1x + z_0 = 0)$$

The theory T_{acf}^p is defined in analogy to T_{id}^p in the previous section.

8.18 Proposition Let $A \subseteq M \models T_{\text{id}}$ and let $\varphi(x) \in L_{\text{at}}(A)$, where $|x| = 1$, be consistent. Then $N \models \exists x \varphi(x)$ for every model $N \models T_{\text{acf}}$.

Note that in the proposition above *consistent* means satisfied in some M' such that $\langle A \rangle_M \subseteq M' \models T_{\text{id}}$.

The claim in the proposition holds more generally for all $\varphi(x) \in L_{\text{qf}}$ when x is a tuple of variables. This follows from Lemma 8.19 whose proof uses the proposition.

Proof Up to equivalence $\varphi(x)$ has the form $a_n x^n + \dots + a_1 x + a_0 = 0$ for some $a_i \in \langle A \rangle_N$. Choose n minimal. If $n = 0$ then $a_0 = 0$ by the consistency of $\varphi(x)$ and the claim is trivial. Otherwise $a_n \neq 0$ and the claim follows from f and ac. \square

8.19 Lemma Let $k : M \rightarrow N$ be a partial isomorphism of cardinality $< \lambda$, where $M \models T_{\text{id}}$ and $N \models T_{\text{acf}}$ has transcendence degree $\geq \lambda$. Then for every $b \in M$ there is $c \in N$ such that $k \cup \{ \langle b, c \rangle \} : M \rightarrow N$ is a partial isomorphism.

The following is the proof of Lemma 8.10 which we repeat here for convenience.

Proof Let a be an enumeration of $\text{dom } k$ and let $p(x; z) = \text{at}^\pm\text{-tp}_M(b; a)$. The required c has to realize $p(x; ka)$. We consider two cases. If b is algebraic over a , then Proposition 8.17 yields a formula $\varphi(x; z) \in L_{\text{at}}$ such that

$$\text{i. } \varphi(x; a) \rightarrow p(x; a)$$

ii. $\varphi(x; a)$ is consistent.

By isomorphism i and ii hold with a replaced by ka . Then by Proposition 8.18 the formula $\varphi(x; ka)$ has a solution in $c \in N$.

The second case, which has no analogue in Lemma 6.1, is when b is transcendent over a . Then by Remark 8.15 we may choose c to be any element of N transcendent over ka . This exists because N has transcendence degree $\geq \lambda$. \square

Below few important consequences of this lemma.

8.20 Corollary *Work in the category of models of T_{id} with partial embeddings as morphisms. Then the following are equivalent.*

1. N is a λ -rich model
2. $N \models T_{\text{acf}}$ and has transcendence degree $\geq \lambda$

Proof Implication $2 \Rightarrow 1$ is an immediate consequence of Lemma 8.19.

In every connected component there is an $M \models T_{\text{acf}}$ of cardinality λ and transcendence degree λ (by Proposition 8.16 when $\lambda > \omega$, by compactness for $\lambda = \omega$). As proved above, M is rich and therefore elementarily equivalent to any λ -rich model N in the same connected component. This proves $1 \Rightarrow 2$. \square

8.21 Corollary *The theory T_{acf} has elimination of quantifiers.*

Proof Let $k : M \rightarrow N$ be a partial embedding between models of T_{acf} . Let M' and N' be elementary superstructures of M and N respectively of sufficiently large cardinality. As M' and N' are rich, $k : M' \rightarrow N'$ is elementary by Theorem 7.11. Hence $k : M \rightarrow N$ is also elementary. \square

8.22 Corollary *The theories T_{acf}^p are complete and uncountably categorical (i.e. λ -categorical for every uncountable λ)*

Proof Two models of T_{acf}^p belong to the same connected component. Then, as every uncountable model of T_{acf}^p is rich, uncountable categoricity and completeness follow. \square

8.23 Exercise Prove that every model of T_{acf} is ω -ultrahomogeneous (independently of cardinality and transcendence degree). \square

7 Hilbert's Nullstellensatz

In this section we fix a tuple of variables x and a subset A of an integral domain. We denote by $\Delta(A)$ the set of formulas of the form $t(x) = 0$ where $t(x)$ is a term with parameters in A . So $\Delta(A)$ -types are (possibly infinite) systems of polynomial equations with coefficients in $\langle A \rangle_M$.

For convenience we define the closure of $p(x)$ under logical consequences as follows

$$\text{ccl } p(x) = \{t(x) = 0 : p(x) \vdash t(x)=0\}$$

Remember that we always work under the assumptions made in Notation 8.1. In particular, in this section we work over the theory $T_{\text{id}} \cup \text{Diag}\langle A \rangle_M$. In general,

closure under logical consequences is an elusive notion. Hence Propositions 8.24 and 8.25 are useful because they give a model theoretical, respectively algebraic, characterisation of $\text{ccl } p(x)$.

8.24 Proposition *Let $A \subseteq M \models T_{\text{id}}$ and let $p(x)$ be a $\Delta(A)$ -type. Fix some N of sufficiently large cardinality such that $\langle A \rangle_M \subseteq N \models T_{\text{acf}}$. Then*

$$\text{ccl } p(x) = \left\{ t(x) = 0 : N \models \forall x [p(x) \rightarrow t(x)=0] \right\}.$$

The cardinality of N is the proposition is sufficiently large when $|A| < |N|$ and $|x| \leq |N|$; note that here x has possibly infinite length. In Corollary 8.26 below we will considerably strengthen this proposition for finite x .

Proof Only the inclusion \supseteq requires a proof, then suppose $t(x)=0 \notin \text{ccl } p(x)$. As $p(x) \wedge t(x) \neq 0$ is consistent, there is a model M' such that $M' \models p(a) \wedge t(a) \neq 0$ for some $a \in M'^{|x|}$. Then there is a partial isomorphism $h : M' \rightarrow N$ that extends id_A and is defined on a , provided N is large enough to accommodate a . This implies that $p(x) \wedge t(x) \neq 0$ has a solution in N . Hence $t(x)$ does not belong to the set on the r.h.s. \square

Recall that $A[x]$ denotes the ring of polynomials with variables in x and coefficients in $\langle A \rangle_M$. We identify $\Delta(A)$ and $A[x]$ in the obvious way. Consequently, a $\Delta(A)$ -type $p(x)$ is identified with a set of polynomials $p \subseteq A[x]$. For $p \subseteq A[x]$ we write $\text{rad } p$ for the **radical ideal generated by p** , that is, the intersection of all prime ideals containing p . When $p = \text{rad } p$, we say that **p is a radical ideal**. Recall from algebra that if $p \subseteq A[x]$ is an ideal then

$$\# \quad \text{rad } p = \left\{ t(x) : t^n(x) \in p \text{ for some positive integer } n \right\}.$$

An identity that justifies the name.

8.25 Proposition *Let $A \subseteq M \models T_{\text{id}}$ and let $p(x)$ be a $\Delta(A)$ -type. Then $\text{ccl } p(x) \simeq \text{rad } p$.*

The proposition holds with a similar proof for the broader class of rings without nilpotent elements. (Which does not come as a surprise.)

Proof (\supseteq) We claim that $\text{ccl } p(x)$ is an ideal. In fact, for every pair of $L(A)$ -terms $t(x)$ and $s(x)$

$$\begin{aligned} t(x) = 0 &\vdash s(x)t(x) = 0 \\ s(x) = t(x) = 0 &\vdash s(x) + t(x) = 0 \end{aligned}$$

Moreover, as integral domains do not have nilpotent elements

$$t^n(x) = 0 \vdash t(x) = 0$$

By # above, $\text{ccl } p(x)$ is a radical ideal which proves $\text{ccl } p(x) \supseteq \text{rad } p$.

(\subseteq) We fix some $t(x) \notin \text{rad } p$ and prove that $p(x) \wedge t(x) \neq 0$ is consistent. Let q be some prime ideal containing p such that $t(x) \notin q$. As q is prime, the ring $A[x]/q$ is an integral domain. The polynomials that vanish in $A[x]/q$ at $x + q$ are exactly those in q . Hence $A[x]/q$ witnesses the consistency of $q(x) \wedge t(x) \neq 0$. \square

When x is a finite tuple of variables, we can extend the validity of Proposition 8.24 to the case $A = M = N$.

8.26 Corollary (Hilbert's Nullstellensatz) Let $N \models T_{\text{acf}}$ and let $p(x)$, where $|x| < \omega$, be a $\Delta(N)$ -type. Then

$$\text{rad } p \simeq \text{ccl } p(x) = \left\{ t(x) : N \models \forall x [p(x) \rightarrow t(x) = 0] \right\}.$$

Proof Let N' be a large elementary extension of N . By Proposition 8.24, the claim holds for N' . By Hilbert's Basis Theorem, the ideal generated by p is finitely generated hence $p(x)$ is equivalent to a formula (cfr. Exercise 8.29). Therefore, by elementarity, the claim holds for N . \square

Hilbert's Nullstellensatz comes in two variants. The one in Corollary 8.26 is sometimes referred to as the *strong* Nullstellensatz. The weaker variant is stated in Exercise 8.28.

We conclude this section by showing that the notions of primeness for types and ideals coincide (if we restrict to types closed under logical consequences).

8.27 Proposition Let $A \subseteq M \models T_{\text{id}}$ and let $p(x)$ be a $\Delta(A)$ -type closed under logical consequences. Then the following are equivalent

1. $p(x)$ is a prime $\Delta(A)$ -type;
2. p is a prime ideal.

Proof $1 \Rightarrow 2$ Assume 1 and suppose that the polynomial $t(x) \cdot s(x)$ belongs to p . Clearly, over $T_{\text{id}} \cup \text{Diag}(A)_M$ we have $\vdash t(x) \cdot s(x) = 0 \rightarrow t(x) = 0 \vee s(x) = 0$. As $p(x)$ is a prime $\Delta(A)$ -type, $p(x) \vdash t(x) = 0$ or $p(x) \vdash s(x) = 0$. By Proposition 8.25, the type $p(x)$ is closed under logical consequences, therefore $t(x) \in p$ or $s(x) \in p$.

$2 \Rightarrow 1$ Assume p is a prime ideal and for some $t_i(x) = 0 \in \Delta(A)$

$$p(x) \vdash \bigvee_{i=1}^n t_i(x) = 0.$$

Then

$$p(x) \vdash \prod_{i=1}^n t_i(x) = 0$$

Since $p(x)$ is closed under logical consequences, and p is a prime ideal, $t_i(x) \in p$ for some i . Hence $p(x)$ contains the equation $t_i(x) = 0$. By Corollary 5.19 this suffices to prove that $p(x)$ is a prime $\Delta(A)$ -type. \square

8.28 Exercise Let $N \models T_{\text{acf}}$ and let $p(x)$ be a $\Delta(N)$ -type where $|x| < \omega$. Prove that the following are equivalent

1. p is a proper ideal;
2. $p(x)$ has a solution in N .

\square

8.29 Exercise Let $A \subseteq M \models T_{\text{id}}$ and let $p(x)$ be a $\Delta(A)$ -type. Prove that the following are equivalent

1. $p(x)$ is a principal $\Delta(A)$ -type;
2. the ideal generated by p is finitely generated.

\square

Chapter 9

Saturation and homogeneity

The first two sections introduce saturation and homogeneity and Section 3 presents the notation we shall use in the following chapters when working inside a monster model.

1 Saturated structures

Recall that a type $p(\mathbf{x}) \subseteq L(M)$ is **finitely consistent in M** if every $\varphi(\mathbf{x})$, conjunction of formulas in $p(\mathbf{x})$, has a solution in M . When $A \subseteq M$ we write $S_{\mathbf{x}}(A)$ for the set of types that are complete and finitely consistent in M . We never display M in the notation as it will always be clear from the context. When A is empty it is usual to write $S_{\mathbf{x}}(T)$ for $S_{\mathbf{x}}(A)$ where $T = \text{Th}(M)$. We write $S(A)$ for the union of $S_{\mathbf{x}}(A)$ as \mathbf{x} ranges over all tuples of variables. Similarly for $S(T)$.

The following remark will be used in the sequel without explicit reference.

9.1 Remark Let $k : M \rightarrow N$ be an elementary map and let \mathbf{a} be an enumeration of $\text{dom } k$. If $p(\mathbf{x}; \mathbf{a})$ is finitely consistent in M , then $p(\mathbf{x}; k\mathbf{a})$ is finitely consistent in N . (We can drop *finitely* in the antecedent but not in the consequent.) \square

9.2 Definition Let \mathbf{x} be a single variable and let λ be an infinite cardinal. We say that a structure N is **λ -saturated** if it realizes every type $p(\mathbf{x})$ such that

1. $p(\mathbf{x}) \subseteq L(A)$ for some $A \subseteq N$ of cardinality $< \lambda$;
2. $p(\mathbf{x})$ is finitely consistent in N .

We say that N is **saturated** if it is λ -saturated and $|N| = \lambda$.

9.3 Exercise Suppose $|L| \leq \omega$ and let M be an infinite structure. Then for every non-principal ultrafilter F on ω the structure M^ω/F is a ω_1 -saturated elementary superstructure of M .

Hint: the notation is as in Chapter 3. Let $|x| = 1$ and $|z| = \omega$. It suffices to consider the types of form $p(x; \hat{c})$ where $p(x; z) = \{\varphi_i(x; z) : i < \omega\} \subseteq L$ and $\hat{c} \in (M^\omega)^{|z|}$. Without loss of generality we can also assume that $\varphi_{i+1}(x; z) \rightarrow \varphi_i(x; z)$, and that all formulas $\varphi_i(x; \hat{c})$ are consistent in M^ω .

Let $\langle X_i : i < \omega \rangle$ be a strictly decreasing chain of elements of the ultrafilter such that $X_{i+1} \subseteq \{j : M \models \exists x \varphi_i(x, \hat{c}_j)\}$. Let $\hat{a} \in M^\omega$ be such that $\varphi_i(\hat{a}_j, \hat{c}_j)$ holds for every $j \in X_i \setminus X_{i+1}$. Then \hat{a} realizes $p(x)$. \square

9.4 Theorem Assume $|L| < \lambda$ where λ is such that $\lambda^{<\lambda} = \lambda$. Then every structure M of cardinality λ has a saturated elementary extension of cardinality λ .

Proof We construct an elementary chain $\langle M_i : i < \lambda \rangle$ of models of cardinality λ . The chain starts with M and is the union at limit stages. Given M_i we choose as

M_{i+1} any model of cardinality λ that realizes all types in $S_x(A)$ for all $A \subseteq M_i$ of cardinality $< \lambda$. The required M_{i+1} exists because there are $2^{|L(A)|} \leq \lambda$ types in $S_x(A)$ and there are $\lambda^{<\lambda} = \lambda$ sets A .

Let N be the union of the chain. We check that N is the required extension. Let $p(x) \in S(A)$ for some $A \subseteq N$ of cardinality $< \lambda$. As λ is a regular cardinal, $A \subseteq M_i$ for some $i < \lambda$. Then M_{i+1} realizes $p(x)$, and so does N , by elementarity. \square

9.5 Theorem Assume $|L| \leq \lambda$ and let N be an infinite structure. Let \mathcal{M} be the category (see Section 7.1) that consists of models of a complete theory T and elementary maps between these. Then the following are equivalent

- 1 N is a λ -saturated structure;
- 2 N is a λ -rich model;
- 3 N realizes all types $p(z) \subseteq L(A)$, with $|z| \leq \lambda$ and $|A| < \lambda$, finitely consistent in N .

Note that it is the completeness of T which makes the category \mathcal{M} connected.

Proof $1 \Rightarrow 2$. Let $k : M \rightarrow N$ be an elementary map of cardinality $< \lambda$. It suffices to show that for every $b \in M$ there is a $c \in N$ such that $k \cup \{ \langle b, c \rangle \} : M \rightarrow N$ is an elementary map. Let a be an enumeration of $\text{dom } k$ and define $p(x; z) = \text{tp}_M(b; a)$. The required c is any element of N such that $N \models p(c; k a)$. As $p(x; a)$ is finitely consistent in M then $p(x; k a)$ is finitely consistent in N . As $|a| < \lambda$, saturation yields the required c .

$2 \Rightarrow 3$. Let $p(z)$ be as in 3. By the compactness theorem $N \preceq K \models p(a)$ for some model K and $a \in K^{|z|}$. By the downward Löwenheim-Skolem theorem there is a model $A, a \subseteq M \preceq K$ of cardinality $\leq \lambda$. (Here we use $|L|, |A|, |z| \leq \lambda$.) By 2, there is an elementary embedding $h : M \hookrightarrow N$ that extends id_A . Finally, as $M \models p(a)$, elementarity yields $N \models p(h a)$.

$3 \Rightarrow 1$. Trivial. \square

Two saturated structures of the same cardinality are isomorphic as soon as they are elementarily equivalent (i.e. as soon as $\emptyset : M \rightarrow N$ is an elementary map.) In fact, from Theorem 9.5 and 7.6 we obtain the following.

9.6 Corollary Every elementary map $k : M \rightarrow N$ of cardinality $< \lambda$ between saturated models of the same cardinality λ extends to an isomorphism. \square

As it turns out, we already have many examples of saturated structures.

9.7 Corollary The following models are ω -saturated

- 1 models of T_{dlo} ;
- 2 models of T_{rg} ;
- 3 models of T_{dag} with infinite rank;
- 4 models of T_{acf} with infinite degree of transcendence.

Countable models of T_{dlo} and T_{rg} and uncountable models of T_{dag} or T_{acf} are saturated.

Proof By quantifier elimination embeddings coincide with elementary embeddings. Then saturation is proved applying Theorem 9.5 and the extension lemmas proved

in Chapter 6 and 8. □

The following is a useful test for quantifier elimination.

9.8 Theorem Assume $|L| \leq \lambda$. Consider the category that consists of models of some theory T_0 and partial isomorphism. Suppose λ -rich models exist and denote by T_1 their theory. Then the following are equivalent

1. every λ -saturated model of T_1 is λ -rich;
2. T_1 has elimination of quantifiers.

Proof $2 \Rightarrow 1$. Let $N \models T_1$ be λ -saturated. Fix a morphism $k : M \rightarrow N$ of cardinality $< \lambda$, some $b \in M$ and let $p(x; z) = \text{qf-tp}_M(b; a)$, where a enumerates $\text{dom } k$. The type $p(x; k a)$ is realized in any λ -rich model N' that contains $\langle k a \rangle_N$. By 2, $N \equiv_{ka} N'$, so $p(x; k a)$ is finitely consistent in N . By saturation, it is realised by some $c \in N$. Then $k \cup \{ \langle b, c \rangle \} : M \rightarrow N$ is the required extension.

$1 \Rightarrow 2$. Let $k : M \rightarrow N$ be a finite partial isomorphism between models of T . We claim that it is an elementary map. Let $M' \succeq M$ and $N' \succeq N$ be λ -saturated models of equal cardinality. As these are λ -rich, $k : M' \rightarrow N'$ extends to an isomorphism $h : M' \xrightarrow{\sim} N'$ and the claim follows. □

2 Homogeneous structures

Definition 7.3 introduces the notion of universal and homogeneous structures in the general context. When the morphisms of the underlying category are the elementary maps we refer to these notions as elementary homogeneity and elementary universality. Though one often omits to specify *elementary*. We repeat the definition in this particular case.

9.9 Definition A structure N is (elementarily) λ -universal if every $M \equiv N$ of cardinality $\leq \lambda$ there is a elementary embedding $h : M \hookrightarrow N$. We say universal if it is λ -universal and of cardinality λ .

We say that N is (elementarily) λ -homogeneous if every elementary map $k : N \rightarrow N$ of cardinality $< \lambda$ extends to an automorphism. We say that N is homogeneous if it is λ -homogeneous and of cardinality λ . □

As saturated structures are rich, the following theorem is an instance of Theorem 7.8.

9.10 Theorem For every structure N of cardinality $\geq |L|$ the following are equivalent

1. N is saturated;
2. N is elementarily universal and homogeneous. □

Given $A \subseteq N$ we denote by $\text{Aut}(N/A)$ the group of A -automorphisms of N . That is the group of automorphisms that fix A point-wise. Let a be a tuple of elements of N . The orbit of a over A in N is the set

$$O_N(a/A) = \{ f a : f \in \text{Aut}(N/A) \}$$

When the model N is clear from the context we omit the subscript.

Orbits are particularly interesting if taken in a homogeneous structure. The following proposition is immediate but its importance cannot be overestimated.

9.11 Proposition *Let N be a λ -homogeneous structure. Let $A \subseteq N$ have cardinality $< \lambda$ and let $a \in N^{<\lambda}$. Then $O_N(a/A) = p(N)$, where $p(x) = \text{tp}_N(a/A)$.* \square

Finally, we want to extend the equivalence in Theorem 9.10 to λ -saturated structures. For this we only need to apply Theorem 7.24.

When the morphisms of the underlying category are the elementary maps, we say **weakly λ -saturated** for weakly λ -universal (cfr. Definition 7.22). This is not the standard definition (i.e. 2 of the proposition below) but the reader can easily verify that it is equivalent by reasoning as in the proof of theorem 9.5.

9.12 Proposition *The following are equivalent*

1. N weakly λ -saturated;
2. N realizes every type $p(x) \subseteq L$, where $|x| < \lambda$, that is finitely consistent in N . \square

The following is an instance of Theorem 7.24 that the reader may prove directly as an exercise.

9.13 Corollary *Let $|L| \leq \lambda$. The following are equivalent*

1. N is λ -saturated;
2. N is weakly λ -saturated and weakly λ -homogeneous. \square

9.14 Exercise Let M be an arbitrary structure. Prove that M has an ω -homogeneous elementary extension of the same cardinality. (There is no assumption on the cardinality of the language.) \square

9.15 Exercise Let M and N be elementarily homogeneous structures of the same cardinality λ . Suppose that $M \models \exists x p(x) \Leftrightarrow N \models \exists x p(x)$ for every $p(x) \subseteq L$ such that $|x| < \lambda$. Prove that the two structures are isomorphic. \square

9.16 Exercise Let L be a language that extends that of strict linear orders with the constants $\{c_i : i \in \omega\}$. Let T be the theory that extends T_{dlo} with the axioms $c_i < c_{i+1}$ for every $i \in \omega$. Prove that T has elimination of quantifiers and is complete (it can be deduced from what is known of T_{dlo}). Exhibit a countable saturated model and a countable model that is not homogeneous. \square

3 The monster model

In this section we present some notation and terminology frequently adopted when dealing with a complete theory T . We fix a saturated structure \mathcal{U} of cardinality larger than $|L|$. We assume \mathcal{U} to be large enough that among its elementary substructures we can find any model of T we might be interested in. For this reason \mathcal{U} is nicknamed the **monster model**. We denote by κ the cardinality of \mathcal{U} when necessary we assume κ to be inaccessible.

Some terms acquire a slightly different meaning when working inside a monster model.

truth	we say that $\varphi(x)$ holds if $\mathcal{U} \models \forall x \varphi(x)$;
small/large	cardinalities smaller than κ are called small;
models	are elementary substructure of \mathcal{U} of small cardinality, they are denoted by the letters M and N , and derived symbols;
parameters	are always in \mathcal{U} ; the symbols A, B, C , etc. denote sets of parameters of small cardinality; calligraphic letters as $\mathcal{A}, \mathcal{B}, \mathcal{C}$, etc. are used for sets of arbitrary cardinality;
tuples	have length $< \kappa$ unless otherwise specified;
global types	are complete types over \mathcal{U} ; the set of global types is denoted by $S(\mathcal{U})$;
formulas	have parameters in \mathcal{U} unless otherwise specified;
definable sets	are sets of the form $\varphi(\mathcal{U})$ for some formula $\varphi(x) \in L(\mathcal{U})$; we may say A -definable if $\varphi(x) \in L(A)$;
type-definable sets	are sets of the form $p(\mathcal{U})$ for some $p(x) \subseteq L(A)$ where, as the symbol suggests, A has small cardinality;
types of tuples	we write $\text{tp}(a/A)$ for $\text{tp}_{\mathcal{U}}(a/A)$ and $a \equiv_A b$ for $\mathcal{U}, a \equiv_A b$;
orbits of tuples	under the action of $\text{Aut}(\mathcal{U}/A)$ are denoted by $\mathcal{O}(a/A)$.

Let x be a tuple of variables. For any fixed $A \subseteq \mathcal{U}$ we introduce a topology on $\mathcal{U}^{|x|}$ that we call the **topology induced by A** or, for short, **A -topology**. (This is non standard terminology, not to be confused with the *logic* A -topology in Section 14.4.) The closed sets of the A -topology are those of the form $p(\mathcal{U})$ where $p(x) \subseteq L(A)$ is any type over A .

For $\varphi(x) \in L(A)$ the sets of the form $\varphi(\mathcal{U})$ are clopen in this topology (and vice versa by Proposition 9.17). They form both a base of closed sets and base of open sets, which makes these topologies *zero-dimensional*. By saturation, the topology induced by A is compact. Actually, saturation is equivalent to the compactness of all these topologies as A ranges over the sets of small cardinality.

These topologies are never T_0 as any pair of tuples $a \equiv_A b$ have exactly the same neighborhoods. Such pairs always exist by cardinality reasons. However it is immediate that the topology induced on the quotient $\mathcal{U}^{|x|} / \equiv_A$ is Hausdorff (this is the so-called *Kolmogorov quotient*). Indeed, this quotient corresponds to $S_x(A)$ with the topology introduced in Section 5.3.

The following proposition is an immediate consequence of compactness. When $A = B$ it says that the topology induced by A is *normal*: any two closed sets are separated by open sets. It could be called **mutual normality** (not a standard name) because the two closed sets belong to different topologies and the separating sets are each found in the corresponding topology.

9.17 Proposition (mutual normality) Let $p(x) \subseteq L(A)$ and $q(x) \subseteq L(B)$ be such that $p(x) \rightarrow \neg q(x)$. Then there are $\varphi(x)$, conjunction of formulas in $p(x)$, and $\psi(x)$, conjunction of formulas in $q(x)$, such that $\varphi(x) \rightarrow \neg\psi(x)$.

Proof The assumptions say that $p(x) \wedge q(x)$ is inconsistent. Then the formulas $\varphi(x)$ and $\psi(x)$ exist by compactness (i.e. saturation). \square

9.18 Remark There are many forms in which the proposition above can be applied. For instance, assuming for brevity that $p(x)$ and $q(x)$ are closed under conjunctions,

- a. if $p(x) \leftrightarrow \neg q(x)$ then $p(x) \leftrightarrow \varphi(x)$ for some $\varphi(x) \in p(x)$;
- b. if $p(x) \leftrightarrow \psi(x)$ for some $\psi(x) \in L(\mathcal{U})$ then $p(x) \leftrightarrow \varphi(x)$ for some $\varphi(x) \in p$;
- d. if $p(x) \rightarrow \psi(x)$ for some $\psi(x) \in L(\mathcal{U})$ then $\varphi(x) \rightarrow \psi(x)$ for some $\varphi(x) \in p$;
- c. if $p(x) \rightarrow \bigvee_{\psi \in \Psi} \psi(x)$, where $|\Psi| < \kappa$, then $p(x) \rightarrow \bigvee_{i=1}^n \psi_i(x)$ for some $\psi_i \in \Psi$. \square

A definable set as the form $\varphi(\mathcal{U}; b)$ for some formula $\varphi(x; z) \in L$ and some $b \in \mathcal{U}^{|z|}$. If $f \in \text{Aut}(\mathcal{U}/A)$ then

$$\begin{aligned} f[\varphi(\mathcal{U}; b)] &= \{fa : \varphi(a; b), \quad a \in \mathcal{U}^{|x|}\} \\ &= \{fa : \varphi(fa; fb), \quad a \in \mathcal{U}^{|x|}\} \\ &= \varphi(\mathcal{U}; fb). \end{aligned}$$

Hence automorphisms act on definable sets in a very natural way. Their action of type-definable sets is similar.

We say that a set $\mathcal{D} \subseteq \mathcal{U}^{|x|}$ is **invariant over A** if $f[\mathcal{D}] = \mathcal{D}$ for every $f \in \text{Aut}(\mathcal{U}/A)$. Equivalently, if $\mathcal{O}(a/A) \subseteq \mathcal{D}$ for every $a \in \mathcal{D}$. By homogeneity this is equivalent to requiring that $q(x) \rightarrow x \in \mathcal{D}$ for every $q(x) = \text{tp}(a/A)$ where $a \in \mathcal{D}$.

Proposition 9.21 below an important fact about invariant type-definable sets. It may clarify the proof to consider first the particular case of definable sets.

9.19 Proposition Let $\varphi(x) \in L(\mathcal{U})$ then the following are equivalent

- 1. $\varphi(x)$ is equivalent to some formula $\psi(x) \in L(A)$;
- 2. $\varphi(\mathcal{U})$ is invariant over A .

We give two proofs of this theorem as they are both instructive.

Proof $1 \Rightarrow 2$ Obvious.

$2 \Rightarrow 1$ From 2 and homogeneity we obtain

$$\varphi(x) \leftrightarrow \bigvee_{q(x) \rightarrow \varphi(x)} q(x)$$

where $q(x)$ above range over all types in $S_x(A)$. By compactness, we can rewrite this equivalence

$$\varphi(x) \leftrightarrow \bigvee_{\vartheta(x) \rightarrow \varphi(x)} \vartheta(x)$$

where $\vartheta(x)$ ranges over all formulas in $L(A)$. This latter equivalence says that $\neg\varphi(x)$

is equivalent to a type over A . Again by compactness we obtain

$$\varphi(x) \leftrightarrow \bigvee_{i=1}^n \vartheta_i(x)$$

for some formula $\vartheta_i(x) \in L(A)$. □

Second proof of Proposition 9.19 $2 \Rightarrow 1$ Let $\varphi(\mathcal{U}; b)$, where $\varphi(x; z) \in L$, be a formula invariant over A . Let $p(z) = \text{tp}(b/A)$. As $f[\varphi(\mathcal{U}; b)] = \varphi(\mathcal{U}; fb)$ for every $f \in \text{Aut}(\mathcal{U}/A)$, homogeneity and invariance yield

$$p(z) \rightarrow \forall x [\varphi(x; z) \leftrightarrow \varphi(x; b)].$$

By compactness there is a formula $\vartheta(z) \in p$ such that

$$\vartheta(z) \rightarrow \forall x [\varphi(x; z) \leftrightarrow \varphi(x; b)].$$

Hence $\varphi(\mathcal{U}; b)$ is defined by the formula $\exists z [\vartheta(z) \wedge \varphi(x; z)]$, which is a formula in $L(A)$ as required. □

9.20 Exercise Let $\varphi(x) \in L$. Prove that the following are equivalent

1. $\varphi(x)$ is equivalent to some $\psi(x) \in L_{\text{qt}}$;
2. $\varphi(a) \leftrightarrow \varphi(fa)$ for every partial isomorphism $f : \mathcal{U} \rightarrow \mathcal{U}$ defined in a .

Use the result to prove Theorem 7.13 for T complete. □

9.21 Proposition Let $p(x) \subseteq L(B)$ then the following are equivalent

1. $p(x)$ is equivalent to some type $q(x) \subseteq L(A)$;
2. $p(\mathcal{U})$ is invariant over A .

We give two proofs of this theorem. The second one requires Proposition 9.22 below.

Proof $1 \Rightarrow 2$ Obvious.

$2 \Rightarrow 1$ It suffices to show that for every formula $\psi(x) \in p(x)$ there is a formula $\varphi(x) \in L(A)$ such that $p(x) \rightarrow \varphi(x) \rightarrow \psi(x)$. Fix $\psi(x) \in p(x)$. By invariance, any $q(x) \in S(A)$ consistent with $p(x)$ implies $p(x)$, hence

$$p(x) \rightarrow \bigvee_{q(x) \rightarrow \psi(x)} q(x) \rightarrow \psi(x)$$

where $q(x)$ above range over all types in $S_x(A)$. By compactness we can rewrite this equivalence as follows

$$p(x) \rightarrow \bigvee_{\vartheta(x) \rightarrow \psi(x)} \vartheta(x) \rightarrow \psi(x)$$

where $\vartheta(x)$ ranges over all formulas in $L(A)$. Applying mutual normality (Proposition 9.17) to the first implication we obtain a finite number of formulas $\vartheta_i(x)$ such that

$$p(x) \rightarrow \bigvee_{i=1}^n \vartheta_i(x) \rightarrow \psi(x).$$

This completes the proof. □

The following easy proposition is very useful. Its proof is left to the reader. Note that it would not hold without saturation: for instance, consider \mathbb{R} as a structure in

the language of strict orders and let $q(x, y) = \text{tp}(-1, 0 / A)$, where $A = \{1/n : 0 < n\}$. By quantifier elimination, $-1 \equiv_A 0$. But $0 \not\equiv \exists y q(x, y)$.

9.22 Proposition Let $p(\bar{x}; \bar{z}) \subseteq L(A)$. Then $\exists \bar{z} p(\bar{x}; \bar{z})$ is equivalent to a type over A , namely to the type $\{\exists \bar{z} \varphi(\bar{x}; \bar{z}) : \varphi(\bar{x}; \bar{z}) \text{ conjunction of formulas in } p(\bar{x}; \bar{z})\}$. The theorem holds also when \bar{x} and \bar{z} have length κ . \square

As an application we give a second proof of the proposition above.

Second proof of Proposition 9.21 $2 \Rightarrow 1$ Write $p(\bar{x})$ as the type $q(\bar{x}; \bar{b})$ for some $q(\bar{x}; \bar{z}) \subseteq L$ and some $\bar{b} \in \mathcal{U}^{|\bar{z}|}$. Let $s(\bar{z}) = \text{tp}(\bar{b} / A)$. By invariance and homogeneity the types $p(\bar{x}; f\bar{b})$ for $f \in \text{Aut}(\mathcal{U}/A)$ are all equivalent. Therefore

$$\begin{aligned} p(\bar{x}) &\leftrightarrow \bigvee_{f \in \text{Aut}(\mathcal{U}/A)} q(\bar{x}; f\bar{b}) \\ p(\bar{x}) &\leftrightarrow \bigvee_{c \equiv_A \bar{b}} q(\bar{x}; c) \\ &\leftrightarrow \exists \bar{z} [s(\bar{z}) \wedge q(\bar{x}; \bar{z})]. \end{aligned}$$

Hence, by Proposition 9.22, $p(\bar{x})$ is equivalent to a type over A . \square

9.23 Exercise Let $p(x) \subseteq L(A)$, with $|x| < \omega$. Prove that if $p(\mathcal{U})$ is infinite then it has cardinality κ . Show that this may not be true if x is an infinite tuple. \square

9.24 Exercise Let $\varphi(x, y) \in L(\mathcal{U})$. Prove that if the set $\{\varphi(a, \mathcal{U}) : a \in \mathcal{U}^{|x|}\}$ is infinite then it has cardinality κ . Does the claim remains true with a type $p(x, y) \subseteq L(A)$ for $\varphi(x, y)$? \square

9.25 Exercise Let $\varphi(x; y) \in L(\mathcal{U})$. Prove that the following are equivalent

1. there is a sequence $\langle a_i : i \in \omega \rangle$ such that $\varphi(\mathcal{U}; a_i) \subset \varphi(\mathcal{U}; a_{i+1})$ for every $i < \omega$;
2. there is a sequence $\langle a_i : i \in \omega \rangle$ such that $\varphi(\mathcal{U}; a_{i+1}) \subset \varphi(\mathcal{U}; a_i)$ for every $i < \omega$. \square

9.26 Exercise Let $\varphi(x; y)$ be such that for every $b \in \mathcal{U}^{|y|}$ there is a $\psi(x) \in L$ such that $\psi(x) \rightarrow \varphi(x; b)$. Prove that we can choose $\psi(x)$ in a finite subset of L . \square

Chapter 10

Preservation theorems

In this chapter we present a few results dating from the 1950s that describe the relationship between syntactic and semantic properties of first-order formulas. These results characterize the classes of formulas that preserved under various sorts of morphisms. Criteria for quantifier-elimination follow from these theorems, see for instance the frequently used back-and-forth method of Corollary 10.12.

1 Lyndon-Robinson Lemma

In this section T is a consistent theory without finite models and Δ is a set of formulas closed under renaming of variables. At a first reading the reader is encouraged to assume that Δ is L_{at} .

10.1 Definition If $C \subseteq \{\forall, \exists, \neg, \vee, \wedge\}$ is a set of connectives, we write $C\Delta$ for the closure of Δ with respect to all connectives in C . We may write Δ^\pm for $\{\neg\}\Delta$. \square

Recall that Δ -morphism is a map $k : M \rightarrow N$ that preserves the truth of formulas in Δ . It is immediate that Δ -morphism are automatically $\{\wedge, \vee\}\Delta$ -morphisms. As Δ is closed under renaming of variables, $\{\exists\}\Delta$ -morphism are $\{\exists \wedge \vee\}\Delta$ -morphisms and similarly $\{\forall\}\Delta$ -morphism are $\{\forall \wedge \vee\}\Delta$ -morphisms.

Below we use the following proposition without further reference.

10.2 Proposition Fix $M \models T$ and $b \in M^{|x|}$. Let $q(x) = \Delta\text{-tp}_M(b)$. Then for every $\varphi(x) \in L$ the following are equivalent

1. $N \models \varphi(kb)$ for every $k : M \rightarrow N \models T$ that is a Δ -morphism defined in b ;
2. $T \vdash q(x) \rightarrow \varphi(x)$.

Proof $2 \Rightarrow 1$ Immediate.

$1 \Rightarrow 2$ Negate 2, then there are $N \models T$ and $c \in N^{|x|}$ such that $q(c) \wedge \neg \varphi(c)$. Therefore the map $k : M \rightarrow N$, where $k = \{ \langle b, c \rangle \}$, contradicts 1. \square

The following is sometimes referred to as the Lyndon-Robinson Lemma.

10.3 Lemma For every $\varphi(x) \in L$ the following are equivalent

1. $\varphi(x)$ is equivalent over T to a formula in $\{\wedge, \vee\}\Delta$;
2. $\varphi(x)$ is preserved by Δ -morphisms between models of T .

Proof $1 \Rightarrow 2$ Immediate.

$2 \Rightarrow 1$ We claim that from 2 it follows that

$$\# \quad T \vdash \varphi(x) \leftrightarrow \bigvee \{ p(x) \subseteq \Delta : T \vdash p(x) \rightarrow \varphi(x) \}$$

Direction \leftarrow is clear. To verify \rightarrow , fix $M \models T$ and let $b \in M^{|x|}$ be such that $M \models \varphi(b)$.

From 2 it follows that $\varphi(x)$ satisfy 1 of Proposition 10.2. Therefore $T \vdash q(x) \rightarrow \varphi(x)$ for $q(x) = \Delta\text{-tp}(b)$. Hence $q(x)$ is one of the types that occur in the disjunction in # which therefore is satisfied by b .

From # and compactness we obtain

$$T \vdash \varphi(x) \leftrightarrow \bigvee \{ \psi(x) \in \{\wedge\}\Delta : T \vdash \psi(x) \rightarrow \varphi(x) \}$$

Applying compactness again, we replace the infinite disjunction above with a finite one and prove 2. \square

10.4 Proposition *Let N be λ -saturated and let $k : M \rightarrow N$ be a Δ -morphism of cardinality $< \lambda$. Then the following are equivalent*

1. $k : M \rightarrow N$ is a $\{\exists\}\Delta$ -morphism;
2. for every $b \in M$ some $\{\exists\}\Delta$ -morphism $h : M \rightarrow N$ defined in b extends k ;
3. for every $b \in M^\omega$ some Δ -morphism $h : M \rightarrow N$ defined in b extends k .

Proof $1 \Rightarrow 2$ Let a enumerate $\text{dom } k$. Define $p(x; z) = \{\exists\}\Delta\text{-tp}_M(b; a)$. By 1, $p(x; ka)$ is finitely consistent in N . By saturation there is a $c \in N$ that realizes $p(x; ka)$. Therefore, $h : M \rightarrow N$ where $h = k \cup \{(b, c)\}$, witnesses 2.

$2 \Rightarrow 3$ Iterate ω -times the extension in 2.

$3 \Rightarrow 1$ Let a enumerate $\text{dom } k$ and let $|z| = |a|$. Formulas in $\{\exists\}\Delta$ with free variables among z are of the form $\exists x \varphi(x; z)$ where $\varphi(x; z)$ is in Δ and x is some fixed tuple of length ω . Assume $M \models \exists x \varphi(x; a)$ and let b be such that $M \models \varphi(b; a)$. By 3, we can extend k to some Δ -morphism $h : M \rightarrow N$ defined in b . Then $N \models \varphi(hb; ha)$ and therefore $N \models \exists x \varphi(x; ka)$. \square

Iterating the lemma above we obtain the following.

10.5 Corollary *Let N be λ -saturated and let $|M| \leq \lambda$. Let $k : M \rightarrow N$ be a Δ -morphism of cardinality $< \lambda$. Then the following are equivalent*

1. $k : M \rightarrow N$ is a $\{\exists\}\Delta$ -morphism;
2. $k : M \rightarrow N$ extends to an $\{\exists\}\Delta$ -embedding;
3. $k : M \rightarrow N$ extends to an Δ -embedding.

\square

The following theorem is often paraphrased as follows: a formula is existential if and only if (its truth) is preserved under extensions of structures.

10.6 Theorem *For every $\varphi(x) \in L$ the following are equivalent*

1. $\varphi(x)$ is equivalent over T to a formula in $\{\exists \wedge \vee\}\Delta$;
2. $\varphi(x)$ is preserved by Δ -embedding between models of T .

Proof $1 \Rightarrow 2$ Immediate.

$2 \Rightarrow 1$ Negate 1. By Lemma 10.3 there is a $\{\exists\}\Delta$ -morphism $k : M \rightarrow N$ between models of T that does not preserve $\varphi(x)$. We can assume that N is λ -saturated for some sufficiently large λ . By Corollary 10.5 there is a Δ -embedding $h : M \hookrightarrow N$ that extends k and contradicts 2. \square

A dual version of the results above is obtained replacing embeddings by epimorphisms (surjective homomorphisms) and $\{\exists\}$ by $\{\forall\}$. If Δ contains the formula $x = y$ and is closed under negation, then $k : M \rightarrow N$ is a Δ -morphism if and only if $k^{-1} : N \rightarrow M$ is a Δ -morphism. In this case the dual version follows from what proved above. Without these assumptions the results need a similar but independent proof.

10.7 Proposition *Let M be λ -saturated and let $k : M \rightarrow N$ be a Δ -morphism of cardinality $< \lambda$. Then the following are equivalent*

1. $k : M \rightarrow N$ is a $\{\forall\}\Delta$ -morphism;
2. for every $c \in N$ some $\{\forall\}\Delta$ -morphism $h : M \rightarrow N$ extends k and $c \in \text{img } h$;
3. for every $c \in N^\omega$ some Δ -morphism $h : M \rightarrow N$ extends k and $c \in (\text{img } h)^\omega$.

We write $\neg\Delta$ for the set containing the negation of the formulas in Δ . Warning: do not confuse $\neg\Delta$ with $\{\neg\}\Delta$.

Proof Left as an exercise for the reader. Hint: to prove implication $1 \Rightarrow 2$ define $p(x, y) = \neg\{\forall\}\Delta\text{-tp}_N(ka, c)$, where a is a tuple that enumerates $\text{dom } k$. From 1 obtain that $p(a, y)$ is finitely consistent in M . Then proceed as in the proof of Proposition 10.4. \square

10.8 Corollary *Let M be λ -saturated and let $|N| \leq \lambda$. Let $k : M \rightarrow N$ be a Δ -morphism of cardinality $< \lambda$. Then the following are equivalent*

1. $k : M \rightarrow N$ is a $\{\forall\}\Delta$ -morphism;
2. $k : M \rightarrow N$ extends to an $\{\forall\}\Delta$ -epimorphism;
3. $k : M \rightarrow N$ extends to an Δ -epimorphism. \square

Finally we obtain the following.

10.9 Theorem *The following are equivalent*

1. $\varphi(x)$ is equivalent to a formula in $\{\forall\}\Delta$;
2. every Δ -epimorphism between models of T preserves $\varphi(x)$. \square

2 Quantifier elimination by back-and-forth

We say that T admits (or has) positive Δ -elimination of quantifiers if for every formula $\varphi(x)$ in $\{\exists\forall\wedge\vee\}\Delta$ there is a formula $\psi(x)$ in $\{\wedge\vee\}\Delta$ such that

$$T \vdash \varphi(x) \leftrightarrow \psi(x).$$

When Δ is closed under negation the attribute *positive* becomes irrelevant and will be omitted. When Δ is L_{at^\pm} or L_{qf} , we simply say that T admits elimination of quantifiers. This is by far the most common case.

Quantifier elimination is often used to prove that a theory is complete because it reduces it to something much simpler to prove. The following is an immediate consequence of the definition above with x replaced by the empty tuple.

10.10 Remark If T has elimination of quantifiers then the following are equivalent

1. T decides all quantifier free sentences;
2. T is complete.

Hence a theory with quantifier elimination is complete if it decides the characteristic, see Definition 5.26). \square

The following is a consequence of Lemma 10.3.

10.11 Corollary *The following are equivalent*

1. T has Δ -elimination of quantifiers;
2. every Δ -morphism between models of T is both a $\{\exists\}\Delta$ and a $\{\forall\}\Delta$ -morphism.

Proof $1 \Rightarrow 2$ Immediate.

$2 \Rightarrow 1$ We prove by induction of syntax that Δ -morphism preserve the truth of all formulas in $\{\exists \forall \wedge \vee\}\Delta$, this suffices by Lemma 10.3. Induction for the connectives \vee and \wedge is trivial. So assume as induction hypothesis that the truth of $\varphi(x, y)$ is preserved. By Lemma 10.3 $\varphi(x, y)$ is equivalent to a formula in $\{\wedge \vee\}\Delta$, hence by 2 the truth of $\exists y \varphi(x, y)$ and $\forall y \varphi(x, y)$ is preserved. \square

Condition 2 of the corollary above may be difficult to verify directly. The following corollary of Proposition 10.4 and 10.7 gives a back-and-forth condition which is easier to verify.

10.12 Corollary *Let $|L| \leq \lambda$. The following are equivalent*

1. T has Δ -elimination of quantifiers;
2. for every finite Δ -morphism $k : M \rightarrow N$ between λ -saturated models of T
 - a. for every $b \in M$ some Δ -morphism $h : M \rightarrow N$ extends k and $b \in \text{dom } h$;
 - b. for every $c \in N$ some Δ -morphism $h : M \rightarrow N$ extends k and $c \in \text{img } h$.

\square

Note that when Δ contains the formula $x = y$ and is closed under negation, then $k : M \rightarrow N$ is a Δ -morphism if and only if $k^{-1} : N \rightarrow M$ is a Δ -morphism. In this case a and b are equivalent.

10.13 Exercise Let T be a complete theory without finite models in a language that consists only of unary predicates. Prove that T has elimination of quantifiers. \square

10.14 Exercise Let L be the language of strict orders. The theory of **discrete linear orders** extends the theory of linear orders without endpoints (see Section 6.1) with the following two axioms

$\text{dis}\uparrow. \exists z [x < z \wedge \neg \exists y x < y < z];$

$\text{dis}\downarrow. \exists z [z < x \wedge \neg \exists y z < y < x].$

Let Δ be the set of formulas that contains (all alphabetic variants of) the formulas $x <_n y := \exists z \geq_n z (x < z < y)$ and their negations (read $<_0$ as $<$). Prove that the theory of discrete linear orders has Δ -elimination of quantifiers. Prove that the structure $\mathbb{Q} \times \mathbb{Z}$ ordered with the lexicographic order

$$(a_1, a_2) < (b_1, b_2) \Leftrightarrow a_1 < b_1 \text{ or } (a_1 = b_1 \text{ e } a_2 < b_2)$$

is a saturated model of T . □

10.15 Exercise Let T be a consistent theory. Suppose that all completions of T are of the form $T \cup S$ for some set S of quantifier-free sentences. Prove that, if all completion of T have elimination of quantifiers, so does T . Show that this fails when the completions of T have arbitrary complexity.

Note. Though the claim follows immediately from Corollary 10.11, a direct proof is also instructive. Prove that for every formula $\varphi(x)$ there are some quantifier-free sentences σ_i and quantifier-free formulas $\psi_i(x)$ such that

$$\sigma_i \vdash \varphi(x) \leftrightarrow \psi_i(x), \quad T \vdash \bigvee_{i=1}^n \sigma_i, \quad \text{and} \quad \sigma_i \vdash \neg \sigma_j \text{ for } i \neq j.$$

For a counter example consider the empty theory in the language with a single unary predicate. □

3 Model-completeness

We say that T is **model-complete** if every embedding $h : M \hookrightarrow N$ between models of T is an elementary embedding.

The notion was introduced by Abraham Robinson and has become standard. It is inspired by the fact that T is model-complete if and only if $T \cup \text{Diag}(M)$ is a complete theory, in the language $L(M)$, for every $M \models T$.

To stress positivity in the next proposition, we generalize the definition as follows. We say that T is **Δ -model-complete** if every Δ -embedding $h : M \hookrightarrow N$ between models of T is a $\{\forall\exists\}$ - Δ -embedding.

Model-completeness is equivalent a sort of elimination of quantifiers.

10.16 Proposition *The following are equivalent*

1. T is Δ -model-complete;
2. T has $\{\exists\}$ - Δ -elimination of quantifiers.

Proof $1 \Rightarrow 2$ By 1, every formula $\{\forall\exists\wedge\vee\}\Delta$ is preserved by Δ -embeddings therefore, by Theorem 10.6, it is equivalent to a formula in $\{\exists\wedge\vee\}\Delta$.

$2 \Rightarrow 1$ Clear, because Δ -embeddings preserve formulas in $\{\exists\wedge\vee\}\Delta$. □

The theory of discrete linear orders defined in Exercise 10.14 is an example of a model-complete theory without elimination of quantifiers.

10.17 Exercise Prove that the theory of discrete linear orders is model-complete. □

The difference between quantifier elimination and model-completeness subtle. It boils down to models of T having or not the amalgamation property.

10.18 Proposition *Assume T is model-complete. Let \mathcal{M} be the category that consists of models of T and partial isomorphisms. Then the following are equivalent*

1. \mathcal{M} has the amalgamation property;

2. T has elimination of quantifiers.

Proof $1 \Rightarrow 2$ By Proposition 7.25 every partial morphism $k : M \rightarrow N$ extends to an embedding $g : M \hookrightarrow N'$ which, by model-completeness, is an elementary embedding. Model-completeness also implies that $N \preceq N'$. Hence $k : M \rightarrow N$ is an elementary map. This proves 2.

$2 \Rightarrow 1$ If all morphisms are elementary maps, amalgamations follows from Proposition 7.28. \square

Note however that the models of a model-complete theory T do have amalgamation when the proper notion of morphism is chosen.

Let \mathcal{M}' be the category that consists of models of T and the maps $k : M \rightarrow N$ such that there is a partial isomorphism $h : M' \rightarrow N'$ with

1. $k \subseteq h; \quad M \preceq M'; \quad N \preceq N';$
2. $\text{dom } h$ contains a substructure of M' that models T (equivalently $\text{img } h$ and N').

It is clear that if T is model-complete then the morphisms of \mathcal{M}' are exactly the elementary maps. In this case \mathcal{M}' has amalgamation. Vice versa if \mathcal{M}' has amalgamation, the theory of rich models is model-complete.

10.19 Exercise Prove that \mathcal{M}' satisfies finite character of morphisms, c6 of Definition 7.1. \square

Chapter 11

Geometry and dimension

In this chapter we fix a signature L , a complete theory T without finite models, and a saturated model \mathcal{U} of inaccessible cardinality κ larger than $|L|$. The notation and implicit assumptions are as in Section 9.3.

1 Algebraic and definable elements

Let $a \in \mathcal{U}$ and let $\mathcal{A} \subseteq \mathcal{U}$ be some set of parameters (of arbitrary cardinality). We say that a is **algebraic over \mathcal{A}** if $\varphi(a) \wedge \exists^{=k} x \varphi(x)$ holds for some formula $\varphi(x) \in L(\mathcal{A})$ and some positive integer k . In particular when $k = 1$ we say that a is **definable over \mathcal{A}** . We write $\text{acl}(\mathcal{A})$ for the **algebraic closure of \mathcal{A}** , that is, set of all elements algebraic over \mathcal{A} . If $\mathcal{A} = \text{acl}(\mathcal{A})$, we say that \mathcal{A} is **algebraically closed**. The **definable closure of \mathcal{A}** is defined similarly and is denoted by $\text{dcl}(\mathcal{A})$.

A formula $\varphi(u) \in L(\mathcal{A})$, or a type $p(u) \subseteq L(\mathcal{A})$, where u is a finite tuple, with finitely many solutions are called an **algebraic**.

11.1 Proposition *For every $A \subseteq \mathcal{U}$ and every type $p(u) \subseteq L(A)$, where $|u| < \omega$, the following are equivalent*

- 1 $\exists^{\leq n} u \ p(u)$;
- 2 $\exists^{\leq n} u \ \varphi(u)$ for some $\varphi(u)$ which is conjunction of formulas $p(u)$.

Proof The non trivial implication is $1 \Rightarrow 2$. Let $\{a_i, \dots, a_n\}$ be all the solutions of $p(u)$. Then

$$p(u) \leftrightarrow \bigvee_{i=1}^n a_i = u$$

Then 2 follows by compactness (cfr. Remark 9.18.b). □

11.2 Exercise Prove that Proposition 11.1 does not hold in general for infinite tuple u . □

11.3 Exercise For every $a \in \mathcal{U}^{|u|}$ and $A \subseteq \mathcal{U}$, the following are equivalent

1. a is solution of some algebraic formula $\varphi(u) \in L(A)$;
2. $a = a_1, \dots, a_n$ for some $a_1, \dots, a_n \in \text{acl}(A)$.

Prove also that if a is definable then so are a_1, \dots, a_n , and vice versa. □

11.4 Theorem *For every $A \subseteq \mathcal{U}$ and every $a \in \mathcal{U}$ the following are equivalent*

- 1 $a \in \text{dcl}(A)$;
- 2 $\mathcal{O}(a/A) = \{a\}$.

Proof Implication $1 \Rightarrow 2$ is obvious. As for $2 \Rightarrow 1$, recall that $\mathcal{O}(a/A)$ is the set of realizations of $\text{tp}(a/A)$, then the theorem follows from Proposition 11.1. \square

11.5 Theorem For every $A \subseteq \mathcal{U}$ and every $a \in \mathcal{U}$ the following are equivalent

- 1 $a \in \text{acl}(A)$;
- 2 $\mathcal{O}(a/A)$ is finite;
- 3 a belongs to every model containing A .

Proof $1 \Leftrightarrow 2$. This is proved as in Theorem 11.4.

$1 \Rightarrow 3$. Assume 1, then there is a formula $\varphi(x) \subseteq L(A)$ such that $\varphi(a) \wedge \exists^{=k} x \varphi(x)$ for some k . By elementarity $\exists^{=k} x \varphi(x)$ holds in every model M containing A . Again by elementarity, the k solutions of $\varphi(x)$ in M are solutions in \mathcal{U} , therefore a is one of these.

$3 \Rightarrow 2$. Assume $\mathcal{O}(a/A)$ is infinite and fix any model M containing A . By Exercise 9.23, $\mathcal{O}(a/A)$ has cardinality κ , hence $\mathcal{O}(a/A) \not\subseteq M$. Pick any $f \in \text{Aut}(\mathcal{U}/A)$ such that $fa \notin M$. Then $a \notin f^{-1}[M]$, so $f^{-1}[M]$ is a models that contradicts 3. \square

11.6 Corollary For every $A \subseteq \mathcal{U}$ and every $a \in \mathcal{U}$ the following hold

- 1 Se $a \in \text{acl } A$ then $a \in \text{acl } B$ for some finite $B \subseteq A$; finite character
- 2 $A \subseteq \text{acl } A$; extensivity
- 3 se $A \subseteq B$ allora $\text{acl } A \subseteq \text{acl } B$; monotonicity
- 4 $\text{acl } A = \text{acl}(\text{acl } A)$; idempotency
- 5 $\text{acl } A = \bigcap_{A \subseteq M} M$.

Properties 1-4 say that the algebraic closure is a closure operator with finite character.

Proof Properties 1-3 are obvious, 4 follow from 5 which in turn follows from Theorem 11.5. \square

11.7 Proposition If $f \in \text{Aut}(\mathcal{U})$ then $f[\text{acl}(A)] = \text{acl}(f[A])$ for every $A \subseteq \mathcal{U}$.

Proof We prove $f[\text{acl}(A)] \subseteq \text{acl}(f[A])$. Fix $a \in \text{acl}(A)$ and let $\varphi(x; z) \in L$ and $b \in A^{|z|}$ be such that $\varphi(x; b)$ is algebraic formula satisfied by a . By elementarity, $\varphi(x; fb)$ is algebraic and satisfied by fa . Therefore fa is algebraic over $f[A]$, which proves the inclusion.

The converse inclusion is obtained by substituting f^{-1} for f and $f[A]$ for A . \square

11.8 Exercise Let $\varphi(z) \in L(A)$ be a consistent formula. Prove that, if $a \in \text{acl}(A, b)$ for every $b \models \varphi(z)$, then $a \in \text{acl}(A)$. Prove the same claim with a type $p(z) \subseteq L(A)$ for $\varphi(z)$. \square

11.9 Exercise Let $a \in \mathcal{U} \setminus \text{acl } \emptyset$. Prove that \mathcal{U} is isomorphic to some $\mathcal{V} \preceq \mathcal{U}$ such that $a \notin \mathcal{V}$. Hint: let c be an enumeration of \mathcal{U} and let $p(u) = \text{tp}(c)$ prove that $p(u) \cup \{u_i \neq a : i < \kappa\}$ is realized in \mathcal{U} and that any realization yields the required substructure of \mathcal{U} . \square

11.10 Exercise Let C be a finite set. Prove that if $C \cap M \neq \emptyset$ for every model M containing A , then $C \cap \text{acl}(A) \neq \emptyset$. Hint: by induction on the cardinality of C . Suppose there is a $c \in C \setminus \text{acl}(A)$, then there is $\mathcal{V} \simeq \mathcal{U}$ such that $A \subseteq \mathcal{V} \preceq \mathcal{U}$ and $c \notin \mathcal{V}$, see Exercise 11.9. Apply the induction hypothesis to $C' = C \cap \mathcal{V}$ with \mathcal{V} for \mathcal{U} . \square

11.11 Exercise Prove that for every $A \subseteq N$ there is an M such that $\text{acl } A = M \cap N$. Hint: add the requirement $\text{acl}(A_i) \cap N \subseteq \text{acl}(A)$ to the construction used to prove the downward Löwenheim-Skolem theorem. You need to prove that every consistent $\varphi(x) \in L(A_i)$ has a solution a such that $\text{acl}(A_i, a) \cap N \subseteq \text{acl}(A)$. The required a has to realize the type

$$\{\varphi(x)\} \cup \left\{ \neg[\psi(b, x) \wedge \exists^{\leq n} y \psi(y, x)] : b \in N \setminus \text{acl}(A), \psi(y, x) \in L(A_i), n < \omega \right\}$$

whose consistence need to be verified. (See Exercise 11.12 for a different hint.) \square

11.12 Exercise Prove that for every $A \subseteq N$ there is an automorphism $f \in \text{Aut}(\mathcal{U}/A)$ such that $\text{acl } A = f[N] \cap N$. (This is a stronger version of the claim in Exercise 11.11.) Hint: let c be an enumeration of N . Let $p(x) = \text{tp}(c/A)$. Consider the type

$$p(x) \cup \left\{ \neg[\psi(b, x) \wedge \exists^{\leq n} y \psi(y, x)] : b \in N \setminus \text{acl}(A), \psi(y, x) \in L_x(A), n < \omega \right\}$$

Any $a \models p(x)$ enumerates a model A -isomorphic to N . \square

11.13 Exercise Let $\varphi(x) \in L(\mathcal{U})$ and fix an arbitrary set A . Prove that the following are equivalent

1. there is some model M containing A and such that $M \cap \varphi(\mathcal{U}) = \emptyset$;
2. there is no consistent formula $\psi(z_1, \dots, z_n) \in L(A)$ such that

$$\psi(z_1, \dots, z_n) \rightarrow \bigwedge_{i=1}^n \varphi(z_i).$$

Hint: let $c = \langle c_i : i < \lambda \rangle$ be an enumeration of $N^{|x|}$, where N is any model containing A . Let $p(z) = \text{tp}(c/A)$. Prove that 2 implies the consistency of the type $p(z) \cup \{\neg \varphi(z_i) : i < \lambda\}$ and deduce the existence of the required M . \square

2 Strongly minimal theories

Finite and cofinite sets are always (trivially) definable in every structure. We say that M is a **minimal structure** all its definable subsets of arity one are finite or cofinite. Unfortunately, this notion is not elementary, i.e. it is not a property of $\text{Th}(M)$. For instance \mathbb{N} with only the order relation in the language is a minimal structure but none of its elementary extensions is. Hence the following definition: we say that M is a **strongly minimal structure** if it is minimal and all its elementary extensions are minimal.

We say that T , a consistent theory without finite models, is **strongly minimal** if for every formula $\varphi(x; z) \in L$, where x has arity one, there is an $n \in \omega$ tale che

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

We show that the semantic notions match with and the syntactic one.

11.14 Proposition *The following are equivalent*

1. $\text{Th}(M)$ is a strongly minimal theory;
2. M is a strongly minimal structure;
3. M has an elementary extension which is minimal and ω -saturated.

Proof Implications $1 \Rightarrow 2 \Rightarrow 3$ are immediate, we prove $3 \Rightarrow 1$. Let $\varphi(x; z) \in L$ and fix an elementary extension N as required by 2. Let $p(z) \subseteq L$ be the following type

$$p(z) = \left\{ \exists^{>n} x \varphi(x; z) \wedge \exists^{>n} x \neg \varphi(x; z) : n \in \omega \right\}.$$

As N is minimal, $N \not\models \exists z p(z)$. By saturation $p(z)$ is not finitely consistent in M . Hence, for some n

$$M \models \forall z \left[\exists^{\leq n} x \varphi(x; z) \vee \exists^{\leq n} x \neg \varphi(x; z) \right].$$

which proves that $\text{Th}(M)$ is strongly minimal. \square

By quantifier elimination, T_{acf} and T_{dag} are strongly minimal theories.

11.15 Exercise Let T be a complete theory without finite models. Prove that the following are equivalent

1. M is minimal;
2. $a \equiv_M b$ for every $a, b \in \mathcal{U} \setminus M$.

\square

3 Independence and dimension

Throughout this section we assume that T is a complete strongly minimal theory.

When $a \notin \text{acl } B$ we say that a is algebraically independent from B . We say that B is an algebraically independent set if every $a \in B$ is independent from $B \setminus \{a\}$. Below we shall abbreviate $B \cup \{a\}$ by B, a and $B \setminus \{a\}$ by $B \setminus a$.

The following is a pivotal property of independence that holds in strongly minimal structures. It is called symmetry or exchange principle. For every B and every pair of elements $a, b \in \mathcal{U} \setminus \text{acl } B$

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

Note that when $T = T_{\text{acf}}$ this principle is the so called Steinitz exchange lemma.

11.16 Theorem (T strongly minimal.) *Independence is symmetric.*

Proof Suppose $b \notin \text{acl}(B, a)$ and $a \in \text{acl}(B, b)$. We prove that $a \in \text{acl } B$. Fix a formula $\varphi(x, y) \in L(B)$ such that $\varphi(x, b)$ witness $a \in \text{acl}(B, b)$, i.e. for some n

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

As $b \notin \text{acl}(B, a)$, the formula

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

is not algebraic. Therefore, by strong minimality, $\psi(a, y)$ has cofinitely many solutions. Hence every model containing B contains a solution of $\psi(a, y)$. As a is algebraic in any of these solutions, a belongs to every model containing B . Therefore, $a \in \text{acl } B$ by Theorem 11.5. \square

We say that $B \subseteq C$ is a **base** of C if B is an independent set and $C \subseteq \text{acl } B$. The following theorem proves that all bases have the same cardinality, which we call the **dimension** of C and denote by **$\dim C$** . First we need the following lemma.

11.17 Lemma (*T strongly minimal.*) *If B is an independent set and $a \notin \text{acl } B$ then B, a is also an independent set.*

Proof Suppose B, a is not independent and that $a \notin \text{acl } B$. Then $b \in \text{acl}(B \setminus b, a)$ for some $b \in B$. As $a, b \notin \text{acl}(B \setminus b)$, from symmetry we obtain $a \in \text{acl}(B \setminus b, b) = \text{acl } B$. Hence B is not an independent set. \square

11.18 Corollary (*T strongly minimal.*) *For every $B \subseteq C$ the following are equivalent*

1. B is a base of C .
2. B is a maximally independent subset of C .

\square

We may write **$\text{acl}(B/A)$** per $\text{acl}(B \cup A)$. The notation is used to suggest to the reader that the role of A in the argument is irrelevant and that it could be absorbed in the language. Independent sets **over A** and bases **over A** are defined in the obvious way.

11.19 Theorem (*T strongly minimal.*) *Fix some arbitrary set C , then*

1. every independent set $B \subseteq C$ can be extended to a base of C ;
2. all bases of C have the same cardinality;
3. claims 1 and 2 hold over any set of parameters A .

Proof By the finite character of algebraic closure, the independent set form an inductive class. Apply Zorn lemma to obtain a maximally independent subset of C containing B . By Corollary 11.18 this set is a base of C . This prove 1 and it is immediate that the argument can be generalized as required in 3.

As for 2, assume for a contradiction that $B_1, B_2 \subseteq C$ are two bases of C and that $|B_1| < |B_2|$. First consider the case when B_2 is infinite. For each $b \in B_1$ fix a set $D_b \subseteq B_2$ such that $b \in \text{acl}(D_b)$. Let

$$D = \bigcup_{b \in B_1} D_b.$$

Then $B_1 \subseteq \text{acl } D$ and $|D| < |B_2|$. By transitivity, $C \subseteq \text{acl } D$ which contradicts the independence of B_2 . Again the argument generalizes immediately as required in 3.

Now we suppose that B_2 is finite and prove directly the generalized version. Let n be the least integer such that, for some set of parameters A , and some B_1 and B_2 bases of C over A , we have $|B_1| < |B_2| = n + 1$. Fix any $c \in B_2$. Then $B_2 \setminus c$ is a base over A, c . Note that B_1 is not independent over A, c . In fact, as $c \in \text{acl}(B/A)$ by symmetry we obtain that $b \in \text{acl}(B \setminus b/A, c)$ for any $b \in B_1$. Now, let $D_1 \subset B_1$ be maximal independent over A, c . Then D_1 and $B_2 \setminus c$ are two bases over A, c such that $|D_1| < |B_2 \setminus c| = n$, which contradicts the minimality of n . \square

11.20 Proposition (*T strongly minimal.*) *Let k be an elementary map. Then $k \cup \{(b, c)\}$ is also an elementary map for every $b \notin \text{acl}(\text{dom } k)$ and $c \notin \text{acl}(\text{img } k)$.*

Proof Let a be an enumeration of $\text{dom } k$. We need to show that $\varphi(b; a) \leftrightarrow \varphi(c; ka)$

holds for every $\varphi(x; z) \in L$. As k is elementary, the formulas $\varphi(x; a)$ and $\varphi(x; ka)$ are either both algebraic or both co-algebraic. As $b \notin \text{acl}(a)$ and $c \notin \text{acl}(ka)$, they are both false or both true respectively. So the proposition follows. \square

11.21 Corollary (*T strongly minimal.*) Every bijection between independent sets is an elementary map. \square

Finally we show that dimension classifies models of T .

11.22 Theorem (*T strongly minimal.*) Models of T with the same dimension are isomorphic.

Proof Let A and B be some bases of M and N respectively. By Corollary 11.21, any bijection between A and B is an elementary map. By Proposition 11.7, it extends to the required isomorphism between $\text{acl } A = M$ and $\text{acl } B = N$. \square

11.23 Corollary (*T strongly minimal.*) Strongly minimal theories are λ -categorical for every $\lambda > |L|$.

Proof As $|\text{acl } A| \leq |L(A)|$, all models of cardinality λ have the same dimension λ . \square

11.24 Proposition (*T strongly minimal.*) For every model N of cardinality $\geq |L|$ the following are equivalent

1. N is saturated;
2. $\dim N = |N|$.

Proof $2 \Rightarrow 1$. Assume 2 and let $k : M \rightarrow N$ be an elementary map of cardinality $< |N|$ and let $b \in M$. We want an extension of k defined in b . If $b \in \text{acl}(\text{dom } k)$ the required extension exists by Proposition 11.7. Otherwise, pick any $c \in N \setminus \text{acl}(\text{img } k)$, which exist as $|k| < \dim N = |N|$. By Proposition 11.20, $k \cup \{ \langle b, c \rangle \}$ is the required extension.

$1 \Rightarrow 2$. If $B \subseteq N$ is a base of N the following type is not realized in N

$$p(x) = \left\{ \neg \varphi(x) : \varphi(x) \in L(B) \text{ is algebraic} \right\}$$

Therefore, if N is saturated, $|B| = |N|$. \square

11.25 Exercise (*T strongly minimal.*) Prove that every infinite algebraically closed set is a model. \square

11.26 Exercise (*T strongly minimal.*) Prove that every model is homogeneous. \square

11.27 Exercise (*T strongly minimal.*) Prove that if $\dim N = \dim M + 1$ then there is no model K such that $M \prec K \prec N$. \square

Chapter 12

Countable models

In this chapter we fix a signature L , a complete theory T without finite models, and a saturated model \mathcal{U} of inaccessible cardinality κ larger than $|L|$. (Expect that all relevant theorems are proved under the assumption that L is countable.) The notation and implicit assumptions are as in Section 9.3.

1 The omitting types theorem

We say that the formula $\varphi(x)$ **isolates** the type $p(x)$ if $\varphi(x)$ is consistent and $\varphi(x) \rightarrow p(x)$. When Δ is a set of formulas, we say that **Δ isolates $p(x)$** if some formula in Δ does. In this chapter Δ is always a set of the form $L_x(A)$ and we say **A isolates $p(x)$** or every simply **$p(x)$ is isolated** when A is clear. We say that a model M **omits $p(x)$** if it does not realize it.

Observe that if $p(x) \subseteq L(M)$ then M realizes $p(x)$ if and only if M isolates $p(x)$. Therefore if A isolates $p(x)$, then every model containing A realizes $p(x)$. Below we prove that the converse also holds when L and A are countable. This a famous classical theorem which is called the *omitting types theorem*.

The construction of a model M omitting $p(x)$ proceeds by stages. Along the construction we preserve the property of being *isolated* since that of being *realized* is not well behaved in sets which are not models. In the limit, when a model is obtained, these two properties coincide.

The omitting types theorem requires the following lemma which is an analogue of the Kuratowski-Ulam theorem (i.e., the so-called Fubini theorem for Baire category).

12.1 Lemma *Assume $L(A)$ is countable. Let $p(x) \subseteq L(A)$ and suppose that A does not isolate $p(x)$. Then every consistent formula $\psi(z) \in L(A)$ has a solution a such that A, a does not isolate $p(x)$.*

Proof We construct sequence of formulas $\langle \psi_i(z) : i < \omega \rangle$ such that any realization a of the type $q(z) = \{\psi_i(z) : i < \omega\}$ is as required by the lemma.

To begin with, we fix an enumeration $\langle \xi_i(x; z) : i < \omega \rangle$ of all formulas in $L_{x,z}(A)$ and set $\psi_0(z) = \psi(z)$. At stage $i + 1$, if $\xi_i(x; z) \wedge \psi_i(z)$ is inconsistent, let $\psi_{i+1}(z) = \psi_i(z)$, otherwise let

$$\psi_{i+1}(z) = \psi_i(z) \wedge \exists x [\xi_i(x; z) \wedge \neg \varphi(x)]$$

for some formula $\varphi(x) \in p$ such that the resulting $\psi_{i+1}(z)$ is consistent. If possible, this guarantees that $\xi_i(x; a)$ for any $a \models q(z)$ does not isolate $p(x)$. The proof is complete if we can show that it is always possible to find a formula $\varphi(x)$ as required.

Suppose by way of contradiction that no formula makes $\psi_{i+1}(z)$ consistent, that is,

$$\xi_i(x; z) \wedge \psi_i(z) \rightarrow \varphi(x)$$

for every $\varphi(\mathbf{x}) \in p$. This immediately implies that

$$\exists z [\zeta_i(\mathbf{x}; z) \wedge \psi_i(z)] \rightarrow p(\mathbf{x}),$$

that is, $p(\mathbf{x})$ is isolated by a formula in $L_{\mathbf{x}}(A)$, which contradicts our assumptions. \square

12.2 Theorem (Omitting types theorem) Assume $L(A)$ is countable. Then for every consistent $p(\mathbf{x}) \subseteq L(A)$ the following are equivalent

1. all models containing A realize $p(\mathbf{x})$;
2. $p(\mathbf{x})$ is isolated.

The theorem owes its name to the contrapositive of implication $1 \Rightarrow 2$.

Proof Implication $2 \Rightarrow 1$ is clear, we prove $1 \Rightarrow 2$. Assume A does not isolate $p(\mathbf{x})$. The model M is the union of a chain $\langle A_i : i < \omega \rangle$ of countable subsets of \mathcal{U} that starts with $A_0 = A$. Along the construction we require as inductive hypothesis that A_i does not isolate $p(\mathbf{x})$. At the end, M will not isolate $p(\mathbf{x})$ which for a model is equivalent to omitting.

We proceed as in the proof of the downward Löwenheim-Skolem theorem (precisely, we use the second proof 2.40). Lemma 12.1 ensure that we can satisfy any consistent formula in A_i and preserve the inductive hypothesis. \square

Gerald Sacks once famously remarked: *Any fool can realize a type but it takes a model theorist to omit one.* (Though, as remarked above, the proof reminds more of set theory than model theory.)

12.3 Example The following example shows that in the omitting types theorem we cannot drop the assumption that $L(A)$ is countable. Let F be the set of all bijection between two uncountable sets, X and Y . Let M be the model with domain the disjoint union of F , X and Y . The language has a ternary relation symbol for $f(x) = y$ and unary relations for X and Y . Let \mathcal{U} be a saturated elementary extension of M .

Let $Y_1 \subseteq Y$ be countable. Let $c \in Y \setminus Y_1$ and set $p(y) = \text{tp}(c/X, Y_1)$. We claim that $p(y)$ is not isolated but that it is realized in every model containing X, Y_1 .

No formula could be equivalent to $p(y)$ (not even a type with finitely many parameters). In fact, for every pair of finite sets $Y_0 \subseteq Y_1$ and $X_0 \subseteq X$ there is an automorphism of M that fixes $Y_0 \cup X_0$ and maps c to some (any) element of $Y_1 \setminus Y_0$. This automorphism extends to an automorphism of \mathcal{U} and maps c to an element that does not realize $p(y)$.

The type $p(y)$ cannot be omitted because every model N containing X has necessarily uncountably many elements of sort Y and therefore realizes $p(y)$. \square

12.4 Exercise Let $p(x) \subseteq L(B)$ and $p_n(x) \subseteq L(A)$, for $n < \omega$, be consistent types such that

$$p(x) \rightarrow \bigvee_{n < \omega} p_n(x)$$

Prove that there is an $n < \omega$ and a formula $\varphi(x) \in L(A)$ consistent with $p(x)$ such that

$$p(x) \wedge \varphi(x) \rightarrow p_n(x).$$

\square

12.5 Exercise Let M be a second countable topological space (i.e. the topology has a countable base). We say that $A \subseteq M$ is meager if it is the countable union of nowhere dense sets.

Use Lemma 12.1 to prove the Kuratowski-Ulam Theorem, i.e. that for $A \subseteq M^2$ the following are equivalent (w.r.t. the product topology)

1. A is meager in M^2 ;
2. $\{x \in M : A \cap \{x\} \times M \text{ is not meager}\}$ is meager in M .

Hint: Use the base of the topology as predicates of a first-order language. □

2 Prime and atomic models

We say that M is **prime over A** if $A \subseteq M$ and for every N containing A there is an elementary embedding $h : M \rightarrow N$ that fixes A . When A is empty we simply say that M is **prime**.

There is no syntactic analogue of primeness; the notion that comes most close (and works pretty well when everything is countable) is atomicity. For $a \in \mathcal{U}^{[x]}$ we say that **a is isolated over A** if the type $p(x) = \text{tp}(a/A)$ is isolated. Note that this is equivalent to claiming that a is an isolated point in $\mathcal{U}^{[x]}$ w.r.t. the A -topology defined in Section 9.3. We say that M is **atomic over A** if $A \subseteq M$ and every $a \in M^{<\omega}$ is isolated over A . When A is empty we say that M is **atomic**.

12.6 Proposition Let b and a be finite tuples. Then the following are equivalent

1. A isolates b, a ;
2. A, a isolates b and A isolates a .

Proof Let $p(x, z) = \text{tp}(b, a/A)$ and note that $p(x, a) = \text{tp}(x/A, a)$ and $\exists x p(x, z) = \text{tp}(a/A)$.

$1 \Rightarrow 2$ Let $\varphi(x, z) \in p$ be such that $\varphi(x, z) \rightarrow p(x, z)$. It follows that $\varphi(x, a) \rightarrow p(x, a)$ and $\exists x \varphi(x, z) \rightarrow \exists x p(x, z)$. Therefore 2 holds.

$2 \Rightarrow 1$ Fix $\varphi(x; z), \psi(z) \in L(A)$ such that $\varphi(x; a)$ isolates $p(x; a)$ and $\psi(z)$ isolates $\exists x p(x; z)$. Let $\xi(x; z) \in p$ be arbitrary. As $\varphi(x; a) \rightarrow \xi(x; a)$, the formula $\forall x [\varphi(x; z) \rightarrow \xi(x; z)]$ belongs to $\exists x p(x, z)$. Hence $\psi(z) \rightarrow \forall x [\varphi(x; z) \rightarrow \xi(x; z)]$. As this holds for all $\xi(x; z) \in p$, we conclude that $\psi(z) \wedge \varphi(x; z)$ isolates $p(x, z)$. □

The straightforward direction of the proposition above yields the following useful proposition.

12.7 Proposition If M is atomic over A then M is atomic over A, a for every finite $a \in M^{<\omega}$.

Proof Let $b \in M^{[x]}$ be a finite tuple. Then A isolates b, a hence A, a isolates b . □

12.8 Proposition Let $k : M \rightarrow N$ be an elementary map and suppose that M is atomic over $\text{dom } k$. Then for every $b \in M$ there is a $c \in N$ such that $k \cup \{ \langle b, c \rangle \} : M \rightarrow N$ is elementary.

Proof Let $p(x; z) = \text{tp}(b; a)$ where a is an enumeration of $\text{dom } k$. Let $\varphi(x; z) \in L$ be such that $\varphi(x; a) \rightarrow p(x; a)$. Note that, by elementarity, $\varphi(x; ka) \rightarrow p(x; ka)$.

Hence the required c is any solution of $\varphi(x;ka)$ in N . \square

A limiting assumption in Proposition 12.7 is that a need to be finite. Therefore the following proposition is restricted to countable models.

12.9 Proposition *Any two countable models atomic over A are isomorphic.*

Proof Easy, using Propositions 12.7 and 12.8 and back-and-forth. \square

12.10 Proposition *Assume $L(A)$ is countable. Then for every model M the following are equivalent*

1. M is countable and atomic over A ;
2. M is prime over A .

Proof $1 \Rightarrow 2$ By Propositions 12.7 and 12.8. $2 \Rightarrow 1$ Some countable model containing A exists, as M embeds in it, M has also to be countable. Now we prove that M is atomic over A . Suppose for a contradiction that there is some $b \in M^{<\omega}$ such that $p(x) = \text{tp}(b/A)$ is not isolated. By the omitting types theorem there is a model N containing A that omits $p(x)$. Then there cannot be any A -elementary embedding of M into N . \square

12.11 Proposition *Assume $L(A)$ is countable. Then the following are equivalent*

1. there are models atomic over A ;
2. for every $|z| < \omega$, every consistent $\varphi(z) \in L(A)$ has a solution that is isolated over A .

Note that 2 says that in $\mathcal{U}^{|z|}$ isolated points are dense w.r.t. the topology defined in Section 9.3.

Proof Implication $1 \Rightarrow 2$ hold by elementarity. To prove $2 \Rightarrow 1$ we construct by induction a sequence $\langle a_i : i < \omega \rangle$. Reasoning as in (the second proof of) the downward Löwenheim-Skolem theorem ensures that $A \cup \{a_i : i < \omega\}$ is a model. To obtain an atomic model we require that $a_{|i}$ is isolated over A .

Suppose $a_{|i}$ has been defined and let $\varphi(z) \in L(A)$ be the formula that isolates $\text{tp}(a_{|i}/A)$. Let $\psi(x;z) \in L(A)$ be such that $\psi(x;a_{|i})$ is consistent (we leave to the reader the details of the enumeration of such formulas). Then $\psi(x;z) \wedge \varphi(z)$ is also consistent and by assumption it has a solution $b;c$ that is isolated over A . As $a_{|i} \equiv_A c$, there is an A -automorphism such that $fc = a_{|i}$. Therefore $fb;a_{|i}$ is a solution $\psi(x;z)$ that is also isolated over A . Then we can set $a_i = fb$. \square

3 Countable categoricity

Here we present some important characterizations of ω -categoricity. The second property below can be stated in different equivalent ways; for convenience, these equivalents are considered in a separate proposition. For the time being we introduce the following generalization (which we will prove is completely unnecessary): we say that T is ω -categorical over A if any two countable models containing A are isomorphic. We say ω -categorical for ω -categorical over \emptyset .

12.12 Theorem (Engeler, Ryll-Nardzewsky, and Svenonius Theorem) Assume $L(A)$ is countable. The following are equivalent:

1. T is ω -categorical over A ;
2. every type $p(\bar{x}) \subseteq L(A)$ with $|\bar{x}| < \omega$ is isolated.

The set A is introduced for convenience. By 3 of Proposition 12.13 below, no theory is ω -categorical over an infinite set, and categoricity over some finite A is equivalent to categoricity over \emptyset (see Exercise 12.14).

Proof The implication $1 \Rightarrow 2$ is an immediate consequence of the omitting types theorem. In fact, if $p(\bar{x})$ is a non-isolated A -type, then there are two countable models M and N containing A such that M realizes $p(\bar{x}) \subseteq L(A)$ while N omits it. Then M and N cannot be isomorphic over A . As for implication $2 \Rightarrow 1$, observe that 2 implies that every countable model containing A is atomic over A . But, by Proposition 12.9, countable atomic models are unique up to isomorphism. \square

12.13 Proposition Fix a set A and a finite tuple of variables \bar{x} . The following are equivalent

1. every A -type $p(\bar{x})$ is isolated;
2. $S_{\bar{x}}(A)$ is finite;
3. $L_{\bar{x}}(A)$ is finite up to equivalence;
4. in $\mathcal{U}^{|\bar{x}|}$ there is a finite number of orbits under $\text{Aut}(\mathcal{U}/A)$.

Proof To prove the implication $1 \Rightarrow 2$ observe that $\mathcal{U}^{|\bar{x}|}$ is the union of sets of the form $p(\mathcal{U})$ where $p \in S_{\bar{x}}(A)$. If these types are isolated then $\mathcal{U}^{|\bar{x}|}$ is the union of A -definable sets. By compactness this union has to be finite. To prove $2 \Rightarrow 1$ let $p \in S_{\bar{x}}(A)$. If $S_{\bar{x}}(A)$ is finite, $\neg p(\mathcal{U})$ is the union of finitely many type definable sets. A finite union of type definable sets is type definable. So $\neg p(\mathcal{U})$ is type definable. Hence $p(\mathcal{U})$ is isolated. We prove implication $2 \Rightarrow 3$ observe that each formula in $L_{\bar{x}}(A)$ is equivalent to the disjunction of the types in $S_{\bar{x}}(A)$ that contain this formula. If $S_{\bar{x}}(A)$ is finite, $L_{\bar{x}}(A)$ is finite up to equivalence. Implication $3 \Rightarrow 2$ is clear and equivalence $2 \Leftrightarrow 4$ follows from the characterization of orbits as type-definable sets. \square

12.14 Exercise Prove that the following are equivalent for every finite set A

1. T is ω -categorical;
2. T is ω -categorical over A .

\square

12.15 Exercise Prove that the following are equivalent

1. T is ω -categorical;
2. there is countable model that is both saturated and atomic.

\square

12.16 Exercise Assume L is countable and that T is complete. Suppose that for every finite tuple \bar{x} there is a model M that realizes only finitely many types in $S_{\bar{x}}(T)$. Prove that T is ω -categorical. \square

4 Small theories

Let T be, as always in this chapter, a complete theory without finite models. We say that T is **small over A** if $S_x(A)$ is countable for every x of finite length. When A is empty, we simply say that T is **small**. The set A is introduced for convenience, in the literature it is used only for $A = \emptyset$. A different term is used in another very interesting case, e.g. a theory small over every countable set A is said to be ω -stable.

12.17 Proposition *No T is small over an uncountable set and if T is small (over \emptyset) then it is small over any finite A .*

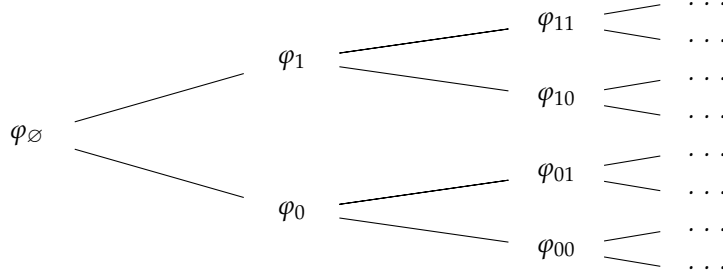
Proof Let a be an enumeration of A . As $S_x(A) = \{p(x; a) : p \in S_{x; z}(T)\}$ the proposition is immediate. \square

Below we identify $S_x(A)$ with $\mathcal{U}^{|x|}/\equiv_A$

12.18 Definition Let Δ be a set of formulas (we mainly use $\Delta = L_x(A)$ in this section). A **binary tree of formulas in Δ** is a sequence $\langle \varphi_s : s \in 2^{<\lambda} \rangle$ of formulas in $\Delta \cup \{\top\}$ such that

1. for each $s \in 2^\lambda$ the type $p_s = \{\varphi_{s|n} : n < |s|\}$ is consistent;
2. $p_s \cup p_r$ is inconsistent for any two distinct $s, r \in 2^\lambda$.

(Condition 2 is usually obtained by taking $\varphi_{s0} \leftrightarrow \neg \varphi_{s1}$ for every s .) We call λ the height of the tree. If the height is not specified, we assume it is ω . We may depict a binary tree of formulas as follows



Where branches are consistent types and distinct branches are inconsistent. \square

Let $S(\Delta)$ be denote the set of maximal consistent Δ -types.

12.19 Lemma *Suppose Δ is countable and closed under negation. Then the following are equivalent*

1. there is a binary tree of formulas in Δ ;
2. $|S(\Delta)| = 2^\omega$;
3. $|S(\Delta)| > \omega$.

Proof As implications $1 \Rightarrow 2 \Rightarrow 3$ are clear, it suffices to prove $3 \Rightarrow 1$. We assume that $S(\Delta)$ is uncountable and define a tree of formulas in Δ by induction. Begin with $\varphi_\emptyset = \top$. For $s \in 2^{<\omega}$ let p_s be as in the definition above. Assume as induction hypothesis that p_s has uncountably many extensions in $S(\Delta)$. This will guarantee the consistency of the branches.

It suffices to show that there is a formula $\psi \in \Delta$ such that both $p_s \cap \{\psi\}$ and $p_s \cap \{\neg\psi\}$ have uncountably many extensions in $S(\Delta)$. In fact, we if we define $\varphi_{s0} = \psi$ and $\varphi_{s1} = \neg\psi$ this preserves the induction hypothesis.

Suppose for a contradiction that such a formula ψ does not exist. Consider the following type

$$q = \left\{ \xi \in \Delta : p_s \cap \{\neg\xi\} \text{ has } \leq \omega \text{ extensions in } S(\Delta) \right\}.$$

This type is consistent otherwise $\neg\xi_1 \vee \dots \vee \neg\xi_n$ would hold for some $\xi_i \in q$. This cannot happen because p_s has uncountably many extensions in $S(\Delta)$ while the $p_s \cap \{\neg\xi_i\}$ have not.

If the formula ψ required above does not exist, q is complete hence belongs to $S(\Delta)$. But there are countably many types distinct from q , so this contradicts 3. \square

12.20 Proposition Suppose $L(A)$ is countable. The following are equivalent

1. T is small over A ;
2. there exists a countable saturated model containing A ;
3. there is no binary tree of formulas in $L_x(A)$ for any finite x .

Proof $1 \Rightarrow 2$ There is a countable model M containing A that is weakly saturated (see Proposition 9.12). There is a countable homogeneous model N containing M (see Exercise 9.13). Clearly N is also weakly saturated. Then it is saturated by Corollary 9.13.

$2 \Rightarrow 3$ Clear.

$3 \Rightarrow 1$ By Lemma 12.19. \square

12.21 Proposition A small theory has countable atomic models over every countable set A .

Proof We prove that every formula in $L_x(A)$, where $|x| < \omega$, has a solution isolated over A . Then it suffices to apply Proposition 12.11.

Suppose for a contradiction that $\varphi(x) \in L(A)$ is consistent but has no solution isolated over A . Then there is a formula $\psi(x) \in L(A)$ such that both $\varphi(x) \wedge \psi(x)$ and $\varphi(x) \wedge \neg\psi(x)$ are consistent, otherwise $\varphi(x)$ would imply a complete type and every solution of $\varphi(x)$ would be isolated. Fix such a $\psi(x)$. Clearly neither $\varphi(x) \wedge \psi(x)$ nor $\varphi(x) \wedge \neg\psi(x)$ have a solution isolated over A . This allows to construct a tree of formulas in $L_x(A)$ and prove that T is not small over A . \square

12.22 Exercise Suppose Δ is countable and closed under negation. Prove that if there is a binary tree of formulas then there is a binary tree such that $\varphi_{s0} = \neg\varphi_{s1}$ and $\varphi_\emptyset = \top$. \square

12.23 Exercise Let $|x| = 1$. Prove that if $S_x(A)$ is countable for every finite set A , then T is small. \square

12.24 Exercise (Vaught) Prove that no complete theory has exactly 2 countable models (assume L is countable – though it is not really necessary).

Hint: suppose T has exactly two countable models. Then T is small and there

are a countable saturated model N and an atomic model $M \subseteq N$. As T is not ω -categorical, $M \not\cong N$ and there is finite tuple a that is not isolated over \emptyset . Let K be an atomic model over a . Clearly $K \not\cong M$ and, by Exercises 12.14 and 12.15, also $K \not\cong N$. \square

5 A toy version of a theorem of Zil'ber

As an application we prove that if T is ω -categorical and strongly minimal then it is not finitely axiomatizable.

We say that T has the **finite model property** if for every sentence $\varphi \in L$ there is a finite substructure $A \subseteq \mathcal{U}$ such that

$$\text{fmp} \quad \mathcal{U} \models \varphi \Leftrightarrow A \models \varphi$$

The property is interesting because of the following proposition.

12.25 Proposition *If T has the finite model property then it is not finitely axiomatizable.*

Proof Assume fmp and suppose for a contradiction that there is a sentence $\varphi \in L$ such that $T \vdash \varphi$ but $T \not\vdash \varphi$. Then $A \models \varphi$ for some finite structure A . But $T \vdash \exists^{>k} x (x = x)$ for every k . A contradiction. \square

We need the following definition. We say that $C \subseteq \mathcal{U}$ is an **homogeneous set** if for every pair of tuples $a, c \in C^{<\omega}$ such that $a \equiv c$ and for every $b \in C$ there is a $d \in C$ such that $a, b \equiv c, d$.

12.26 Lemma *Suppose L is countable. If T is ω -categorical and every finite set is contained in a finite homogeneous set, then T has the finite model property.*

Proof We prove fmp also for formulas with parameters. We prove that for all n there is a finite structure $A \subseteq \mathcal{U}$ where fmp holds for all sentences $\varphi \in L(A)$ such that

$$\# \quad \text{number of parameters in } \varphi + \text{number of quantifiers in } \varphi \leq n.$$

Fix n and pick some finite set A that is homogeneous and such that all types $p(z) \subseteq L$ with $|z| \leq n$ have a realization in $A^{|z|}$. Now we prove fmp by induction on the syntax of φ .

The claim for atomic formulas is witnessed by any finite structure that contains the parameters of the formula. Such finite substructure exists in fact it suffices to take the algebraic closure which, in an ω -categorical theory, is finite (by 3 of Lemma 12.13). Induction for Boolean connectives is straightforward. As for induction step for the existential quantifier, consider the formula $\exists x \varphi(x; c)$, where $c \in A^{<n}$ and $|x| = 1$. Implication \Leftarrow of fmp follows immediately from the induction hypothesis and from the fact that, if $\exists x \varphi(x; c)$ satisfy $\#$, also $\varphi(d; c)$ satisfies it. As for \Rightarrow , assume $\mathcal{U} \models \exists x \varphi(x; c)$. Let $a, b \in A^{<\omega}$ be a solution of $\varphi(x; z)$ such that $a \equiv c$. Such a solution exists because all types with $\leq n$ variables are realized in A . By homogeneity there is a $d \in A$ such that $a, b \equiv c, d$ and therefore $A \models \varphi(d; c)$. Note that in $\#$ we can add the requirement that all function symbols in φ have arity $< n$. Now note that if all types $p(z) \subseteq L$ with $|z| \leq n$ have a realization in $A^{|z|}$, then A is a substructure w.r.t. a fragment which only contains functions of arity $< n$. \square

12.27 Proposition *If T is strongly minimal, then every algebraically closed set is homogeneous.*

Proof Let A be algebraically closed and fix some $a, c \in A^{<\omega}$ such that $a \equiv c$. Let b be an element of A . Suppose first the case $b \in \text{acl } a$. Fix an $f \in \text{Aut}(\mathcal{U})$ such that $f(a) = c$. Then $d = fb$ is the required element, in fact $a, b \equiv c, d$ and $d \in \text{acl } c \subseteq A$. Now, suppose instead that $b \notin \text{acl } a$. Then any $d \notin \text{acl } c$ satisfies $a, b \equiv c, d$. Such a d exists in A otherwise $A = \text{acl } c \neq \text{acl } a$ which contradicts $a \equiv c$. \square

From the propositions above we finally obtain the following.

12.28 Theorem *A theory which is ω -categorical and strongly minimal is not finitely axiomatizable.*

Proof If T is ω -categorical the algebraic closure of a finite set is finite. Therefore from Proposition 12.27 we infer that T satisfies the assumptions of Lemma 12.26. Hence T has the finite model property, so, by Proposition 12.25 it is not finitely axiomatizable. \square

12.29 Exercise Assume L is countable and let T be strongly minimal. Prove that the following are equivalent

1. T is ω -categorical;
2. the algebraic closure of a finite set is finite.

Implication $1 \Rightarrow 2$ does not require the strong minimality of T . \square

6 Notes and references

An uncountable, non-isolated, complete type that cannot be omitted was produced by Gebhard Fuhrken in 1962. Example 12.3 is inspired by a post of Alex Kruckman to StackExchange [1]. I am not aware of other expositions of this (or other) example.

A famous theorem of Boris Zil'ber claims that Theorem 12.28 holds for any totally categorical theory. The same theorem has been proved independently by Cherlin, Harrington and Lachlan with a proof that uses the classification of finite simple groups. This theorem signs the birth of a subject known as *geometric stability theory* which studies in depth the geometric properties of model theories which we briefly hinted to in Chapter 11. The interested reader may consult Pillay's monograph [2].

[1] Alex Kruckman, *Counterexample to the omitting types in uncountable language* (2017), available at <https://math.stackexchange.com/q/2434851>. URL accessed 2017-11-19.

[2] Anand Pillay, *Geometric stability theory*, Oxford Logic Guides, vol. 32, 1996.

Chapter 13

Imaginaries

The description of first-order definability is simplified if we allow definable sets to be used as second-order parameters in formulas. This leads to the theory of (elimination of) *imaginaries*. The technical reason that induced Shaloh to introduce imaginaries will only be clear later, see Sections 17.5, but the theory is of independent interest.

In this chapter we fix a signature L , a complete theory T without finite models, and a saturated model \mathcal{U} of inaccessible cardinality κ strictly larger than $|L|$. The notation and implicit assumptions are as in Section 9.3.

1 Many-sorted structures

A many-sorted language consists of three disjoint sets. Besides the usual L_{fun} and L_{rel} , we have a set L_{srt} whose elements are called **sorts**. The language also includes a **(many-sorted) arity function** that assigns to function and relation symbols r, f a tuple of sorts of finite positive length which we call **arity**.

A many-sorted structure M consists of

1. a set M_s , for each $s \in L_{\text{srt}}$;
2. a function $f^M : M_{s_1} \times \cdots \times M_{s_n} \rightarrow M_{s_0}$, for each $f \in L_{\text{fun}}$ of arity $\langle s_0, \dots, s_n \rangle$;
3. a relation $r^M \subseteq M_{s_0} \times \cdots \times M_{s_n}$, for each $r \in L_{\text{rel}}$ of arity $\langle s_0, \dots, s_n \rangle$.

For every sort s we fix a sufficiently large set of variables V_s . Now we define terms and their respective sorts by induction.

All variables are terms of their respective sort. If t_1, \dots, t_n are terms of sorts s_1, \dots, s_n and $f \in L_{\text{fun}}$ is of arity $\langle s_0, \dots, s_n \rangle$ then $f t_1, \dots, t_n$ is a term of sort s_0 .

Formulas are defined as follows. If $r \in L_{\text{rel}}$ has arity $\langle s_0, \dots, s_n \rangle$ then $r t_0, \dots, t_n$ is a formula. Also, $t_1 = t_2$ is formula for every pair of terms of equal sort. All other formulas are constructed by induction using the propositional connectives \neg and \vee and the quantifier $\exists x$ (or any other reasonable choice of logical connectives).

Truth of formulas is defined as for one-sorted languages, except that here we require that the witness of the quantifier $\exists x$ belongs to M_s , where s is the sort of the variable x .

Models of second-order logic are arguably the most widely used examples of many-sorted structures. They may be described using a language with a sort n for every $n \in \omega$. The sort 0 is used for the first-order elements; the sort $n > 0$ is used for relations of arity n . For every $n > 0$ the language has a relation symbol \in_n of arity $\langle 0^n, n \rangle$, where $0^n = 0, \overset{n}{\text{times}}, 0$. There are also arbitrarily many function and relation symbols of sort $\langle 0^n \rangle$ for any $n > 0$.

2 The eq-expansion

 **Warning:** the structure \mathcal{U}^{eq} and the theory T^{eq} defined below do not coincide with the standard ones introduced by Shelah. As the difference is merely cosmetic, introducing new notation would be overkill and we prefer to abuse the existing terminology. In Section 6 below we compare our definition with the standard one.

Given a language L we define a many-sorted language L^{eq} which has a sort for each partitioned formula $\sigma(x; z) \in L$ and a sort 0 which we call the **home sort**. (Partitioned formulas have been introduced in Definition 1.14.)

For better legibility, we will pretend that all formulas σ depend on the same pair of tuples $x; z$, so we assume that $x; z$ are infinite tuples.

The home sort is also called the **first-order sort**. All other sorts are **second-order**. First of all, L^{eq} contains all relations and functions of L . The many-sorted arity of a relation r is $\langle 0^{n_r} \rangle$, where n_r is the arity of r in L . Similarly, the many-sorted arity of a function f is $\langle 0^{1+n_f} \rangle$, where n_f is the arity of f in L . Moreover, L^{eq} contains a relation symbol $\in_{\sigma(x; z)}$ for each sort $\sigma(x; z)$. These relation symbols have arity $\langle 0^{|x|}, \sigma(x; z) \rangle$. As there is no risk of ambiguity, in what follows we write \in without subscript.

The model \mathcal{U}^{eq} has \mathcal{U} as domain for the home sort. The domain for the sort $\sigma(x; z)$ contains the definable sets $\mathcal{A} = \sigma(\mathcal{U}; b)$ for some $b \in \mathcal{U}^{|z|}$. The symbols in L have the same interpretation as in the one-sorted case, and \in is interpreted as set membership. We write T^{eq} for $\text{Th}(\mathcal{U}^{\text{eq}})$.

As usual L^{eq} also denotes the set of formulas constructed in this language and, if $A \subseteq \mathcal{U}^{\text{eq}}$, we write $L^{\text{eq}}(A)$ for the language and the set of formulas that use elements of A as parameters. We write $L(A)$ for the set of formulas in $L^{\text{eq}}(A)$ that contain no second-order variables (neither free nor quantified).

We use the symbol \mathcal{X} to denote a generic second-order variable.

It is important to note right away that this expansion of \mathcal{U} is a mild one: the definable subsets of the home sort of \mathcal{U}^{eq} are the same as those of \mathcal{U} . In particular, iterating the expansion would not yield anything new.

13.1 Proposition *Let $\mathcal{X} = \mathcal{X}_1, \dots, \mathcal{X}_n$ be a tuple of second order variables of sort $\sigma_i(x; z)$ for $i = 1, \dots, n$. Let $\varphi(u; \mathcal{X}) \in L^{\text{eq}}$ where u is a tuple of first-order variables. Then there is a formula $\varphi'(u; z) \in L$ such that*

$$\forall \mathcal{X}, z \left[\bigwedge_{i=1}^n \mathcal{X}_i = \{x : \sigma_i(x; z)\} \rightarrow \forall u [\varphi(u; \mathcal{X}) \leftrightarrow \varphi'(u; z)] \right]$$

When $n = 0$ the proposition asserts that L_u^{eq} and L_u have the same expressive power.

Proof By induction on syntax. When φ is atomic, we set $\varphi' = \varphi$ unless it is of the form $t \in \mathcal{X}$ for some tuple of terms t or it has the form $\mathcal{X}_1 = \mathcal{X}_2$. In the first case φ' is the formula $\sigma(t; z)$. In the second case it is the formula $\forall x [\sigma_1(x; z) \leftrightarrow \sigma_2(x; z)]$.

The connectives stay unchanged except for the quantifiers $\exists \mathcal{X}$, where \mathcal{X} is a second-order variable, say of sort $\sigma(x; z)$. These quantifiers are replaced by $\exists z$. □

Proposition 13.1 implies in particular that we can always eliminate second-order

quantifiers. This is an obvious fact that may be obscured by the notation: we can replace $\exists \mathcal{X}$ by $\exists z$ if we substitute $\sigma(t; z)$ for $t \in \mathcal{X}$ in the quantified formula.

Proposition 13.1 should convince the reader that the move from \mathcal{U} to \mathcal{U}^{eq} is almost trivial.

13.2 Remark From Proposition 13.1 it follows that for every $A \subseteq \mathcal{U}^{\text{eq}}$, there is a $B \subseteq \mathcal{U}$ such that $L(B)$ is at least as expressive as $L(A)$. The point of \mathcal{U}^{eq} is that there might not be any $B \subseteq \mathcal{U}$ such that $L(B)$ is exactly as expressive as $L^{\text{eq}}(A)$. For instance, suppose L contains only an equivalence relation with infinitely many classes, all with infinite elements. Let \mathcal{A} be an equivalence class. Then \mathcal{A} is definable in $L(B)$ if and only if $B \cap \mathcal{A} \neq \emptyset$. But no element of \mathcal{A} is definable in $L^{\text{eq}}(\{\mathcal{A}\})$. \square

If $\mathcal{V} \preceq \mathcal{U}$ we write \mathcal{V}^{eq} for the substructure of \mathcal{U}^{eq} that has \mathcal{V} as domain of the home sort and the set of definable sets of the form $\sigma(\mathcal{U}; b)$ for some $b \in \mathcal{V}^{|z|}$ as domain of the sort $\sigma(x; z)$. The following proposition claims that the elementary substructures of \mathcal{U}^{eq} are exactly those of the form \mathcal{V}^{eq} for some $\mathcal{V} \preceq \mathcal{U}$.

13.3 Proposition *The following are equivalent for every structure \mathcal{V}^+ of signature L^{eq}*

1. $\mathcal{V}^+ \preceq \mathcal{U}^{\text{eq}}$;
2. $\mathcal{V}^+ = \mathcal{V}^{\text{eq}}$ for some $\mathcal{V} \preceq \mathcal{U}$.

Proof Implication $2 \Rightarrow 1$ is a direct consequence of Proposition 13.1. We prove $1 \Rightarrow 2$. Let \mathcal{V} be the domain of the home sort of \mathcal{V}^+ . It is clear that $\mathcal{V} \preceq \mathcal{U}$. Let $\mathcal{A} \in \mathcal{V}^{\text{eq}}$ have sort $\sigma(x; z)$, say $\mathcal{A} = \sigma(\mathcal{U}; b)$ for some $b \in \mathcal{V}^{|z|}$. As $\exists^1 \mathcal{X} \forall x [x \in \mathcal{X} \leftrightarrow \sigma(x; b)]$ holds in \mathcal{U}^{eq} , by elementarity it holds in \mathcal{V}^+ and therefore $\mathcal{A} \in \mathcal{V}^+$. This proves $\mathcal{V}^{\text{eq}} \subseteq \mathcal{V}^+$. A similar argument proves the converse inclusion. \square

13.4 Proposition *Let $A \subseteq \mathcal{U}^{\text{eq}}$. Then every type $p(u; \mathcal{X}) \subseteq L^{\text{eq}}(A)$ finitely consistent in \mathcal{U}^{eq} is realized in \mathcal{U}^{eq} . That is, \mathcal{U}^{eq} is saturated.*

Proof By Remark 13.2, there are some $B \subseteq \mathcal{U}$ and some $q(u; \mathcal{X}) \subseteq L^{\text{eq}}(B)$ equivalent to $p(u; \mathcal{X})$. This already proves the proposition when \mathcal{X} is the empty tuple. Otherwise, let $q'(u; z)$ be obtained replacing every formula $\varphi(u; \mathcal{X})$ in $q(u; \mathcal{X})$ with the formula $\varphi'(u; z)$ given in Proposition 13.1. Then $q'(u; z)$ is finitely consistent in \mathcal{U} . Assume for clarity of notation that \mathcal{X} is a single variable of sort $\sigma(x; z)$. If $c; b \models q'(u; z)$, then $c; \sigma(\mathcal{U}; b) \models q(u; \mathcal{X})$. \square

Automorphisms of a many-sorted structure are defined in the obvious way: sorts are preserved as well as functions and relations. Every automorphism $f : \mathcal{U} \rightarrow \mathcal{U}$ extends to an automorphism $f : \mathcal{U}^{\text{eq}} \rightarrow \mathcal{U}^{\text{eq}}$ as follows. If $\mathcal{A} = \sigma(\mathcal{U}; b)$ we define $f\mathcal{A} = \sigma(\mathcal{U}; fb) = f[\mathcal{A}]$, which clearly preserves the sort and the relation \in . Clearly, this extension is unique.

The homogeneity of \mathcal{U}^{eq} follows by back-and-forth as in the one-sorted case.

13.5 Proposition *Every elementary map $k : \mathcal{U}^{\text{eq}} \rightarrow \mathcal{U}^{\text{eq}}$ of cardinality $< \kappa$ extends to an automorphism of \mathcal{U}^{eq} .* \square

3 The definable closure in the eq-expansion

We may safely identify automorphism of \mathcal{U} with automorphisms of \mathcal{U}^{eq} . Let $A \subseteq \mathcal{U}^{\text{eq}}$ and let a be a tuple of elements of \mathcal{U}^{eq} . We denote by $\text{Aut}(\mathcal{U}/A)$ the set of automorphisms (of \mathcal{U}^{eq}) that fix all elements of A . The symbol $\mathcal{O}(a/A)$ denotes the orbit of a over A . This has been defined in Section 9.2 and now we apply it to \mathcal{U}^{eq}

$$\mathcal{O}(a/A) = \{fa : f \in \text{Aut}(\mathcal{U}/A)\}.$$

By homogeneity, $\mathcal{O}(a/A) = p(\mathcal{U}^{\text{eq}})$ where $p(v) = \text{tp}(a/A)$. When $\mathcal{O}(a/A) = \{a\}$ we say that a is invariant over A or A -invariant, for short.

13.6 Definition Let $A \subseteq \mathcal{U}^{\text{eq}}$ and $a \in \mathcal{U}^{\text{eq}}$. When $\varphi(a) \wedge \exists^{=1} v \varphi(v)$ holds for some formula $\varphi(v) \in L^{\text{eq}}(A)$, we say that a is definable over A . We write $\text{dcl}^{\text{eq}}(A)$ for the set of those $a \in \mathcal{U}^{\text{eq}}$ that are definable over A . We write $\text{dcl}(A)$ for $\text{dcl}^{\text{eq}}(A) \cap \mathcal{U}$. This is the natural generalization of the notion of definability introduced in Section 11.1. \square

The saturation and homogeneity of \mathcal{U}^{eq} allow us to prove the following proposition with virtually the same proof as for Theorem 11.4

13.7 Theorem For any $A \subseteq \mathcal{U}^{\text{eq}}$ and $a \in \mathcal{U}^{\text{eq}}$ the following are equivalent

1. a is invariant over A ;
2. $a \in \text{dcl}^{\text{eq}}(A)$.

\square

Note that a tuple is invariant if and only if all its component are definable. Then in Theorem 13.7 we may replace a and/or A by a tuple.

Definition 13.6 treats first- and second-order elements of \mathcal{U}^{eq} uniformly. However, for sets it can be rephrased in a more natural way.

13.8 Proposition Let $A \subseteq \mathcal{U}^{\text{eq}}$ and let $\mathcal{A} \in \mathcal{U}^{\text{eq}}$ have sort $\sigma(x; z)$. Then the following are equivalent

1. \mathcal{A} is definable over A ;
2. $\mathcal{A} = \psi(\mathcal{U})$ for some $\psi(x) \in L(A)$.

Proof Implication $2 \Rightarrow 1$ is clear because extensionality is implicit in the definition of \mathcal{U}^{eq} . We prove $1 \Rightarrow 2$. Let $\varphi(x) \in L^{\text{eq}}(A)$ be a formula \mathcal{A} is the unique solution of. Then the required formula $\psi(x)$ is $\exists x [x \in \mathcal{A} \wedge \varphi(x)]$. \square

By the characterization above, Theorem 13.7 when applied to a definable set \mathcal{A} gives an alternative proof of Proposition 9.19.

The formula $\psi(x)$ in Proposition 13.8 need not be related to the sort $\sigma(x; z)$. For example, consider the theory of a binary equivalence relation $e(x; z)$ with two infinite classes, let \mathcal{A} be one of these classes and let $A \neq \emptyset$ be such that $A \cap \mathcal{A} = \emptyset$. Then \mathcal{A} is definable over A though not by some formula of the form $e(x; b)$ for some $b \in A$. Things change radically if we replace A with a model.

13.9 Proposition Let M be a model and let \mathcal{A} be an element of sort $\sigma(x; z)$. Then the following are equivalent

1. $\mathcal{A} \in \text{dcl}^{\text{eq}}(M)$;
2. $\mathcal{A} = \sigma(\mathcal{U}; b)$ for some $b \in M^{|z|}$.

In particular $M^{\text{eq}} = \text{dcl}^{\text{eq}}(M)$.

Proof Assume 1 and let $\psi(x) \in L(M)$ be such that $\mathcal{A} = \psi(\mathcal{U})$. Such a formula exists by Proposition 13.8. Then $\exists z \forall x [\psi(x) \leftrightarrow \sigma(x; z)]$ holds in \mathcal{U}^{eq} . By elementarity it holds in M^{eq} , therefore $\exists z$ has a witness in M . This proves $1 \Rightarrow 2$, the converse implication is obvious. \square

4 The algebraic closure in the eq-expansion

Let $A \subseteq \mathcal{U}^{\text{eq}}$ and $a \in \mathcal{U}^{\text{eq}}$. We say that a is algebraic over A if $\varphi(a) \wedge \exists^{-k} v \varphi(v)$ holds for some formula $\varphi(v) \in L^{\text{eq}}(A)$ and some positive integer k . We write $\text{acl}^{\text{eq}}(A)$ for the set of those $a \in \mathcal{U}^{\text{eq}}$ that are algebraic over A . We write $\text{acl}(A)$ for $\text{acl}^{\text{eq}}(A) \cap \mathcal{U}$. This is the natural generalization of the notion introduced in Section 11.1.

The following proposition is proved with virtually the same proof of Theorem 11.5

13.10 Theorem For every $A \subseteq \mathcal{U}^{\text{eq}}$ and every $a \in \mathcal{U}^{\text{eq}}$ the following are equivalent

1. $\mathcal{O}(a/A)$ is finite;
2. $a \in \text{acl}^{\text{eq}}(A)$;
3. $a \in M^{\text{eq}}$ for every model such that $A \subseteq M^{\text{eq}}$.

\square

We say **finite equivalence relation** for an equivalence relation with finitely many classes. A **finite equivalence formula** or **type** is a formula, respectively a type, that defines a finite equivalence relation. Theorem 13.11 belows proves that sets algebraic over A are union of classes of a finite equivalence relations definable over A .

13.11 Theorem Let $A \subseteq \mathcal{U}^{\text{eq}}$ and let $\mathcal{A} \in \mathcal{U}^{\text{eq}}$ be an element of sort $\sigma(x; z)$. Then the following are equivalent

1. $\mathcal{A} \in \text{acl}^{\text{eq}}(A)$
2. for some finite equivalence formula $\varepsilon(x; y) \in L(A)$ and some $c_1, \dots, c_n \in \mathcal{U}^{|y|}$

$$x \in \mathcal{A} \leftrightarrow \bigvee_{i=1}^n \varepsilon(x; c_i).$$

Proof $2 \Rightarrow 1$ If $\varepsilon(x; y)$ has m classes, then $\mathcal{O}(\mathcal{A}/A)$ contains at most $\binom{m}{n}$ sets.

$1 \Rightarrow 2$ Let $\varphi(\mathcal{X}) \in L^{\text{eq}}(A)$ be an algebraic formula that has \mathcal{A} among its solutions and define

$$\varepsilon(x; y) = \forall \mathcal{X} \left[\varphi(\mathcal{X}) \rightarrow [x \in \mathcal{X} \leftrightarrow y \in \mathcal{X}] \right]$$

If $\varphi(\mathcal{X})$ has n , solutions, then $\varepsilon(x; y)$ has at most 2^n equivalence classes. Clearly, \mathcal{A} is union of some these classes. \square

13.12 Definition We write $a \overset{\text{Sh}}{\equiv}_A b$ when $\varepsilon(a; b)$ holds for every finite equivalence formula $\varepsilon(x; y) \in L(A)$. In words we say that a and b have the same *Shelah strong-type* over A . \square

By the following proposition, the Shelah strong type of a over A is $\text{tp}(a / \text{acl}^{\text{eq}} A)$.

13.13 Proposition Let $A \subseteq \mathcal{U}^{\text{eq}}$ and let $a, b \in \mathcal{U}^{|x|}$. Then the following are equivalent

1. $a \overset{\text{Sh}}{\equiv}_A b$;
2. $a \equiv_{\text{acl}^{\text{eq}} A} b$.

Proof $2 \Rightarrow 1$ Assume $\neg 1$ and let $\varepsilon(x; y) \in L(A)$ be a finite equivalence formula such that $\neg \varepsilon(a; b)$. Let $\mathcal{D} = \varepsilon(\mathcal{U}; b)$, then $b \in \mathcal{D}$ and $a \notin \mathcal{D}$. As $\varepsilon(x; y)$ is an A -invariant finite equivalence formula, $\mathcal{D} \in \text{acl}^{\text{eq}}(A)$, and $\neg 2$ follows.

$1 \Rightarrow 2$ Assume $\neg 2$ and let $\varphi(x) \in L(\text{acl}^{\text{eq}}(A))$ be such that $\varphi(a) \not\leftrightarrow \varphi(b)$. Let $\mathcal{D} = \varphi(\mathcal{U})$, then $\mathcal{D} \in \text{acl}^{\text{eq}}(A)$. Therefore, by Proposition 13.11, the set \mathcal{D} is union of equivalence classes of some finite equivalence formula $\varepsilon(x; y) \in L(A)$. Then $\neg \varepsilon(a; b)$ and $\neg 1$ follows. \square

We may write $\mathcal{S}(a/A)$ be the intersection of all definable sets that contain a and are algebraic over A . Then by the proposition above $\mathcal{S}(a/A) = \{b : b \overset{\text{Sh}}{\equiv}_A a\}$.

13.14 Exercise Let $p(x) \subseteq L(A)$ and let $\varphi(x; y) \in L(A)$ be a formula that defines, when restricted to $p(\mathcal{U})$, an equivalence relation with finitely many classes. Prove that there is a finite equivalence relation definable over A that coincides with $\varphi(x; y)$ on $p(\mathcal{U})$. \square

13.15 Exercise Let $A \subseteq \mathcal{U}$, let \mathcal{A} be a definable set with finite orbit over A . Without using the eq-expansion, prove that \mathcal{A} is union of classes of a finite equivalence relation definable over A . \square

13.16 Exercise Let T be strongly minimal and let $\varphi(x; z) \in L(A)$ with $|x| = 1$. For arbitrary $b \in \mathcal{U}^{|z|}$, prove that if the orbit of $\varphi(\mathcal{U}; b)$ over A is finite, then $\varphi(\mathcal{U}; b)$ is definable over $\text{acl } A$.

Hint: you can use Theorem 13.11. \square

5 Elimination of imaginaries

For the time being, we agree that *imaginary* is just another word for definable set. Though this is not formally correct (cfr. Section 6), it is morally true and helps to understand the terminology. The concept of elimination of imaginaries has been introduced by Poizat who also proved Theorem 13.23 below. A theory has elimination of imaginaries if for every $A \subseteq \mathcal{U}^{\text{eq}}$, there is a $B \subseteq \mathcal{U}$ such that $L(B)$ and $L(A)$ have the same expressive power (i.e. they are the same up to equivalence).

13.17 Definition We say that T has *elimination of imaginaries* if for every definable set \mathcal{A} there is a formula $\varphi(x; z) \in L$ such that

$$\text{ei} \quad \exists^=1 z \forall x \left[x \in \mathcal{A} \leftrightarrow \varphi(x; z) \right]$$

We say that the witness of $\exists^=1 z$ in the formula above is a **canonical parameter** of \mathcal{A} . It is also called a **canonical name** for \mathcal{A} . A set may have different canonical parameters for different formulas $\varphi(x; z)$.

We say that T has **weak elimination of imaginaries** if

$$\text{wei} \quad \exists^=k z \forall x \left[x \in \mathcal{A} \leftrightarrow \varphi(x; z) \right]$$

for some positive integer k . □

In the formulas above we allow z to be the empty string. In this case we read ei and wei omitting the quantifiers $\exists^=1 z$, respectively $\exists^=k z$. Therefore \emptyset -definable sets have all (at least) the empty string as a canonical parameter.

To show that the notions above are well-defined properties of a theory one needs to check that they are independent of our choice of monster model. We leave this to the reader as an exercise.

13.18 Exercise Let M be an arbitrary model. Prove that ei and wei hold (in \mathcal{U}^{eq}) if and only if they hold in M^{eq} . □

We say that two tuples a and b of elements of \mathcal{U}^{eq} are **interdefinable** if $\text{dcl}^{\text{eq}}(a) = \text{dcl}^{\text{eq}}(b)$. By Theorem 13.7 this is equivalent to saying that $\text{Aut}(\mathcal{U}/a) = \text{Aut}(\mathcal{U}/b)$, that is, the automorphisms that fix a fix also b , and vice versa.

13.19 Theorem *The following are equivalent*

1. T has weak elimination of imaginaries;
2. every definable set is interdefinable with a finite set;
3. every definable set \mathcal{A} is definable over $\text{acl}(\{\mathcal{A}\})$.

Proof $1 \Rightarrow 2$ Assume 1 and let \mathcal{B} be the set of solutions of the formula

$$\forall x \left[x \in \mathcal{A} \leftrightarrow \sigma(x; z) \right].$$

Hence \mathcal{B} is finite and $\mathcal{B} \in \text{dcl}^{\text{eq}}\{\mathcal{A}\}$. We also have $\mathcal{A} \in \text{dcl}^{\text{eq}}\{\mathcal{B}\}$ because \mathcal{A} is definable by the formula $\exists z [z \in \mathcal{B} \wedge \sigma(x; z)]$. Therefore $\text{dcl}^{\text{eq}}\{\mathcal{A}\} = \text{dcl}^{\text{eq}}\{\mathcal{B}\}$.

$2 \Rightarrow 3$ Assume $\text{dcl}^{\text{eq}}\{\mathcal{A}\} = \text{dcl}^{\text{eq}}\{\mathcal{B}\}$ for some finite set \mathcal{B} . The elements of \mathcal{B} , say b_1, \dots, b_n , are the (finitely many) solutions of the formula $z \in \mathcal{B}$. Therefore $b_1, \dots, b_n \in \text{acl}(\mathcal{B}) = \text{acl}(\mathcal{A})$. Let $\varphi(\mathcal{X}; \mathcal{B})$ be a formula that has \mathcal{A} as unique solution. Then $\exists y [y = \{b_1, \dots, b_n\} \wedge \varphi(\mathcal{X}; y)]$ is the formula that proves 3.

$3 \Rightarrow 1$ Assume 3. As wei holds trivially for all \emptyset -definable sets, we may assume $\mathcal{A} \neq \emptyset$. Let $\sigma(x; z)$ be such that

$$\forall x \left[x \in \mathcal{A} \leftrightarrow \sigma(x; b) \right].$$

for some tuple b of elements of $\text{acl}(\{\mathcal{A}\})$. Fix some algebraic formula $\delta(z; \mathcal{A})$ satisfied by b and write $\psi(z; \mathcal{X})$ for the formula

$$\forall x \left[x \in \mathcal{X} \leftrightarrow \sigma(x; z) \right] \wedge \delta(z; \mathcal{X}).$$

The following formula is clearly satisfied by b therefore, if we can prove that it has finitely many solutions, we follow from Proposition 13.1

$$\# \quad \forall x \left[x \in \mathcal{A} \leftrightarrow \sigma(x; z) \wedge \exists \mathcal{X} \psi(z; \mathcal{X}) \right].$$

We check that any c that satisfies $\#$ also satisfies $\delta(z; \mathcal{A})$. As \mathcal{A} is non empty, $\psi(c; \mathcal{A}')$ holds for some \mathcal{A}' . By $\#$ and the definition of $\psi(z; \mathcal{X})$ we obtain $\mathcal{A}' = \mathcal{A}$ and $\delta(c; \mathcal{A})$. \square

13.20 Theorem *The following are equivalent*

1. T has elimination of imaginaries;
2. every definable set is interdefinable with a tuple of real elements;
3. every definable set \mathcal{A} is definable over $\text{dcl}(\{\mathcal{A}\})$.

Proof Implications $1 \Rightarrow 2 \Rightarrow 3$ are immediate. Implication $3 \Rightarrow 1$ is identical to the homologous implication in Theorem 13.19, just substitute algebraic with definable. \square

We now consider elimination of imaginaries in two concrete structures: algebraically closed fields and real closed fields. The following lemma is required in the proof of Theorem 13.22 below.

13.21 Lemma *The following is a sufficient condition for weak elimination of imaginaries*

$\#$ for every $A \subseteq \mathcal{U}^{\text{eq}}$, every consistent $\varphi(z) \in L(A)$ has a solution in $\text{acl } A$.

Proof Let $\mathcal{A} \in \mathcal{U}^{\text{eq}}$ be a definable set of sort $\sigma(x; z)$. Then $\forall x [x \in \mathcal{A} \leftrightarrow \sigma(x; z)]$ is consistent and, by $\#$ it has a solution in $\text{acl}(\{\mathcal{A}\})$. Hence weak elimination follows from Theorem 13.19. \square

13.22 Theorem *Let T be a complete, strongly minimal theory. Then, if $\text{acl } \emptyset$ is infinite, T has weak elimination of imaginaries.*

Proof If $\text{acl } \emptyset$ is infinite, $\text{acl } A$ is a model for every A (cfr. Exercise 11.25) so condition $\#$ of lemma 13.21 holds by elementarity and the theorem follows. \square

13.23 Theorem *The theories T_{acf}^p have elimination of imaginaries.*

Proof By Theorem 13.22 we know that T_{acf}^p has weak elimination of imaginaries. Therefore, by Theorem 13.19 it suffices to prove that every finite set \mathcal{A} is interdefinable with a tuple. Let $\mathcal{A} = \{a_1, \dots, a_n\}$ where each a_i is a tuple $a_{i,1}, \dots, a_{i,m}$ of elements of \mathcal{U} . Given \mathcal{A} we define the term

$$t_{\mathcal{A}}(x; y) = \prod_{i=1}^n \left(x - \sum_{k=1}^m a_{i,k} y_k \right). \quad \text{where } y = y_1, \dots, y_m.$$

Note that (the interpretation of) the term $t_{\mathcal{A}}(x; y)$ is independent on particular indexing of the set \mathcal{A} . So, any automorphism that fixes \mathcal{A} , fixes the $t_{\mathcal{A}}(x; y)$. Now rewrite $t_{\mathcal{A}}(x; y)$ as a sum of monomials and let c be the tuple of coefficients of these monomials. The tuple c uniquely determines $t_{\mathcal{A}}(x; y)$ and vice versa. Therefore every automorphism that fixes \mathcal{A} fixes c and vice versa. Hence \mathcal{A} and c are interdefinable. \square

13.24 Exercise Let T have elimination of imaginaries and $\varphi(x; z) \in L(A)$. For arbitrary $c \in \mathcal{U}^{|z|}$, prove that if the orbit of $\varphi(\mathcal{U}; c)$ over A is finite, then $\varphi(\mathcal{U}; c)$ is definable over $\text{acl } A$. \square

6 The true story of imaginaries

The point of the expansion to \mathcal{U}^{eq} is to add a canonical parameter for each definable set. In fact, in \mathcal{U}^{eq} every definable subset of $\mathcal{U}^{|z|}$ is the canonical parameter if itself. This allows to deal with theories without elimination of imaginaries in the most straightforward way.

The expansion to \mathcal{U}^{eq} that was originally introduced by Shelah (and still used everywhere else) is slightly different from the one introduced here. For a given set $\mathcal{A} = \sigma(\mathcal{U}; b)$ Shelah considers the equivalence relation defined by the formula

$$\varepsilon(z; z') \stackrel{\text{def}}{=} \forall x \left[\sigma(x; z) \leftrightarrow \sigma(x; z') \right].$$

The equivalence class of b in the relation $\varepsilon(z; z')$ is what Shelah uses as canonical parameter of the set \mathcal{A} .

Shelah's \mathcal{U}^{eq} has a sort for each \emptyset -definable equivalence relation $\varepsilon(z; z')$. The domain of the sort $\varepsilon(z; z')$ contains the classes of the equivalence relation defined by $\varepsilon(z; z')$. These equivalence classes are called **imaginaries**. Shelah's L^{eq} contains functions that map tuples in the home sort to their equivalence class.

Tortuous routes are somewhat typical of Shelah. This did not hinder him from becoming one of the most productive mathematician of his century. Lesser minds may find it useful to take a simplified route.

7 Uniform elimination of imaginaries

Sometimes in the literature elimination of imaginaries is confused with uniform elimination of imaginaries, see e.g. [1, Definition 8.4.2]. Theorem 13.26 below shows that the difference is immaterial. This section is more technical and could be skipped at a first reading.

Let us rephrase the definition of elimination of imaginaries: for every formula $\varphi(x; u) \in L$ and every tuple $c \in \mathcal{U}^{|u|}$ there is a formula $\sigma(x; z) \in L$ such that

$$\exists^1 z \forall x \left[\varphi(x; c) \leftrightarrow \sigma(x; z) \right].$$

A priori, the formula $\sigma(x; z)$ may depend on c in a very wild manner. We say that T has **uniform elimination of imaginaries** if for every $\varphi(x; u)$ there are a formula $\sigma(x; z)$ and a formula $\rho(z)$ such that

$$\text{uei} \quad \forall u \exists^1 z \left[\rho(z) \wedge \forall x \left[\varphi(x; u) \leftrightarrow \sigma(x; z) \right] \right].$$

The role of the formula $\rho(z)$ above is mysterious. It is clarified by the following propositions. In fact, uniform elimination of imaginaries is equivalent to a very natural property which in words says: every definable equivalence relation is the kernel of a definable function. Recall that the kernel of the function f is the relation

$$fa = fb.$$

Uniform elimination of imaginaries is convenient when dealing with interpretations of structure inside other structures. Let us consider a simple concrete example. Suppose \mathcal{U} is a group and let \mathcal{H} be a definable normal subgroup of \mathcal{U} . The elements of the quotient structure \mathcal{U}/\mathcal{H} are equivalent classes of a definable equivalence relation. If there is uniform elimination of imaginaries we can identify \mathcal{U}/\mathcal{H} with an actual definable subset of \mathcal{G} (the range of the function f above). Moreover, the group operation of \mathcal{G} are definable functions. As working in \mathcal{U}/\mathcal{H} may be notationally cumbersome, \mathcal{G} may offer a convenient alternative.

13.25 Proposition *The following are equivalent*

1. T has uniform elimination of imaginaries;
2. for every $\varphi(\mathbf{x}; u)$ such that $\forall u \exists \mathbf{x} \varphi(\mathbf{x}; u)$ there is a formula $\sigma(\mathbf{x}; z)$ such that

$$\forall u \exists^1 z \forall \mathbf{x} \left[\varphi(\mathbf{x}; u) \leftrightarrow \sigma(\mathbf{x}; z) \right];$$

3. for every equivalence formula $\varepsilon(\mathbf{x}; u) \in L$ there is given by $\sigma(\mathbf{x}; z) \in L$ such that

$$\forall u \exists^1 z \forall \mathbf{x} \left[\varepsilon(\mathbf{x}; u) \leftrightarrow \sigma(\mathbf{x}; z) \right].$$

Note that the definable function $f u = z$ mentioned above is defined by the formula

$$\vartheta(u; z) = \forall \mathbf{x} \left[\varepsilon(\mathbf{x}; u) \leftrightarrow \sigma(\mathbf{x}; z) \right].$$

Proof $1 \Rightarrow 2$. If $\forall u \exists \mathbf{x} \varphi(\mathbf{x}; u)$ we can rewrite uei as

$$\forall u \exists^1 z \forall \mathbf{x} \left[\varphi(\mathbf{x}; u) \leftrightarrow \rho(z) \wedge \sigma(\mathbf{x}; z) \right].$$

$2 \Rightarrow 3$. Clear.

$3 \Rightarrow 1$. Apply 3 to the equivalence formula

$$\varepsilon(u; v) = \forall \mathbf{x} \left[\varphi(\mathbf{x}; u) \leftrightarrow \varphi(\mathbf{x}; v) \right]$$

Let $\vartheta(u; z)$ be defined as above. The reader may check that uei holds substituting for $\delta(z)$ the formula $\exists u \vartheta(u; z)$ and for $\sigma(\mathbf{x}; z)$ the formula $\exists u [\varphi(\mathbf{x}; u) \wedge \vartheta(u; z)]$. \square

By the following theorem, uniformity comes almost for free.

13.26 Theorem *The following are equivalent*

1. T has uniform elimination of imaginaries;
2. $\text{dcl } \emptyset$ contains at least two elements and T has elimination of imaginaries.

Proof $1 \Rightarrow 2$. Let $\varphi(\mathbf{x}, u)$ be the formula $u_1 = u_2$. From 1 we obtain a formula $\sigma(\mathbf{x}; z) \in L$ such that

$$\forall u_1, u_2 \exists^1 z \left[\rho(z) \wedge \forall \mathbf{x} [u_1 = u_2 \leftrightarrow \sigma(\mathbf{x}; z)] \right].$$

Therefore the formulas $\exists^1 z [\rho(z) \wedge \forall \mathbf{x} \sigma(\mathbf{x}; z)]$ and $\exists^1 z [\rho(z) \wedge \forall \mathbf{x} \neg \sigma(\mathbf{x}; z)]$ are both true. The witnesses of $\exists^1 z$ in these two formulas are two distinct elements of $\text{dcl } \emptyset$.

$2 \Rightarrow 1$. Assume 2 and fix a formula $\varphi(\mathbf{x}; u)$ such that $\varphi(\mathbf{x}, a)$ is consistent for every $a \in \mathcal{U}^{|\mathbf{u}|}$. We prove 2 of Proposition 13.25.

Let $p(u)$ be the type that contains the formulas

$$\neg \exists^=1 \mathbf{z} \forall \mathbf{x} \left[\varphi(\mathbf{x}; u) \leftrightarrow \sigma(\mathbf{x}; \mathbf{z}) \right],$$

where $\sigma(\mathbf{x}; \mathbf{z})$ ranges over all formulas in L . By elimination of imaginaries $p(u)$ is not consistent. Therefore, by compactness, there are some formulas $\sigma_i(\mathbf{x}, \mathbf{z})$ such that

$$\# \quad \forall u \bigvee_{i=0}^n \exists^=1 \mathbf{z} \forall \mathbf{x} \left[\varphi(\mathbf{x}; u) \leftrightarrow \sigma_i(\mathbf{x}; \mathbf{z}) \right].$$

To prove the theorem we need to move the disjunction in front of the $\sigma_i(\mathbf{x}; \mathbf{z})$.

We can assume that if $\sigma_i(\mathbf{x}; \mathbf{b}) \leftrightarrow \sigma'_i(\mathbf{x}; \mathbf{b}')$ for some $\langle \mathbf{b}, i \rangle \neq \langle \mathbf{b}', i' \rangle$ then $\sigma_i(\mathbf{x}; \mathbf{b})$ is inconsistent. Otherwise we can substitute the formula $\sigma_i(\mathbf{x}; \mathbf{z})$ with

$$\sigma_i(\mathbf{x}; \mathbf{z}) \wedge \bigwedge_{j \leq i} \neg \exists \mathbf{y} \neq \mathbf{b} \forall \mathbf{x} \left[\sigma_j(\mathbf{x}; \mathbf{y}) \leftrightarrow \sigma_i(\mathbf{x}; \mathbf{z}) \right].$$

As $\varphi(\mathbf{x}, a)$ is consistent for every a , the substitution does not break the validity of $\#$.

Fix some distinct \emptyset -definable tuples d_0, \dots, d_n of the same length (these are easy to obtain from two \emptyset -definable elements). We claim that from $\#$ it follows that

$$\forall u \exists^=1 \mathbf{z}, \mathbf{y} \forall \mathbf{x} \left[\varphi(\mathbf{x}; u) \leftrightarrow \bigvee_{i=1}^n \left[\sigma_i(\mathbf{x}; \mathbf{z}) \wedge \mathbf{y} = d_i \right] \right].$$

(The tuple \mathbf{z}, \mathbf{y} plays the role of \mathbf{z} .) We fix some a and check that the formula below has a unique solution

$$\flat \quad \forall \mathbf{x} \left[\varphi(\mathbf{x}; a) \leftrightarrow \bigvee_{i=1}^n \left[\sigma_i(\mathbf{x}; \mathbf{z}) \wedge \mathbf{y} = d_i \right] \right].$$

Existence follows immediately from $\#$. As for uniqueness, note that if \mathbf{b}, d_i and $\mathbf{b}', d_{i'}$ are two distinct solution of \flat then $\sigma_i(\mathbf{x}; \mathbf{b}) \leftrightarrow \sigma_{i'}(\mathbf{x}; \mathbf{b}')$ for some $\langle \mathbf{b}, i \rangle \neq \langle \mathbf{b}', i' \rangle$. By what assumed on $\sigma_i(\mathbf{x}; \mathbf{z})$, we obtain that $\varphi(\mathbf{x}; a)$ is inconsistent. A contradiction which proves the theorem. \square

8 Notes and references

- [1] Katrin Tent and Martin Ziegler, *A course in model theory*, Lecture Notes in Logic, vol. 40, Association for Symbolic Logic, Cambridge University Press, 2012.

Chapter 14

Invariant sets

In this chapter we fix a signature L , a complete theory T without finite models, and a saturated model \mathcal{U} of inaccessible cardinality κ strictly larger than $|L|$. Notation and implicit assumptions are as presented in Section 9.3.

1 Invariant sets and types

Let $\mathcal{D} \subseteq \mathcal{U}^{|z|}$, where z is a tuple of length $< \kappa$. We say that \mathcal{D} is an **A -invariant set** if it is fixed (set-wise) by A -automorphisms. That is, $f[\mathcal{D}] = \mathcal{D}$ for every automorphism $f \in \text{Aut}(\mathcal{U}/A)$ or, yet in other words,

is1. $a \in \mathcal{D} \leftrightarrow fa \in \mathcal{D}$ for every $a \in \mathcal{U}^{|z|}$ and every $f \in \text{Aut}(\mathcal{U}/A)$,

which, by homogeneity is equivalent to,

is2. $a \in \mathcal{D} \leftrightarrow b \in \mathcal{D}$ for all $a, b \in \mathcal{U}^{|z|}$ such that $a \equiv_A b$.

This yields the following bound on the number of invariant sets

14.1 Proposition *Let $\lambda = |L_z(A)|$. There are at most 2^{2^λ} sets $\mathcal{D} \subseteq \mathcal{U}^{|z|}$ that are invariant over A .*

Proof By is2, sets that are invariant over A are union of equivalence classes of the relation \equiv_A , that is, union of sets of the form $p(\mathcal{U})$ where $p(z) \in S(A)$. Then the number of A -invariant sets is $2^{|S_z(A)|}$. Clearly $|S_z(A)| \leq 2^\lambda$. \square

We say that \mathcal{D} is an **invariant set** if it is invariant over some (small) set A . As we require κ to be inaccessible, there are exactly κ invariant sets.

In this chapter we work with Δ -types where Δ may be either $L(\mathcal{A})$ or the set of Boolean combinations of $\varphi(x; b)$ for $b \in \mathcal{A}^{|z|}$ and some fixed $\varphi(x; z) \in L$. In the latter case Δ -types are called a **φ -types**. We denote by $S_\varphi(\mathcal{A})$ the set of complete φ -types with parameters in \mathcal{A} . Typically, \mathcal{A} is either the whole of \mathcal{U} or some small set $A \subseteq \mathcal{U}$. Types in $S_\varphi(\mathcal{U})$ are called **global φ -types**.

Let $p(x) \subseteq L(\mathcal{U})$ be a consistent type. For every formula $\varphi(x; z) \in L$ we define

$$\mathcal{D}_{p, \varphi} = \left\{ a \in \mathcal{U}^{|z|} : \varphi(x; a) \in p \right\}$$

We can read the notation in two ways. Either the tuple z has infinite length and is the same for all formulas, or it is finite and depends on φ . This is possible because adding or erasing dummy variables to the second tuple of $\varphi(x; z)$ does not change $\mathcal{D}_{p, \varphi}$ in any relevant way, in particular invariance is preserved.

Let $p(x) \subseteq L(\mathcal{U})$ be a consistent type. We say that $p(x)$ is an **A -invariant type**, if for every formula $\varphi(x; z) \in L$,

it1. $\varphi(x; a) \in p \leftrightarrow \varphi(x; fa) \in p$ for every $a \in \mathcal{U}^{|z|}$ and every $f \in \text{Aut}(\mathcal{U}/A)$.

By **invariant type** we mean invariant over some (small) set A .

A global φ -type can be identified with $\mathcal{D}_{p,\varphi}$ and a global type can be identified with the collection of all these sets. The notions of invariance for types and sets coincide.

We say that the type $p(x) \subseteq L(\mathcal{U})$ **does not split** over A if

$$\text{it2.} \quad a \equiv_A b \Rightarrow \left(\varphi(x; a) \in p \Leftrightarrow \varphi(x; b) \in p \right) \quad \text{for all } a, b \in \mathcal{U}^{|z|}$$

for every formula $\varphi(x; z) \in L$. For global type (or a global φ -types when φ is fixed) it2' is equivalent to

$$\text{it2'.} \quad a \equiv_A b \Rightarrow \varphi(x; a) \leftrightarrow \varphi(x; b) \in p$$


By homogeneity, non splitting is equivalent to invariance.

The following is yet another important equivalent of invariance over A that easily follows from it2'

$$\text{it3.} \quad a \equiv_A b \Rightarrow a \equiv_{A,c} b \quad \text{for all } a, b \in \mathcal{U}^{|z|} \text{ and for all } c \models p|_{A,a,b}.$$

Note that it3 applies to global types $p(x) \in S(\mathcal{U})$ but not to φ -types.

2 Invariance from the dual perspective

 The following terminology is not standard. We say that the set $\mathcal{B} \subseteq \mathcal{U}^{|x|}$, typically a definable set, is **quasi-invariant** over A if for any finitely many automorphisms $f_1, \dots, f_n \in \text{Aut}(\mathcal{U}/A)$ the sets $f_i[\mathcal{B}]$ have non-empty intersection.

We say that the type $p(x) \subseteq L(\mathcal{U})$, typically a global type, is **quasi-invariant** over A if $\varphi(\mathcal{U})$ is quasi-invariant over A for every $\varphi(x)$ conjunction of formulas in $p(x)$. For types of small cardinality, this is equivalent to requiring that $p(\mathcal{U})$ is quasi-invariant.

For global types quasi-invariance coincides with invariance, in fact we have the following.

14.2 Proposition *Let $p(x) \in S_\varphi(\mathcal{U})$ be a global φ -type, then the following are equivalent*

1. $p(x)$ is invariant over A ;
2. $p(x)$ is quasi-invariant over A .

Proof $1 \Rightarrow 2$. Assume $p(x)$ is invariant and let $\varphi(x; b) \in p$ and some $b \in \mathcal{U}^{|z|}$. Then $\varphi(x; fb) \in p$ for every $f \in \text{Aut}(\mathcal{U}/A)$, so 2 follows from the finite consistency of $p(x)$.

$2 \Rightarrow 1$. Assume $p(x)$ is not invariant. Then there is $b \in \mathcal{U}^{|z|}$ such that $\varphi(x; b) \in p$ and $\varphi(x; fb) \notin p$ for some $f \in \text{Aut}(\mathcal{U}/A)$. By completeness, $p(x)$ contains the formula $\varphi(x; b) \wedge \neg \varphi(x; fb)$ which clearly is not consistent with its f -translate. \square

14.3 Exercise We say that \mathcal{B} *strongly* quasi-invariant if for every definable set \mathcal{D} at least one of $\mathcal{B} \cap \mathcal{D}$ and $\mathcal{B} \cap \neg \mathcal{D}$ is quasi-invariant. Strongly quasi invariant types are defined in analogy to the definition of quasi-invariant type. Note parenthetically that for global types the two notions coincide. Prove that every strongly quasi-invariant type has an extension to a global invariant type.

Hint: it may help to prove that if \mathcal{B} is strongly quasi-invariant then for every definable \mathcal{D} either $\mathcal{B} \cap \mathcal{D}$ or $\mathcal{B} \cap \neg \mathcal{D}$ is strongly quasi-invariant. Then the maximal strongly quasi-invariant set is the required global extension. \square

Unfortunately it is not true in general that every quasi-invariant type can be extended to a global one. In next section we consider a stronger notion, *coheirs*, which has this desirable property, see Proposition 14.6. In the next chapters we introduce a weaker notion, *non-forking*, that also allows to extend types to global types.

3 Heirs and coheirs

The easiest way to obtain types that are invariant over a set A is via types that are finitely satisfiable in A . We say that a type $p(x)$ is **finitely satisfiable** in A if every conjunction of formulas in $p(x)$ has a solution in $A^{|x|}$.

14.4 Proposition *Every type $p(x) \subseteq L(\mathcal{U})$ finitely satisfied in A is quasi-invariant over A .*

Proof Clearly, the very same $a \in A^{|x|}$ that satisfies $\varphi(x)$ satisfies also every $\text{Aut}(\mathcal{U}/A)$ -translates of $\varphi(x)$. \square

The proposition above and Propositions 14.2 yield the following

14.5 Proposition *Let $p(x) \in S_\varphi(\mathcal{U})$ be a global φ -type finitely satisfiable in A . Then $p(x)$ is A -invariant.* \square

14.6 Proposition *Every type $q(x) \subseteq L(\mathcal{U})$ finitely satisfiable in A has an extension to a global type finitely satisfiable in A .*

Proof Let $p(x) \subseteq L(\mathcal{U})$ be maximal among the types containing $q(x)$ and finitely satisfiable in A . We prove that $p(x)$ is complete. If for a contradiction that $p(x)$ contains neither $\psi(x)$ nor $\neg\psi(x)$. Then neither $p(x) \cup \{\psi(x)\}$ nor $p(x) \cup \{\neg\psi(x)\}$ is finitely satisfiable in A . This contradicts the finite satisfiability of $p(x)$. \square

Note that by elementarity every type over a model is finitely satisfiable in the model, that is, if $p(x) \subseteq L(M)$ for some model M , then $p(x)$ is finitely satisfiable in M . For this reason the notion is mainly applied to models.

If $p(x)$ is a type finitely satisfied in some set A , then any extension of $p(x)$ that is also finitely satisfied in A is a **coheir** of $p(x)$.

In many cases it is useful to focus on elements instead of types. We introduce the following notation to express that $\text{tp}(b/A, a)$ is finitely satisfied in A

14.7 Definition *For every $a \in \mathcal{U}^{|z|}$ and $b \in \mathcal{U}^{|x|}$ we define*

$$\begin{aligned} \triangle! \quad a \perp_A b &\Leftrightarrow \varphi(a; b) \text{ for all } \varphi(z; x) \in L(A) \text{ such that } A^{|x|} \subseteq \varphi(a; \mathcal{U}) \\ &\Leftrightarrow \varphi(a; \mathcal{U}) \cap A^{|x|} \neq \emptyset \text{ for all } \varphi(z; x) \in L(A) \text{ such that } \varphi(a; b) \end{aligned}$$

We call this the **heir/coheir** relation. The symbol \perp is not standard. More properly one says that $\text{tp}(a/A, b)$ is the heir of $\text{tp}(a/A)$ or that $\text{tp}(b/A, a)$ is the coheir of $\text{tp}(b/A)$.

We also write

$$a \perp_A x = \left\{ \varphi(a; x) : \varphi(z; x) \in L(A) \text{ and } A \subseteq \varphi(a; \mathcal{U}) \right\}$$

and we will use the symbol $a \perp_A x \equiv_A b$ with the obvious meaning. \square

We imagine $a \perp_A b$ as saying that b is **independent** of a over A . This is the strongest

form of independence we will consider. In general it is not symmetric, that is $a \perp_A b$ is not always equivalent to $b \perp_A a$ (symmetry being equivalent to stability).

We shall use, sometimes without reference, the following easy lemma

14.8 Lemma *The following properties hold for all A, a, b , and c*

1. $a \perp_A b \Rightarrow fa \perp_A fb$ for every $f \in \text{Aut}(\mathcal{U}/A)$ invariance
2. $a \perp_A b \Leftrightarrow a_0 \perp_{A_0} b_0$ for all finite $A_0 \subseteq A, a_0 \subseteq a, b_0 \subseteq b$ finite character
3. $a, c \perp_A b$ and $a \perp_A c \Rightarrow a \perp_A c, b$ right transitivity
4. $a \perp_A b \Rightarrow$ there exists $b' \equiv_{A, a} b$ such that $a, c \perp_A b'$ right extension

Proof Properties 1-3 follow immediately from Definition 14.7. We prove 4. Let $p(x)$ be a global coheir of $\text{tp}(b/A, a)$, which exists by Proposition 14.6. Then any $b' \models p|_{A, a, c}(x)$ proves the lemma. □

Transitivity has dual version that holds under stronger assumptions.

The type $a \perp_A x \equiv_A b$ defined above is the intersection of all coheirs of $\text{tp}(b/A)$. In general coheirs of $\text{tp}(b/A)$ may not exist i.e., $a \perp_A x \equiv_A b$ is inconsistent. However, it is always consistent when A is a model. Even when consistent it need not be a complete. In fact, completeness of the type $a \perp_A x \equiv_A b$ is a very strong property. An example is given in Lemma 15.10.

14.9 Definition We say that \perp_A is **stationary** if $a \perp_A x \equiv_A b$ is a complete type (over A, a) for every $a \in \mathcal{U}^{<\omega}$, every $b \in \mathcal{U}^{[x]}$, and every tuple of variables x . We say **n -stationary** if this is restricted to $|x| = n$. □

Stationarity of \perp_A is often ensured by the following property that will receive the due attention in Section 17.5.

14.10 Proposition Fix a tuple of variable x of length n . If for every $\varphi(x) \in L(\mathcal{U})$ there is a formula $\psi(x) \in L(A)$ such that $\varphi(\mathcal{U}) =_A \psi(\mathcal{U})$ then \perp_A is n -stationary.

Proof Fix $a \in \mathcal{U}^{[z]}$ and $b_i \in \mathcal{U}^{[x]}$ such that $a \perp_A b_i$ and $b_1 \equiv_A b_2$. We claim that $b_1 \equiv_{A, a} b_2$. We need to prove that $\varphi(a, b_1) \leftrightarrow \varphi(a, b_2)$ for every $\varphi(z, x) \in L(A)$. Let $\psi(x) \in L(A)$ be such that $\varphi(a, \mathcal{U}) =_A \psi(\mathcal{U})$. From $a \perp_A b_i$ we obtain that $\varphi(a, b_i) \leftrightarrow \psi(b_i)$. Finally, the claim follows because $b_1 \equiv_A b_2$. □

14.11 Example Stationarity of \perp_A over every set A , or just over every model, is equivalent to the stability of T , see Section 17.5. However, there are many more theories where the assumption holds for some particular set A . For example, if every subset of A^n is the trace of a definable set, \perp_A is clearly n -stationary. This simple observation will be of help in the proof of Theorem 15.11. For natural example let $T = T_{\text{dlo}}$ and let $A \subseteq \mathcal{U}$ have the order-type of \mathbb{R} . By quantifier elimination every definable of \mathcal{U} union of finitely many intervals. By Dedekind completeness, the trace on A of any interval of \mathcal{U} coincides with that of an A -definable interval.

4 Morley sequences and indiscernibles

In the following α is some ordinal $\leq \kappa$, typically ω , and x is a tuple of variables of length $< \kappa$. Let $p(x) \in S(\mathcal{U})$ be a global type. We say that $\bar{c} = \langle c_i : i < \alpha \rangle$ is a **Morley sequence** of $p(x)$ over A if for every $i < \alpha$

$$\text{Ms.} \quad c_i \models p_{\upharpoonright A, c_{\upharpoonright i}}(x).$$

We will usually require that $p(x)$ is invariant over A . In particular, when $p(x)$ is finitely satisfiable in A , we say that \bar{c} is a **coheir sequence** over A .

The following is a convenient characterization of coheir sequences.

14.12 Lemma *The following are equivalent*

1. $\bar{c} = \langle c_n : n < \alpha \rangle$ is a coheir sequence over A ;
2. $c_{\upharpoonright n} \downarrow_A c_n$ and $c_{n+1} \equiv_{A, c_{\upharpoonright n}} c_n$ per ogni $n < \alpha$.

Proof $1 \Rightarrow 2$. Assume 1 and let $p(x) \in S(\mathcal{U})$ be a global type finitely satisfiable in A and such that $c_i \models p_{\upharpoonright A, c_{\upharpoonright i}}(x)$. The requirement $c_{n+1} \equiv_{A, c_{\upharpoonright n}} c_n$ is clear. Now, suppose $\varphi(c_{n+1})$ for some $\varphi(x) \in L(A, c_{\upharpoonright n+1})$. Then $\varphi(x)$ belongs to $p(x)$ hence $\varphi(\mathcal{U}) \cap A^{|x|} \neq \emptyset$ because $p(x)$ is finitely satisfiable in A .

$2 \Rightarrow 1$. Assume 2. Then it is immediate that \bar{c} is a coheir sequence of any global type that extends $\bar{c} \downarrow_A x$. □

Let $I, <_I$ be a linear order. We call a function $\bar{a} : I \rightarrow \mathcal{U}^{|x|}$ an **I -sequence**, or simply a **sequence** when I is clear. Often we introduce an I -sequence by writing $\bar{a} = \langle a_i : i \in I \rangle$.

If $I_0 \subseteq I$ we call $a_{\upharpoonright I_0}$ a **subsequence** of \bar{a} . Most relevant are the subsets $I_0 \subseteq I$ that are well-ordered by $<_I$ and, in particular, the finite ones. When I_0 has order-type α , an ordinal, we identify $a_{\upharpoonright I_0}$ with a tuple of length α .

14.13 Definition *Let $I, <_I$ be an infinite linear order and let \bar{a} be an I -sequence. We say that \bar{a} is a **sequence of indiscernibles** over A or, a sequence of **A -indiscernibles**, if $a_{\upharpoonright I_0} \equiv_A a_{\upharpoonright I_1}$ for every $I_0, I_1 \in [I]^n$ and $n < \omega$. Recall that $[I]^n$ denotes that the set of **n -subsets** of I , i.e. the subsets of I of cardinality n . It is also common to write*

$$\binom{I}{n} = [I]^n. \quad \square$$

The condition above can be formulated in a number of equivalent ways. We can require that for every formula $\varphi(x_1, \dots, x_n) \in L(A)$ and every pairs of tuples in I^n such that $i_0 < \dots < i_n$ and $j_0 < \dots < j_n$.

$$\varphi(a_{i_0}, \dots, a_{i_n}) \leftrightarrow \varphi(a_{j_0}, \dots, a_{j_n})$$

Or we can simply say that for every $i_0, \dots, i_n \in I$ the type $\text{tp}(a_{i_0}, \dots, a_{i_n} / A)$ only depends on the order type of i_0, \dots, i_n .

14.14 Proposition *Let $p(x) \in S(\mathcal{U})$ be a global A -invariant type and let $\bar{c} = \langle c_i : i < \alpha \rangle$ be a Morley sequence of $p(x)$ over A . Then \bar{c} is a sequence of indiscernibles over A .*

Proof We prove by induction on $n < \omega$ that

$$\# \quad c_{\upharpoonright n} \equiv_A c_{\upharpoonright I_0} \quad \text{for every } I_0 \subseteq \alpha \text{ of cardinality } n.$$

For $n = 0$ the claim is trivial, then we assume $\#$ above is true and prove that

$$c_{\upharpoonright n}, c_n \equiv_A c_{\upharpoonright I_0}, c_i \text{ for every } I_0 < i < \alpha.$$

As c is Morley sequence, $c_n \equiv_{A, c_{\upharpoonright n}} c_i$ whenever $n < i$. Hence we can equivalently prove that

$$c_{\upharpoonright n}, c_i \equiv_A c_{\upharpoonright I_0}, c_i,$$

which is equivalent to

$$c_{\upharpoonright n} \equiv_{A, c_i} c_{\upharpoonright I_0}.$$

The latter holds by induction hypothesis \sharp and the invariance of $p(x)$ as formulated in it3 of Section 14. \square

Chapter 15

Ramsey theory

In Section 1 we prove Ramsey's theorem and in Section 2 we present its major application in model theory: the Ehrenfeucht-Mostowsky construction of indiscernibles.

In the remaining sections we prove a few famous results Ramsey theory. Their proof is *not the usual one*. It is an interesting application of the notion of coheir. These results will not be used elsewhere in these notes. The only purpose is to illustrate a concrete (relatively speaking) application of the notion of coheir.

1 Ramsey theorem from coheir sequences

In this chapter we are interest in finite partitions. We may represent the partition of a set X into k subsets with a map $f : X \rightarrow [k]$. The elements of $[k] = \{1, \dots, k\}$ are also called **colors**, and the partition a **coloring**, or **k -coloring**, of X . We say that $Y \subseteq X$ is **monochromatic** if $f|_Y$ is constant on Y .

Let M be an arbitrary infinite set. Fix $n, k < \omega$ and fix a coloring f of the set of all **n -subsets** of M , aleas the **complete n -uniform hypergraph** with vertex set M ,

$$f : \binom{M}{n} \rightarrow [k].$$

We say that $H \subseteq M$ is a **monochromatic subgraph** if the subgraph induced by H is monochromatic. In the literature monochromatic subgraph are also called **homogeneous sets**.

The following is a very famous theorem which here we prove it in unusual way. It will serve as blueprint for other constructions in this chapter.

15.1 Ramsey Theorem *Let M be an infinite set and fix some positive integers n and k . Fix also an arbitrary k -coloring of the (edges of the) complete n -uniform hypergraph with vertex set M . Then there infinite monochromatic subgraph $H \subseteq M$.*

Proof Let L be a language that contains k relation symbols r_1, \dots, r_k of arity n . Given a k -coloring f we define a structure with domain M . The interpretation the relation symbols is

$$r_i^M = \{a_1, \dots, a_n \in M : f(\{a_1, \dots, a_n\}) = i\}.$$

We may assume that M is an elementary substructure of some large saturated model \mathcal{U} . Pick any type $p(\bar{x}) \in S(\mathcal{U})$ finitely satisfied in M but not realized in M and let $\bar{c} = \langle c_i : i < \omega \rangle$ be a coheir sequence of $p(\bar{x})$.

There is a first-order sentence saying that the formulas $r_i(x_1, \dots, x_n)$ are a coloring of $\binom{M}{n}$. Then by elementarity the same hols in \mathcal{U} . By indiscernibility, all tuples of n distinct elements of \bar{c} have the same color.

Note parenthetically that no element of \bar{c} is in M . The theorem is proved if we can find in M a sequence $\bar{a} = \langle a_i : i < \omega \rangle$ with the same property. We construct $a_{\bar{i}}$ by

induction on i as follows.

Assume as induction hypothesis that the subsequences of length n of $a_{\upharpoonright i}, c_{\upharpoonright n}$ are monochromatic. Our goal is to find a_i such as the same property holds for $a_{\upharpoonright i}, a_i, c_{\upharpoonright n}$. By the indiscernibility of \bar{c} , the property holds for $a_{\upharpoonright i}, c_{\upharpoonright n}, c_n$. And this can be written by a formula $\varphi(a_{\upharpoonright i}, c_{\upharpoonright n}, c_n)$. As \bar{c} is a coheir sequence, by Lemma 14.12 we can find $a_i \in M$ such that $\varphi(a_{\upharpoonright i}, c_{\upharpoonright n}, a_i)$. So, as the order is irrelevant, $a_{\upharpoonright i}, a_i, c_{\upharpoonright n}$ satisfies the induction hypothesis. \square

2 Ehrenfeucht-Mostowski construction of indiscernibles

Let $I, <_I$ be an infinite linear order and let \bar{a} be an I -sequence. Fix a tuple of distinct variables $\bar{x} = \langle x_i : i < \omega \rangle$. We write $p(\bar{x}) = \text{EM-tp}(\bar{a}/A)$ and say that $p(\bar{x})$ is the Ehrenfeucht-Mostowski type of \bar{a} over A if

$$p(\bar{x}) = \left\{ \varphi(x_{\upharpoonright n}) \in L(A) : \varphi(a_{\upharpoonright I_0}) \text{ holds for every } I_0 \in \binom{I}{n} \right\}.$$

Note that \bar{x} is always of order-type ω , while \bar{a} is an arbitrary infinite sequence. Clearly, x_i and a_i are tuple of the same sort.

Note also that if \bar{a} is A -indiscernible then $\text{EM-tp}(\bar{a}/A)$ is a complete type, and vice versa. So, if \bar{a} and \bar{c} are two A -indiscernible I -sequences with the same Ehrenfeucht-Mostowski type over A , then $\bar{a} \equiv_A \bar{c}$.

15.2 Ehrenfeucht-Mostowski's Theorem *Let $I, <_I$ and $J, <_J$ be two infinite linear orders such that $|J| \leq \kappa$. Then for every sequence $\bar{a} = \langle a_i : i \in I \rangle$ there is an J -sequence of A -indiscernibles \bar{c} such that $\text{EM-tp}(\bar{a}/A) \subseteq \text{EM-tp}(\bar{c}/A)$.*

Proof We prove the theorem for $I = J = \omega$ and leave the general case to the reader. Let \bar{c} be any realization of the following type yields a J -sequence of A -indiscernibles.

$$q(\bar{x}) \cup \left\{ \varphi(x_{\upharpoonright I_0}) \leftrightarrow \varphi(x_{\upharpoonright J_0}) : \varphi(x_{\upharpoonright n}) \in L(A), I_0, J_0 \in \binom{\omega}{n}, n < \omega \right\}.$$

We will prove that any finite subset of the type above is realized by a finite subsequence of \bar{a} . First note that any finite subset of $q(\bar{x})$ is realized by any subsequence of \bar{a} of the proper length by the definition of EM-type. Then we only need to pay attention to the set on the right.

We prove that for k and n arbitrary large and every $\varphi_1, \dots, \varphi_k \in L_{x_{\upharpoonright n}}(A)$ there is an infinite $H \subseteq \omega$ such that $a_{\upharpoonright H}$ realizes

$$\# \quad \left\{ \varphi_i(x_{\upharpoonright J_0}) \leftrightarrow \varphi_i(x_{\upharpoonright I_0}) : I_0, J_0 \in \binom{\omega}{n} \text{ and } i \in [k] \right\}.$$

Consider the subsets of $[k]$ as colors and let f be the coloring of $\binom{\omega}{n}$ that maps I_0 to the set $\{i : \varphi_i(a_{\upharpoonright I_0})\}$. By the Ramsey theorem, there is some infinite monochromatic set $H \subseteq \omega$. As ω has order type ω , so does H , and it is immediate that $a_{\upharpoonright H}$ realizes $\#$, as required to prove the theorem with $I = J = \omega$. \square

15.3 Proposition *Let $\bar{a} = \langle a_i : i \in I \rangle$ be a sequence of A -indiscernibles. Then \bar{a} is indiscernible over some model M containing A .*

Proof Fix an arbitrary model M containing A . By Theorem 15.2 there is an I -sequence of M -indiscernibles \bar{c} such that $\text{EM-tp}(\bar{a}/M) \subseteq \text{EM-tp}(\bar{c}/M)$. As \bar{a} is an A -indiscernible

sequence $\bar{a} \equiv_A \bar{c}$. Therefore $h\bar{c} = \bar{a}$ for some $h \in \text{Aut}(\mathcal{U}/A)$. Hence \bar{a} is indiscernible over $h[M]$. \square

15.4 Exercise Let $\bar{a} = \langle a_i : i \in I \rangle$ be an A -indiscernible sequence and let $J \supseteq I$ with $|J| \leq \kappa$. Then there is an A -indiscernible sequence $\bar{c} = \langle c_i : i \in J \rangle$ such that $c_{\upharpoonright I} = \bar{a}$. \square

15.5 Exercise Let $p(x) \in S(\mathcal{U})$ be a global type invariant over A . Let $a, b \models p_{\upharpoonright A}(x)$. Prove that there is a sequence $\bar{c} = \langle c_i : i < \omega \rangle$ such that a, \bar{c} and b, \bar{c} are both sequences of A -indiscernibles. \square

3 Indempotent orbits in semigroups

In this and the following sections we focus on semigroups definable in a first-order structure. For a lighter notation, we identify our semigroup with \mathcal{U} , which here denotes the domain of a sort in a many-sorted monster model. The language contains, among others, the symbol \cdot which is interpreted as a binary associative operation on \mathcal{U} .

We fix a set of parameters A , not necessarily all of the same sort. For any two sets $\mathcal{A}, \mathcal{B} \subseteq \mathcal{U}$ we define

$$\mathcal{A} \cdot_A \mathcal{B} = \{a \cdot b : a \in \mathcal{A}, b \in \mathcal{B} \text{ and } a \downarrow_A b\}$$

We write $a \cdot_A \mathcal{B}$ for $\mathcal{O}(a/A) \cdot_A \mathcal{B}$. Similarly for $\mathcal{A} \cdot_A b$ and $a \cdot_A b$. In this and the next section we abbreviate $\mathcal{O}(a/A)$ with a_A .

By the invariance of \downarrow_A , for every $f \in \text{Aut}(\mathcal{U}/A)$ we have $f[\mathcal{A} \cdot_A \mathcal{B}] = f[\mathcal{A}] \cdot_A f[\mathcal{B}]$. Therefore when \mathcal{A} and \mathcal{B} are invariant over A , also $\mathcal{A} \cdot_A \mathcal{B}$ is invariant over A . Below we mainly deal with invariant sets.

15.6 Proposition For every A -invariant sets \mathcal{A} , \mathcal{B} , and \mathcal{C} .

$$(\mathcal{A} \cdot_A \mathcal{B}) \cdot_A \mathcal{C} \subseteq \mathcal{A} \cdot_A (\mathcal{B} \cdot_A \mathcal{C})$$

Proof Let $a \cdot b \cdot c$ be an arbitrary element of the l.h.s. for some $a \downarrow_A b$ and $a \cdot b \downarrow_A c$. By extension (Lemma 14.8), there exists c' such that $a, b, a \cdot b \downarrow_A c' \equiv_{A, a \cdot b} c$. By transitivity (again Lemma 14.8), $a \downarrow_A b \cdot c'$. Therefore $a \cdot b \cdot c'$ belongs to the r.h.s. Finally, as $c' \equiv_{A, a \cdot b} c$, also $a \cdot b \cdot c$ belongs to the r.h.s. by invariance. \square

Let \mathcal{A} be a non empty set. When $\mathcal{A} \cdot_A \mathcal{A} \subseteq \mathcal{A}$, we say that it is **idempotent** (over A).

15.7 Corollary Assume $\mathcal{B} \subseteq \mathcal{A}$ are both A -invariant. Then if \mathcal{A} is idempotent, also $\mathcal{B} \cdot_A \mathcal{A}$ is idempotent.

Proof We check that if \mathcal{A} is idempotent so is $\mathcal{B} \cdot_A \mathcal{A} = \mathcal{A}$

$$\begin{aligned} (\mathcal{B} \cdot_A \mathcal{A}) \cdot_A (\mathcal{B} \cdot_A \mathcal{A}) &\subseteq (\mathcal{B} \cdot_A \mathcal{A}) \cdot_A (\mathcal{A} \cdot_A \mathcal{A}) \\ &\subseteq \mathcal{B} \cdot_A (\mathcal{A} \cdot_A (\mathcal{A} \cdot_A \mathcal{A})) && \text{by the lemma above} \\ &\subseteq \mathcal{B} \cdot_A \mathcal{A} \end{aligned} \quad \square$$

We show that, under the assumption of stationarity, the operation \cdot_A is associative. The quotient map $\mathcal{U} \rightarrow \mathcal{U}/\equiv_A$ comes close to (but not quite) a homeomorphism.

15.8 Proposition Assume \downarrow_A is 1-stationary, see Definition 14.9. Then for every $a \downarrow_A b$

$$(a \cdot b)_A = a \cdot_A b$$

Proof We prove two inclusions, only the second one requires stationarity.

\subseteq As $a \downarrow_A b$ holds by hypothesis, $a \cdot b \in a \cdot_A b$. Hence the inclusion follows by invariance.

\supseteq By invariance it suffices to show the l.h.s. contains $\{a\} \cdot_A b$. Let $b' \in b_A$ be such that $a \downarrow_A b'$. We claim that $a \cdot b' \in (a \cdot b)_A$. Both b and b' satisfy $a \downarrow_A x \equiv_A b$. By 1-stationarity, $b' \equiv_{A,a} b$. Hence $a \cdot b \equiv_A a \cdot b'$ which proves the claim. \square

15.9 Corollary (associativity) Assume \downarrow_M is 1-stationary and let M be a model. Then for every M -invariant sets \mathcal{A}, \mathcal{B} and \mathcal{C} .

$$(\mathcal{A} \cdot_M \mathcal{B}) \cdot_M \mathcal{C} = \mathcal{A} \cdot_M (\mathcal{B} \cdot_M \mathcal{C})$$

Proof We can assume that \mathcal{A}, \mathcal{B} and \mathcal{C} are M -orbits of elements of \mathcal{U} . Say a, b , and c respectively. As we are working over models, we can assume that $a \downarrow_M b$ and $a \cdot b \downarrow_M c$. By Proposition 15.8 the set on the l.h.s. equals $(a \cdot b \cdot c)_M$. By a similar argument the set on the r.h.s. equals $(a' \cdot b' \cdot c')_M$ for some elements a', b' , and c' . Proposition 15.6 proves that inclusion \subseteq holds in general. But inclusion between orbits amounts to equality. \square

15.10 Lemma Assume \downarrow_M is 1-stationary and let M be a model. If \mathcal{A} is minimal among the M -invariant, idempotent, type-definable sets then $\mathcal{A} = \mathcal{O}(a/M)$ for some element a .

Proof By Corollary 15.7, for every $a \in \mathcal{A}$ the set $a \cdot_M \mathcal{A}$ is idempotent. It is also type-definable and contained in \mathcal{A} , therefore by minimality $a \cdot_M \mathcal{A} = \mathcal{A}$. Then there is a $b \in \mathcal{A}$ such that $a \downarrow_M b$ and $a \cdot b = a$. By associativity, the set $a \cdot_M b$ is idempotent. By Corollary 15.9, it coincides with $(a \cdot b)_M = (a)_M$. The theorem follows by minimality. \square

4 Hindman theorem

Let G be an infinite semigroup. Let $\bar{a} = \langle a_i : i < \alpha \rangle$ be a tuple of elements of G . We write $\text{fp}_n(\bar{a})$ for the sets of products of n elements of \bar{a} taken in increasing order. Namely,

$$\text{fp}_n(\bar{a}) = \{a_{i_1} \cdots a_{i_n} : i_0 < \cdots < i_{n-1} < \alpha\}.$$

We agree that when \bar{a} is the empty tuple then $\text{fp}_n(\bar{a}) = \emptyset$. Finally we define

$$\text{fp}(\bar{a}) = \bigcup_{n \in \omega} \text{fp}_n(\bar{a}).$$

This section is dedicated to the proof of the following theorem.

15.11 Hindman Theorem Let G be an infinite semigroup. Then for every finite coloring of G there is an infinite tuple \bar{c} such that $\text{fp}(\bar{c})$ is monochromatic.

Note that when G is commutative this amounts to claiming that there is an infinite monochromatic set closed under finite sum of distinct elements.

The proof below follows closely the proof of Ramsey's Theorem 15.1. The novelty is all in Lemma 15.10.

We now consider G as a structure a language L containing a symbol for semigroup multiplication and possibly other symbols. Let \mathcal{U} be a saturated elementary superstructure of G .

Proof We think G as a structure in a language L that extends the language of multiplicative groups with a unary relation symbol for each subset of G . As observed in Example 14.11, this language makes \downarrow_G trivially 1-stationary.

The colors corresponds to a definable partition of G and, by elementarity, of \mathcal{U} . Let $p(x) \in S(\mathcal{U})$ be a global coheir of the type $q(x) \in S(G)$ obtained from Lemma 15.10.

Let $\bar{c} = \langle c_i : i < \omega \rangle$ be a sequence such that

$$c_i \models p_{\upharpoonright G, \text{fp}(c_{\upharpoonright i})}(x),$$

By Lemma 15.10, if $a \in \text{fp}(c_{\upharpoonright i})$ then $a \cdot c_i \models q(x)$. It follows in particular that $\text{fp}(\bar{c})$ is monochromatic.

Now, we use the sequence \bar{c} to define $\bar{a} \in G^\omega$ such that $\text{fp}(\bar{a})$ is monochromatic.

Assume as induction hypothesis that $\text{fp}(a_{\upharpoonright i}, \bar{c})$ is monochromatic. Our goal is to find a_i such as the same property holds for $a_{\upharpoonright i}, a_i, \bar{c}$.

Let $\varphi(a_{\upharpoonright i}, c_i, c_{\upharpoonright i})$ be the sentence that says $\text{fp}_{i+1}(a_{\upharpoonright i}, c_i, c_{\upharpoonright i})$ is monochromatic. As \bar{c} is a coheir sequence we can find $a_i \in M$ such that $\varphi(a_{\upharpoonright i}, a_i, c_{\upharpoonright i})$. Hence $\text{fp}_{i+1}(a_{\upharpoonright i}, a_i, c_{\upharpoonright i})$ is monochromatic. As \bar{c} is indiscernible over G , this is equivalent to $\text{fp}(a_{\upharpoonright i}, a_i, \bar{c})$. \square

5 Hales-Jewett theorem

Assume the notation of Section 3. Assume also that \downarrow_M is 1-stationary and let M be a model.

We write $a \leq_M b$ if $a \in (b \cdot_M \mathcal{U}) \cap (\mathcal{U} \cdot_M b)$. This relation is easily seen to be transitive. Contrary to what the symbol may suggest, when \mathcal{U} is not a monoid, $a \leq_M a$ may not hold.

15.12 Proposition *If $a \leq_M b \leq_M a$ then $a \equiv_M b$.*

Proof By definition, $a \leq_M b$ implies that $a_M = b \cdot_M r = l \cdot_M b$ for some $r, l \in \mathcal{U}$. It follows that $b_M = b \cdot_M a = a \cdot_M b$. The symmetric argument shows that $b \leq_M a$ implies $a_M = a \cdot_M b = b \cdot_M a$. Hence $a \equiv_M b$ follows. \square

15.13 Proposition *For every idempotent a_M , there is a \leq_M -minimal $b \leq_M a$ with idempotent orbit.*

Proof Construct a decreasing \leq_M -chain of elements with idempotent orbit. Let $b_0 = a$. At stage i , if b_i is \leq_M -minimal we are finished. Otherwise, there is some $b_{i+1} <_M b_i$. At a limit stage λ note that the intersection of the sets $b_i \cdot_M \mathcal{U} \cap \mathcal{U} \cdot_M b_i$ for $i < \lambda$ is type definable (???). It is also idempotent and therefore, by Lemma 15.10, it contains an element b_λ with idempotent orbit. Then $b_\lambda \leq_M b_i$ for every $i < \lambda$. Clearly, the construction has to stop at some stage yielding a \leq_M -minimal b . \square

The following is a technical lemma that is required for the proof of the main theorem.

15.14 Proposition Assume \perp_M is 1-stationary and let M be a model. Let $\sigma : \mathcal{U} \rightarrow \mathcal{U}$ be a definable semigroup homomorphism. Then

1. $\sigma[a_M] = \sigma(a)_M$
2. $\sigma[a \cdot_M b] = \sigma(a) \cdot_M \sigma(b)$.

Proof

1. As $a \equiv_M a'$ implies $\sigma(a) \equiv_M \sigma(a')$, inclusion \subseteq is clear. For the converse, note that the type $\exists y [\sigma(y) = x \wedge y \equiv_M a]$ is trivially realized by $\sigma(a)$. By invariance it is equivalent to a type over A . Therefore it is realized by all elements of $\sigma(a)_M$. Hence all elements of $\sigma(a)_M$ are image of some element in a_M .

2. We have to prove the following equality

$$\{\sigma(a' \cdot b') : a \equiv_M a' \perp_M b' \equiv_M b\} = \{a' \cdot b' : \sigma(a) \equiv_M a' \perp_M b' \equiv_M \sigma(b)\}.$$

It suffices to prove one inclusion because by Proposition 15.8 both sides are orbits. We prove \subseteq . Note that the set on r.h.s. is equal to

$$\{\sigma(a' \cdot b') : \sigma(a') \perp_M \sigma(b'), a' \equiv_M a, b' \equiv_M b\}.$$

Hence it suffices to note that $a' \perp_M b'$ implies $\sigma(a') \perp_M \sigma(b')$. □

Let G be a semigroup. A **nice subsemigroup** of G is a subsemigroup C with the property that if $a \cdot b \in C$ then both $a, b \in C$.

The following is an abstract version of the Hales-Jewett Theorem which is slightly easier to prove.

15.15 Theorem Let G be a semigroups and let $C \subseteq G$ be a nice subsemigroup. Let $\sigma_i : G \rightarrow C$ for $i = 1, \dots, n$ be **retractions**, that is, homomorphisms such that $\sigma_i|_C = \text{id}_C$. Then, for every finite coloring of C , there is a $g \in G \setminus C$ such that $\{\sigma_i(g) : i = 1, \dots, n\}$ is monochromatic.

Proof Let $G \preceq \mathcal{V}$. Here \mathcal{V} is a monster model in a language contains a symbol for multiplication and for all subsets of G . Let \mathcal{U} be the definable set such that $C = G \cap \mathcal{U}$. By elementarity, \mathcal{U} is a nice subsemigroup of \mathcal{V} . The language contains also symbols for the retractions $\sigma_i : \mathcal{V} \rightarrow \mathcal{U}$.

In \mathcal{U} we define the order relation \leq_G as above. By Proposition 15.13, there is an $a \in \mathcal{U}$ such that $a \equiv_M b$ for every $b \in (a \cdot_G \mathcal{U}) \cap (\mathcal{U} \cdot_G a)$.

Pick any $u \in \mathcal{V} \setminus \mathcal{U}$ and let $g = a \cdot u \cdot a$. As \mathcal{U} is a nice subsemigroup, $g \notin \mathcal{U}$. Clearly $g \in (a \cdot_G \mathcal{V}) \cap (\mathcal{V} \cdot_G a)$. By Proposition 15.14, $\sigma_i(g) \in (a \cdot_G \mathcal{U}) \cap (\mathcal{U} \cdot_G a)$. Hence, by Proposition 15.12, $\sigma_i(g) \equiv_G a$. In particular the set $\{\sigma_i(g) : i = 1, \dots, n\}$ is monochromatic. This very g need not belong to $G \setminus C$ but, by elementarity, $G \setminus C$ contains some g' with the same property proving the theorem. □

15.16 Hales-Jewett Theorem Let C be an infinite semigroup. Fix a tuple of variable x and let $F \subseteq C^{|x|}$ be an arbitrary finite set. Fix also a finite coloring of C . Then there is a non constant term $t(x)$ of the language of semigroups with parameters in C such that $\{t(a) : a \in F\}$ is monochromatic.

Proof Let G be the set of terms quotiented by equality modulo the theory of semi-groups. Then to every tuple $a \in F$ the map $t(x) \mapsto t(x/a)$ is a retraction. Then we can apply the theorem above. \square

Chapter 16

Lascar invariant sets

In this chapter we fix a signature L , a complete theory T without finite models, and a saturated model \mathcal{U} of inaccessible cardinality κ strictly larger than $|L|$. The notation and implicit assumptions are as in Section 9.3.

1 Expansions

This section is only marginally required in the present chapter so it can be postponed with minor consequences.

We will find it convenient to expand the language L with a predicate for a given $\mathcal{D} \subseteq \mathcal{U}^{|z|}$. We denote by $\langle \mathcal{U}, \mathcal{D} \rangle$ the corresponding expansion of \mathcal{U} . Generally, we write $L(\mathcal{X})$ for the expanded language but, if the intended interpretation of \mathcal{X} is only going to be \mathcal{D} , we may write $L(\mathcal{D})$ and abbreviate $\langle \mathcal{U}; \mathcal{D} \rangle \models \varphi(\mathcal{X})$ as $\varphi(\mathcal{D})$.

16.1 Remark The definitions above are straightforward when z finite tuple. When z is an infinite tuple the intuition stays the same but a more involved definition is required. In fact, first-order logic does not allow infinitary predicates. We think of $L(\mathcal{X})$ for a two sorted language. The *home sort*, denoted by 0, and the *z-sort*, denoted by z . The expansion $\langle \mathcal{U}, \mathcal{D} \rangle$ has domain \mathcal{U} for the home sort, and $\mathcal{U}^{|z|}$ for the z -sort. Besides the symbols of L , there is a function symbol π_i for every $i < |z|$ which is interpreted as the projection to the i -coordinate. These functions have arity $\langle z, 0 \rangle$ (see Section 13.1 for the notation). There is also a predicate of sort $\langle z \rangle$ interpreted as \mathcal{D} . □

What said above is adapted to define the expansion $L(\mathcal{X}_i : i < \lambda)$, where \mathcal{X}_i are predicates of arity $|z_i|$. Again, when the sets $\mathcal{D}_i \subseteq \mathcal{U}^{|z_i|}$ are the only intended interpretation of \mathcal{X}_i , we may write $L(\mathcal{D}_i : i < \lambda)$.

If $\mathcal{C}, \mathcal{D} \subseteq \mathcal{U}^{|z|}$ we abbreviate $\langle \mathcal{U}, \mathcal{C} \rangle \equiv_A \langle \mathcal{U}, \mathcal{D} \rangle$ as $\mathcal{C} \equiv_A \mathcal{D}$. We also say that \mathcal{D} is **saturated** if so is the model $\langle \mathcal{U}; \mathcal{D} \rangle$.

16.2 Remark For every $\mathcal{D} \subseteq \mathcal{U}^{|z|}$ there is a saturated $\mathcal{C} \equiv \mathcal{D}$. In fact, it suffices to find a saturated model $\langle \mathcal{U}', \mathcal{D}' \rangle \equiv \langle \mathcal{U}, \mathcal{D} \rangle$ of cardinality κ . By saturation, there is an isomorphism $f : \mathcal{U}' \rightarrow \mathcal{U}$. Therefore $f[\mathcal{D}']$ is the required set \mathcal{C} . □

16.3 Exercise Prove that if $\mathcal{D} \subseteq \mathcal{U}^{|z|}$ is saturated and invariant over A than it is definable over A . □

16.4 Proposition If $\mathcal{D} \subseteq \mathcal{U}^{|z|}$ is invariant over A then every A -indiscernible sequence is indiscernible in the language $L(A; \mathcal{D})$.

Proof Let $\bar{c} = \langle c_i : i \in I \rangle$ be an A -indiscernible sequence. For every $I_0, I_1 \in I^{[n]}$ there is an $f \in \text{Aut}(\mathcal{U}/A)$ such that $f c_{\upharpoonright I_0} = c_{\upharpoonright I_1}$, Hence

$$\varphi(c_{\upharpoonright I_0}; \mathcal{D}) \leftrightarrow \varphi(fc_{\upharpoonright I_0}; f[\mathcal{D}]) \leftrightarrow \varphi(c_{\upharpoonright I_1}; \mathcal{D}). \quad \square$$

16.5 Exercise Prove that if $\mathcal{C} \subseteq \mathcal{U}^{[z]}$ is type-definable over B then $\equiv_{A,B}$ implies $\equiv_{A;\mathcal{C}}$. \square

2 Lascar strong types

Let $\mathcal{D} \subseteq \mathcal{U}^{[z]}$, where z is a tuple of length $< \kappa$. The **orbit of \mathcal{D} over A** is the set

$$o(\mathcal{D}/A) \stackrel{\text{def}}{=} \{f[\mathcal{D}] : f \in \text{Aut}(\mathcal{U}/A)\}$$

So, \mathcal{D} is invariant over A when $o(\mathcal{D}/A) = \{\mathcal{D}\}$. We say that \mathcal{D} is **Lascar invariant** over A if it is invariant over every model $M \supseteq A$. Recall that this means that if $a \equiv_M c$ for some model M containing A then $a \in \mathcal{D} \leftrightarrow c \in \mathcal{D}$.

16.6 Proposition Let $\lambda = |L_z(A)|$. There are at most 2^{2^λ} sets $\mathcal{D} \subseteq \mathcal{U}^{[z]}$ that are Lascar invariant over A .

Proof Let N be a model containing A of cardinality $\leq \lambda$. Every set that is Lascar invariant over A is invariant over N . As $|L_z(N)| = \lambda$ the bound follows from Proposition 14.1. \square

16.7 Theorem For every \mathcal{D} and every $A \subseteq M$ the following are equivalent

1. \mathcal{D} is Lascar invariant over A ;
2. every set in $o(\mathcal{D}/A)$ is M -invariant;
3. $o(\mathcal{D}/A)$ has cardinality $\leq 2^{2^{|L(A)|}}$;
4. $o(\mathcal{D}/A)$ has cardinality $< \kappa$;
5. $c_0 \in \mathcal{D} \leftrightarrow c_1 \in \mathcal{D}$ for every A -indiscernible sequence $\langle c_i : i < \omega \rangle$.

Proof $1 \Rightarrow 2$. This implication is clear because all sets in $o(\mathcal{D}/A)$ are Lascar invariant over A .

$2 \Rightarrow 3$. When $|M| \leq |L(A)|$ the implication follows from the bounds discussed in Section 14.1. We temporarily add this assumption on M . Once the proof of the proposition is completed, is easily seen to be redundant.

$3 \Rightarrow 4$. This implication holds because κ is a strong limit cardinal.

$4 \Rightarrow 5$. Assume $\neg 5$. Then we can find an A -indiscernible sequence $\langle c_i : i < \kappa \rangle$ such that $c_0 \in \mathcal{D} \nleftrightarrow c_1 \in \mathcal{D}$. Define

$$E(u; v) \Leftrightarrow u \in \mathcal{C} \leftrightarrow v \in \mathcal{C} \text{ for every } \mathcal{C} \in o(\mathcal{D}/A).$$

Then $E(u; v)$ is an A -invariant equivalence relation. As $\neg E(c_0; c_1)$, by Proposition 16.4, indiscernibility over A implies that $\neg E(c_i; c_j)$ for every $i < j < \kappa$. Then $E(u; v)$ has κ equivalence classes. As κ is inaccessible, this implies $\neg 4$.

$5 \Rightarrow 1$. Fix any $a \equiv_N b$ where $A \subseteq N$. It suffices to prove that $a \in \mathcal{D} \leftrightarrow b \in \mathcal{D}$. Let $p(z) \in S(\mathcal{U})$ be a global coheir of $\text{tp}(a/N) = \text{tp}(b/N)$. Let $\bar{c} = \langle c_i : i < \omega \rangle$ be a Morley sequence of $p(z)$ over N, a, b . Then both a, \bar{c} and b, \bar{c} are A -indiscernible sequences. Therefore, from 5 we obtain $a \in \mathcal{D} \leftrightarrow c_0 \in \mathcal{D} \leftrightarrow b \in \mathcal{D}$. \square

For definable sets Lascar invariance reduces to definability over the algebraic closure.

16.8 Corollary For every definable set \mathcal{D} the following are equivalent

1. \mathcal{D} is Lascar invariant over A ;
2. \mathcal{D} is definable over $\text{acl}^{\text{eq}}(A)$. □

The following corollary easily follows from Theorem 16.7 and Proposition 16.4. As an exercise the reader may wish to prove it using Proposition 15.3.

16.9 Corollary The following are equivalent

1. \mathcal{D} is Lascar invariant over A ;
2. every sequence of A -indiscernibles is $L(A; \mathcal{D})$ -indiscernible. □

⚠ Given a tuple $a \in \mathcal{U}^{|z|}$, we write $\mathcal{L}(a/A)$ for the intersection of all sets containing a that are Lascar invariant over A . Clearly $\mathcal{L}(a/A)$ is Lascar invariant over A . The symbol $\mathcal{L}(a/A)$ is not standard.

16.10 Definition We write $a \stackrel{L}{\equiv}_A b$ and say that a and b have the same Lascar strong type over A if the equivalence $a \in \mathcal{D} \leftrightarrow b \in \mathcal{D}$ holds for every set \mathcal{D} that is Lascar invariant over A or, in other words, if $\mathcal{L}(a/A) = \mathcal{L}(b/A)$. The notation $\text{L-stp}(a/A) = \text{L-stp}(b/A)$ and $aE_{L/A}b$ are also common in the literature. □

16.11 Proposition The relation $\stackrel{L}{\equiv}_A$ is the finest equivalence relation with $< \kappa$ classes that is invariant over A . □

Proof Clearly $\stackrel{L}{\equiv}_A$ is an equivalence relation invariant over A . Each equivalence class is Lascar invariant over A , hence the number of equivalence classes is bounded by the number of Lascar invariant sets over A . To see that $\stackrel{L}{\equiv}_A$ is the finest of such equivalences. Suppose \mathcal{D} is an equivalence class of an A -invariant equivalence relation with $< \kappa$ classes. Then $\sigma(\mathcal{D}/A)$ has also cardinality $< \kappa$. Then \mathcal{D} is Lascar invariant and as such it is union of classes of the relation $\stackrel{L}{\equiv}_A$. □

Let $p(x) \in S(\mathcal{U})$ be global type; we say that p is Lascar invariant over A if the sets $\mathcal{D}_{p,\varphi}$ for $\varphi(x;z) \in L$ all Lascar invariant over A . (The sets $\mathcal{D}_{p,\varphi}$ are defined in Section 14.1.)

16.12 Proposition Let $p(x) \in S(\mathcal{U})$ be a global type. Then the following are equivalent

1. $p(x)$ is Lascar invariant over A ;
2. every A -indiscernible sequence $\bar{c} = \langle c_i : i < \omega \rangle$ is also A, a -indiscernible for every $a \models p_{\upharpoonright A, \bar{c}}(x)$;
3. every A -indiscernible sequence $\bar{c} = \langle c_i : i < \omega \rangle$ is indiscernible over any $a \models p_{\upharpoonright \bar{c}}(x)$.

For convenience all tuples c_i have length $|z| = \omega$.

Proof We prove $1 \Leftrightarrow 3$. Equivalence $1 \Leftrightarrow 2$ can be proved similarly because the Lascar invariance of $p(x)$ easily implies the Lascar invariance of the sets $\mathcal{D}_{p,\varphi}$ for all $\varphi(x;z) \in L(A)$.

$3 \Rightarrow 1$ If $p(x)$ is not Lascar invariant over A then $c_0 \in \mathcal{D}_{p,\varphi} \not\leftrightarrow c_1 \in \mathcal{D}_{p,\varphi}$ for some A -indiscernible sequence $\bar{c} = \langle c_i : i < \omega \rangle$ and some $\varphi(x;z) \in L$. Then $p(x)$ contains

the formula $\varphi(\bar{x}; c_0) \not\equiv \varphi(\bar{x}; c_1)$. Hence, \bar{c} is not indiscernible over any realization of $p(\bar{x})|_{c_0, c_1}$.

1 \Rightarrow 3 Assume 1 and fix an A -indiscernible sequence $\bar{c} = \langle c_i : i < \omega \rangle$ and some $a \models p|_{\bar{c}}$. We need to prove that for every formula $\varphi(\bar{x}; \bar{z}') \in L$, where $\bar{z}' = z_1, \dots, z_n$,

$$\varphi(a; c_0, \dots, c_{n-1}) \leftrightarrow \varphi(a; c_{i_1}, \dots, c_{i_{n-1}}).$$

holds for every $i_0 < \dots < i_{n-1} < \omega$. Suppose not and let m be any integer larger than i_{n-1} . Then the following equivalences cannot both be true

$$\varphi(a; c_m, \dots, c_{m+n-1}) \leftrightarrow \varphi(a; c_0, \dots, c_{n-1});$$

$$\varphi(a; c_m, \dots, c_{m+n-1}) \leftrightarrow \varphi(a; c_{i_0}, \dots, c_{i_{n-1}}).$$

If the first is false, define $c'_k = c_{km}, \dots, c_{km+n-1}$ for all $k < \omega$. Otherwise, do this only for positive k and set $c'_0 = c_{i_0}, \dots, c_{i_{n-1}}$. In either cases $\langle c'_k : k < \omega \rangle$ is a sequence of A -indiscernibles and $c'_0 \in \mathcal{D}_{p, \varphi} \not\equiv c'_1 \in \mathcal{D}_{p, \varphi}$. This contradicts 1. \square

16.13 Exercise Prove that the equivalence relation $a \stackrel{L}{\equiv}_A b$ is the transitive closure of the relation: there is a sequence $\langle c_i : i < \omega \rangle$ indiscernible over A such that $c_0 = a$ and $c_1 = b$. Hint: apply Theorem 16.7. \square

3 The Lascar graph and Newelski's theorem

Here we study Lascar strong types from a different viewpoint. The **Lascar graph** over A has an arc between all pairs $a, b \in \mathcal{U}^{|z|}$ such that $a \equiv_M b$ for some model M containing A . We write $d_A(a, b)$ for the distance between a and b in the Lascar graph over A . Let us spell this out: $d_A(a, b) \leq n$ if there is a sequence a_0, \dots, a_n such that $a = a_0$, $b = a_n$, and $a_i \equiv_{M_i} a_{i+1}$ for some models M_i containing A . We write $d_A(a, b) < \infty$ if a and b are in the same connected component of the Lascar graph over A .

16.14 Proposition For every $a \in \mathcal{U}^{|z|}$

$$\mathcal{L}(a/A) = \{c : d_A(a, c) < \infty\}.$$

Proof To prove inclusion \supseteq it suffices to show that every Lascar A -invariant set containing a contains the set on the r.h.s. Let \mathcal{D} be Lascar A -invariant, and let $b \in \mathcal{D}$. Then \mathcal{D} contains also every c such that $b \equiv_M c$ for some model M containing A . That is, \mathcal{D} contains every c such that $d_A(b, c) \leq 1$. It follows that \mathcal{D} contains every c such that $d_A(a, c) < \infty$.

To prove inclusion \subseteq we prove the set on the r.h.s. is Lascar A -invariant. Suppose the sequence a_0, \dots, a_n , where $a_0 = a$ and $a_n = c$, witnesses $d_A(a, c) \leq n$ and suppose that $c \equiv_M b$ for some M containing A , then the sequence a_0, \dots, a_n, b witnesses $d_A(a, b) \leq n + 1$. \square

We write $\text{Autf}(\mathcal{U}/A)$ for the subgroup of $\text{Aut}(\mathcal{U}/A)$ that is generated by the automorphisms that fix point-wise some model M containing A . (The “f” in the symbol stands for *fort*, the French word for *strong*.) It is easy to verify that $\text{Autf}(\mathcal{U}/A)$ is a normal subgroup of $\text{Aut}(\mathcal{U}/A)$. The following is a corollary of Proposition 16.14.

16.15 Corollary The following are equivalent

1. $a \stackrel{L}{\equiv}_A b$
2. $a = fb$ for some $f \in \text{Autf}(\mathcal{U}/A)$.

□

It may not be immediately obvious that the relation $d_A(z, y) \leq n$ is type-definable.

16.16 Proposition *For every $n < \omega$ there is a type $p_n(z, y) \subseteq L(A)$ equivalent to $d_A(z, y) \leq n$.*

Proof It suffices to prove the proposition with $n = 1$. Let $\lambda = |L(A)|$ and fix a tuple of distinct variables $w = \langle w_i : i < \lambda \rangle$, then $p_1(z, y) = \exists w p(w, z, y)$ where

$$p(w, z, y) = q(w) \cup \left\{ \varphi(z, w) \leftrightarrow \varphi(y, w) : \varphi(z, w) \in L(A) \right\}$$

and $q(w) \subseteq L(A)$ is a consistent type with the property that all its realizations enumerate a model containing A .

It remains to verify that such a type exist. Let $\langle \psi_i(x, w_{\upharpoonright i}) : i < \lambda \rangle$ be an enumeration of the formulas in $L_{x, w}(A)$, where x is a single variable. Let

$$q(w) = \left\{ \exists x \psi_i(x, w_{\upharpoonright i}) \rightarrow \psi_i(w_i, w_{\upharpoonright i}) : i < \lambda \right\}.$$

Any realization of $q(w)$ satisfy the Tarski-Vaught test therefore it enumerates a model containing A . Vice versa it is clear that we can realize $q(w)$ in any model containing A . □

We conclude this section with a theorem of Ludomir Newelski.

The following notions apply generally to any group G acting on some set \mathcal{X} and to any set $\mathcal{D} \subseteq \mathcal{X}$. Below we always have $G = \text{Autf}(\mathcal{U}/A)$ and $\mathcal{X} = \mathcal{U}^{|z|}$. We say that \mathcal{D} is **drifting** if for every finitely many $f_1, \dots, f_n \in G$ there is a $g \in G$ such that $g[\mathcal{D}]$ is disjoint from all the $f_i[\mathcal{D}]$. We say that \mathcal{D} is **quasi-invariant** if for every finitely many $f_1, \dots, f_n \in G$ the sets $f_i[\mathcal{D}]$ have non-empty intersection. We say that a **formula** or a **type is drifting** or quasi-invariant if the set it defines is.

The union of drifting sets need not be drifting. However, by the following lemma it cannot be quasi-invariant.

16.17 Lemma *The union of finitely many drifting sets is not quasi-invariant.*

Proof It is convenient to prove an apparently more general claim. If $\mathcal{D}_1, \dots, \mathcal{D}_n$ are all drifting and \mathcal{L} is such that for some finite $F \subseteq G$

$$\# \quad \mathcal{L} \subseteq \bigcup_{f \in F} f[\mathcal{D}_1 \cup \dots \cup \mathcal{D}_n],$$

then \mathcal{L} is not quasi-invariant. The claim is vacuously true for $n = 0$. Now, assume n is positive and that the claim holds for $n - 1$. Define $\mathcal{C} = \mathcal{D}_1 \cup \dots \cup \mathcal{D}_{n-1}$ and rewrite $\#$ as follows

$$\mathcal{L} \subseteq \bigcup_{f \in F} f[\mathcal{C}] \cup \bigcup_{h \in F} h[\mathcal{D}_n]$$

Since \mathcal{D}_n is drifting there is a $g \in G$ such that $g[\mathcal{D}_n]$ is disjoint from $h[\mathcal{D}_n]$ for every $h \in F$, which implies that

$$\mathcal{L} \cap g[\mathcal{D}_n] \subseteq \bigcup_{f \in F} f[\mathcal{C}].$$

Hence for every h there holds

$$hg^{-1}[\mathcal{L}] \cap h[\mathcal{D}_n] \subseteq \bigcup_{f \in F} hg^{-1}f[\mathcal{C}]$$

So, from \sharp we obtain

$$\mathcal{L} \cap \bigcap_{h \in F} hg^{-1}[\mathcal{L}] \subseteq \bigcup_{f \in F} f[\mathcal{C}] \cup \bigcup_{h \in F} \bigcup_{f \in F} hg^{-1}f[\mathcal{C}].$$

By the induction hypothesis, the set on the r.h.s. is not quasi-invariant. Hence neither is \mathcal{L} , proving the claim and with it the lemma. \square

The following is a consequence of Baire's category theorem. We sketch a proof for the convenience of the reader.

16.18 Lemma *Let $p(x) \subseteq L(B)$ and $p_n(x) \subseteq L(A)$, for $n < \omega$, be consistent types such that*

$$1. \quad p(x) \rightarrow \bigvee_{n < \omega} p_n(x)$$

Then there is an $n < \omega$ and a formula $\varphi(x) \in L(A)$ consistent with $p(x)$ such that

$$2. \quad p(x) \wedge \varphi(x) \rightarrow p_n(x)$$

Proof Negate 2 and choose inductively for every $n < \omega$ a formula $\psi_n(x) \in p_n(x)$ such that $p(x) \wedge \neg\psi_0(x) \wedge \dots \wedge \neg\psi_n(x)$ is consistent. By compactness, this contradicts 1. \square

Finally we can prove Newelski's theorem on the diameter of Lascar types.

16.19 Theorem (Newelski) *For every $a \in \mathcal{U}^{|z|}$ the following are equivalent*

1. $\mathcal{L}(a/A)$ is type-definable;
2. $\mathcal{L}(a/A) = \{c : d_A(a, c) < n\}$ for some $n < \omega$.

Proof Implications $2 \Rightarrow 1$ holds by Proposition 16.16. We prove $1 \Rightarrow 2$. Suppose $\mathcal{L}(a/A)$ is type-definable, say by the type $l(z)$. Let $p(z, y)$ be some consistent type (to be defined below) such that $p(z, y) \rightarrow l(z) \wedge l(y)$. Then, in particular

$$p(z, y) \rightarrow \bigvee_{n < \omega} d_A(z, y) < n.$$

By Proposition 16.16 and Lemma 16.18, there is some $n < \omega$ and some $\varphi(z, y) \in L(A)$ consistent with $p(z, y)$ such that

$$\sharp_1 \quad p(z, y) \wedge \varphi(z, y) \rightarrow d_A(z, y) < n.$$

Below we define $p(z, y)$ so that for every $\psi(z, y) \in L(A)$

$$\sharp_2 \quad p(z, a) \wedge \psi(z, a) \quad \text{is non-drifting whenever it is consistent.}$$

Drifting and quasi-invariance are relative to the action of $\text{Autf}(\mathcal{U}/A)$ on $\mathcal{U}^{|z|}$. Then, in particular, $p(z, a) \wedge \varphi(z, a)$ is non-drifting and the theorem follows. In fact, by non-drifting, there are some $a_0, \dots, a_k \in \mathcal{L}(a/A)$ such that every set $p(\mathcal{U}, c) \cap \varphi(\mathcal{U}, c)$ for $c \in \mathcal{L}(a/A)$ intersects some $p(\mathcal{U}, a_i) \cap \varphi(\mathcal{U}, a_i)$. Let m be such that $d_A(a_i, a_j) \leq m$ for every $i, j \leq k$. From \sharp_1 we obtain that $d_A(a, c) \leq m + 2n$. As $c \in \mathcal{L}(a/A)$ is arbitrary, the theorem follows.

The required type $p(z, y)$ is union of a chain of types $p_\alpha(z, y)$ defined as follows

$$p_0(z, y) = l(z) \cup l(y);$$

$$\begin{aligned} \#_3 \quad p_{\alpha+1}(z, y) &= p_\alpha(z, y) \cup \left\{ \neg\psi(z, y) : p_\alpha(z, a) \wedge \psi(z, a) \text{ is drifting} \right\}; \\ p_\alpha(z, y) &= \bigcup_{n < \alpha} p_n(z, y) \quad \text{for limit } \alpha. \end{aligned}$$

Clearly, the chain stabilizes at some stage $\leq |L(A)|$ yielding a type which satisfies $\#_2$. So we only need to prove consistency. We prove that $p_\alpha(z, a)$ is quasi-invariant (so, in particular, consistent). Suppose that $p_n(z, a)$ is quasi-invariant for every $n < \alpha$ but, for a contradiction, $p_\alpha(z, a)$ is not. Then for some $f_1, \dots, f_k \in \text{Autf}(\mathcal{U}/A)$

$$p_\alpha(z, a) \cup \bigcup_{i=1}^k p_\alpha(z, f_i a)$$

is inconsistent. By compactness there is some $n < \alpha$ and some $\psi_i(z, y)$ as in $\#_3$ such that

$$p_n(z, a) \rightarrow \neg \bigwedge_{j=1}^m \bigwedge_{i=1}^k \neg \psi_j(z, f_i a)$$

As $p_n(z, a)$ is quasi-invariant, from Lemma 16.17 we obtain that $p_n(z, f_i a) \wedge \psi_j(z, f_i a)$ is non-drifting for some i, j . Clearly we can replace $f_i a$ with a , then this contradicts the construction of $p_\alpha(z, y)$ and proves the theorem. \square

16.20 Exercise Let \mathcal{L} be quasi-invariant and let \mathcal{D} be drifting, prove that $\mathcal{L} \setminus \mathcal{D}$ is quasi-invariant. \square

4 Kim-Pillay types


Given a tuple $a \in \mathcal{U}^{|z|}$, we write $\mathcal{K}(a/A)$ for the intersection of all type-definable sets containing a that are Lascar invariant over A . Or, more concisely, the intersection of all sets that are type-definable over a model containing A . We call $\mathcal{K}(a/A)$ the **Kim-Pillay strong type** over A . Clearly $\mathcal{K}(a/A)$ is Lascar invariant over A . It also easy to see that $\mathcal{K}(a/A)$ is type-definable. In fact, by invariance, we can assume that all types in the intersection above are over M , for any fixed model containing A . Hence $\mathcal{K}(a/A)$ is the minimal type-definable set containing a and closed under the relation $\stackrel{L}{\equiv}_A$. It follows that if $b \in \mathcal{K}(a/A)$ then $\mathcal{K}(b/A) \subseteq \mathcal{K}(a/A)$.

To summarize, we recall that we have defined a whole hierarchy of strong types obtained from the intersection of different sets with various sorts of invariance

$$\mathcal{L}(a/A) \subseteq \mathcal{K}(a/A) \subseteq \mathcal{S}(a/A) \subseteq \mathcal{O}(a/A).$$

Recall that $\mathcal{S}(a/A)$ was defined after Proposition 13.13.

If $\mathcal{K}(a/A) = \mathcal{K}(b/A)$, we say that a and b have the same **Kim-Pillay strong type** over A . We abbreviate this by $a \stackrel{\text{KP}}{\equiv}_A b$. In other words, we write $a \stackrel{\text{KP}}{\equiv}_A b$ when $a \in \mathcal{D} \leftrightarrow b \in \mathcal{D}$ for every type-definable set \mathcal{D} that is Lascar invariant over A .

 **Warning:** the symbol $\mathcal{K}(a/A)$ is not standard. The symbol $a \stackrel{\text{KP}}{\equiv}_A b$ is not unusual, but some author write $\text{KP-stp}(a/A) = \text{KP-stp}(b/A)$ or $a E_{\text{KP}/A} b$.

16.21 Proposition Fix some $a \in \mathcal{U}^{|z|}$ and some $A \subseteq \mathcal{U}$. Then there is a type $e(z; w) \subseteq L(A)$ such that $\mathcal{K}(b/A) = e(\mathcal{U}; b)$ for all $b \in \mathcal{O}(a/A)$ and $e(z; w)$ defines an equivalence relation on $\mathcal{O}(a/A)$.

Proof Notice that $\mathcal{K}(a/A)$ is type-definable over A, a . In fact, if $f \in \text{Aut}(\mathcal{U}/A, a)$ and \mathcal{D} is a set containing a that is type-definable and Lascar invariant over A , then so is $f[\mathcal{D}]$. Therefore $\mathcal{K}(a/A)$ is invariant over A, a . As $\mathcal{K}(a/A)$ is type-definable, invariance implies that it is type-definable over A, a . Let $e(z; w) \subseteq L(A)$ be such that $\mathcal{K}(a/A) = e(\mathcal{U}; a)$.

We prove that $\mathcal{K}(b/A) = e(\mathcal{U}; b)$ for all $b \in \mathcal{O}(a/A)$. Let $f \in \text{Aut}(\mathcal{U}/A)$ be such that $fa = b$. If \mathcal{D} is a type-definable Lascar invariant over A , then so is $f[\mathcal{D}]$. Therefore, f is a bijection between type-definable sets that are Lascar invariant over A and contain a and analogous sets containing b . Then $f[\mathcal{K}(a/A)] = \mathcal{K}(b/A)$ and $\mathcal{K}(b/A) = e(\mathcal{U}; b)$ follows.

We prove that $e(b; \mathcal{U}) \cap \mathcal{O}(a/A)$ is Lascar invariant over A . Let $f \in \text{Autf}(\mathcal{U}/A)$ and $c \in \mathcal{O}(a/A)$. Then $e(b; fc)$ is equivalent to $e(f^{-1}b; c)$ which in turn is equivalent to $e(b; c)$, by the invariance of $e(\mathcal{U}; c)$.

Finally we are ready to prove that $e(z; w)$ defines a symmetric relation on $\mathcal{O}(a/A)$. From what proved above, $e(b; \mathcal{U}) \cap \mathcal{O}(a/A)$ is a type-definable Lascar invariant set containing b and therefore it contains $\mathcal{K}(b/A)$. We conclude that for all $b, c \in \mathcal{O}(a/A)$

$$e(c; b) \leftrightarrow c \in e(\mathcal{U}; b) \leftrightarrow c \in \mathcal{K}(b/A) \rightarrow e(b; c)$$

Reflexivity is clear; we prove transitivity. As remarked above, $\mathcal{K}(b/A) \subseteq \mathcal{K}(c/A)$, for all $b \in \mathcal{K}(c/A)$ or equivalently $e(b; c)$. Hence if $e(b; c)$ then

$$e(d; b) \rightarrow d \in \mathcal{K}(b/A) \leftrightarrow d \in \mathcal{K}(c/A) \rightarrow e(d; c).$$

Which completes the proof. \square

16.22 Corollary For every $a, b \in \mathcal{U}^{|\mathcal{Z}|}$ and $A \subseteq \mathcal{U}$ the following are equivalent

1. $a \in \mathcal{K}(b/A)$;
2. $b \in \mathcal{K}(a/A)$;
3. $\mathcal{K}(a/A) = \mathcal{K}(b/A)$.

\square

The following useful lemma is the key ingredient in the proof of Theorem 16.24.

16.23 Lemma Let $p(z) \subseteq L(A)$ and let $e(z; w) \subseteq L(A)$ define a bounded equivalence relation on $p(\mathcal{U})$. Then there is a type $e'(z; w) \subseteq L(A)$ which defines a bounded equivalence relation (on \mathcal{U}) and refines $e(z; w)$ on $p(\mathcal{U})$.

Proof Let $\mathcal{C} = \langle \mathcal{C}_i : i < \lambda \rangle$ enumerate the partition of $p(\mathcal{U})$ induced by $e(z; w)$. Note that each \mathcal{C}_i is type-definable over A, a for any $a \in \mathcal{C}_i$. If $x = \langle x_i : i < \lambda \rangle$, we write $x \in \mathcal{C}$ for the type that is the conjunction of $x_i \in \mathcal{C}_i$ for $i < \lambda$.

We claim that the required type is

$$e'(a; b) \stackrel{\text{def}}{=} \exists x' \in \mathcal{C} \exists x'' \in \mathcal{C} \quad a, x' \equiv_A b, x''$$

As the type above is invariant over A , we can assume that $e'(a; b)$ is type-definable over A . Moreover, it is clearly a reflexive and symmetric relation, so we only check it is transitive. Suppose $a, x' \equiv_A b, x''$ and $b, y' \equiv_A c, y''$ for some $x', x'', y', y'' \in \mathcal{C}$. Let z be such that $a, x', z \equiv_A b, x'', y'$ then $z \in \mathcal{C}$ and $a, z \equiv_A c, y''$.

The relation $e'(a; b)$ clearly refines the equivalence defined by $e(z; w)$ when re-

stricted to to $p(\mathcal{U})$. To prove that it is bounded fix some $c \in \mathcal{C}$ and note that $e'(a; b)$ is refined by $a \equiv_{A, c} b$, which is bounded. \square

Finally, we have the following.

16.24 Theorem Denote by $e_A(z; w)$ be the finest bounded equivalence relation on $\mathcal{U}^{[z]}$ that is type-definable over A . Then for every $a, b \in \mathcal{U}^{[z]}$ the following are equivalent

1. $a \overset{\text{KP}}{\equiv} b$
2. $e_A(a; b)$. \square

Proof As $a \overset{\text{KP}}{\equiv} b$ is equivalent to $a \in \mathcal{K}(b/A)$, it suffices to prove that $e_A(\mathcal{U}; b) = \mathcal{K}(b/A)$ for every $b \in \mathcal{U}^{[z]}$.

\subseteq The orbit of $e_A(\mathcal{U}; b)$ under $\text{Aut}(\mathcal{U}/A)$ has cardinality $< \kappa$. Hence, by Theorem 16.7, it is Lascar invariant over A . As $\mathcal{K}(b/A)$ is the least of such sets, $\mathcal{K}(b/A) \subseteq e_A(\mathcal{U}; b)$.

\supseteq Let $e(z; w)$ be the type-definable equivalence relation given by Proposition 16.21. The orbit of $\mathcal{K}(b/A)$ under $\text{Aut}(\mathcal{U}/A)$ has cardinality $< \kappa$. Hence the equivalence relation that $e(z; w)$ defines on $\mathcal{O}(b/A)$ is bounded. By Lemma 16.23 there is a type-definable bounded equivalence relation $e'(z; w) \subseteq L(A)$ that refines $e(z; w)$ on $\mathcal{O}(b/A)$. As $e'(z; w)$ is refined by $e_A(z; w)$, we obtain $e_A(\mathcal{U}; b) \subseteq e(\mathcal{U}; b) = \mathcal{K}(b/A)$. \square

The **logic A -topology**, or simply the **logic topology** when A is empty, is the topology on $\mathcal{U}^{[z]}$ whose closed sets are the type-definable Lascar A -invariant sets. It is clearly a compact topology. Its Kolmogorov quotient, that is $\mathcal{U}^{[z]} / \overset{\text{KP}}{\equiv}$, is Hausdorff. In fact, by Corollary 16.22, the open sets $\neg\mathcal{K}(a/A)$ and $\neg\mathcal{K}(b/A)$ separate $b \overset{\text{KP}}{\not\equiv} a$.

16.25 Exercise Prove that the clopen sets in the logic A -topology are exactly the sets that are definable over $\text{acl}^{\text{eq}} A$. \square

5 Notes and references

The original proof of Newelski theorem is rather long and complex. A simplified proof appears in Rodrigo Peláez's thesis [1, Section 3.3]. The proof here is a streamlined version the latter.

We are grateful to Volodya Shavrukov for fixing a wrong proof of Lemma 16.17.

- [1] Rodrigo Peláez, *About the Lascar group*, PhD Thesis, Universitat de Barcelona, Departament de Lògica, Història i Filosofia de la Ciència, 2008.
- [2] Pierre Simon, *A guide to NIP theories*, Lecture Notes in Logic, vol. 44, Association for Symbolic Logic, Cambridge University Press, 2015.

=

Chapter 17

Externally definable sets

In this chapter we fix a signature L , a complete theory T without finite models, and a saturated model \mathcal{U} of inaccessible cardinality $\kappa > |L|$. The notation and implicit assumptions are as in Section 9.3.

1 Approximable sets

Let $\mathcal{C}, \mathcal{D} \subseteq \mathcal{U}^{|z|}$. The set $\mathcal{D} \cap A^{|z|}$ is called the **trace** of \mathcal{D} over A . We write $\mathcal{C} =_A \mathcal{D}$ if \mathcal{C} and \mathcal{D} have the same trace on A .

We say that \mathcal{D} is **externally definable** if it is of the form $\mathcal{D}_{p,\varphi}$ for some global type $p \in S_x(\mathcal{U})$ and some formula $\varphi(x; z) \in L$, see Section 14.1 for the notation. We may say that \mathcal{D} is externally definable **by $p(x)$ and $\varphi(x; z)$** . Equivalently, a set \mathcal{D} is externally definable if it is the trace over \mathcal{U} of a set which is definable in some elementary extension of \mathcal{U} . Precisely, \mathcal{D} is the trace on \mathcal{U} of a set of the form $\varphi(b'; \mathcal{U}')$ where \mathcal{U}' is elementary extension of \mathcal{U} and $b' \in \mathcal{U}'^{|x|}$. The latter interpretation explains the terminology.

⚠ We prefer to deal with external definability in a different, though equivalent, way. This is not the most common approach.

17.1 Definition We say that \mathcal{D} is **approximated** by the formula $\varphi(x; z)$ if for every finite B there is a $b \in \mathcal{U}^{|x|}$ such that $\varphi(b; \mathcal{U}) =_B \mathcal{D}$. If in addition we have that $\varphi(b; \mathcal{U}) \subseteq \mathcal{D}$, we say that \mathcal{D} is **approximated from below**. Similarly, when $\mathcal{D} \subseteq \varphi(b; \mathcal{U})$ we say that \mathcal{D} is **approximated from above**. We may call $\varphi(x; z)$ the **sort** of \mathcal{D} . □

The following proposition is clear by compactness.

17.2 Proposition For every \mathcal{D} the following are equivalent

1. \mathcal{D} is approximated by $\varphi(x; z)$;
2. \mathcal{D} is externally definable by $\varphi(x; z)$.

Approximability from below is an adaptation to our context of the notion of *having an honest definition* in [1].

17.3 Definition We say that the global type $p \in S_x(\mathcal{U})$ is **honestly definable** if for every $\varphi(x; z) \in L$ the set $\mathcal{D}_{p,\varphi}$ is approximated from below (by some formula). We say that p is **definable** if the sets $\mathcal{D}_{p,\varphi}$ are all definable (over \mathcal{U}). Note that the terminology is misleading: *honestly definable* is a weaker than *definable*.

17.4 Example Every definable set is trivially approximable. Sets may be approximable by different formulas. For instance, if $T = T_{\text{dlo}}$, then $\mathcal{D} = \{z \in \mathcal{U} : a \leq z \leq b\}$ is approximable both from below and from above by the formula $x_1 < z < x_2$ though it is not definable by this formula.

Now, let $T = T_{\text{rg}}$. Then every $\mathcal{D} \subseteq \mathcal{U}$ is approximable and, when \mathcal{D} has small infinite cardinality, it is approximable from above but not from below, see Exercise 6.22. \square

In Definition 17.1, the sort $\varphi(\mathbf{x}; \mathbf{z})$ is fixed (otherwise any set would be approximable) but this requirement of uniformity may be dropped if we allow B to have larger cardinality.

17.5 Proposition *For every \mathcal{D} the following are equivalent*

1. \mathcal{D} is approximable;
2. for every $C \subseteq \mathcal{U}$ of cardinality $\leq |T|$ there is $\psi(\mathbf{z}) \in L(\mathcal{U})$ such that $\psi(\mathcal{U}) =_C \mathcal{D}$.

Similarly, the following are equivalent

3. \mathcal{D} is approximable from below;
4. for every $C \subseteq \mathcal{D}$ of cardinality $\leq |T|$ there is $\psi(\mathbf{z}) \in L(\mathcal{U})$ such that $C \subseteq \psi(\mathcal{U}) \subseteq \mathcal{D}$.

Proof To prove $2 \Rightarrow 1$ assume 2 and negate 1 for a contradiction. For each formula $\varphi(\mathbf{x}; \mathbf{z}) \in L$ choose a finite set B such that $\varphi(\mathbf{b}; \mathcal{U}) \neq_B \mathcal{D}$ for every $\mathbf{b} \in \mathcal{U}^{|\mathbf{x}|}$. Let C be the union of all these finite sets. Clearly $|C| \leq |T|$. By 2 there are a formula $\varphi(\mathbf{x}; \mathbf{z})$ and a tuple \mathbf{c} such that $\varphi(\mathbf{c}; \mathcal{U}) =_C \mathcal{D}$, contradicting the definition of C .

Implication $1 \Rightarrow 2$ is obtained by compactness and the equivalence $3 \Leftrightarrow 4$ is proved similarly. \square

17.6 Remark If $\mathcal{D} \subseteq \mathcal{U}^{|\mathbf{z}|}$ is approximated by $\varphi(\mathbf{x}; \mathbf{z})$ then so is any \mathcal{C} such that $\mathcal{C} \equiv \mathcal{D}$, see Section 16.1 for the notation. In fact, if the set \mathcal{D} is approximable by $\varphi(\mathbf{x}; \mathbf{z})$ then for every n

$$\forall z_1, \dots, z_n \exists \mathbf{x} \bigwedge_{i=1}^n [\varphi(\mathbf{x}; z_i) \leftrightarrow z_i \in \mathcal{D}].$$

So the same holds for any $\mathcal{C} \equiv \mathcal{D}$. A similar remark apply to approximability from below and from above (e.g. for approximability from below, add the conjunct $\forall \mathbf{z} [\varphi(\mathbf{x}; \mathbf{z}) \rightarrow \mathbf{z} \in \mathcal{D}]$ to the formula above). \square

From the following easy observation of Chernikov and Simon [1] we obtain an interesting (and mysterious) quantifier elimination result originally due to Shelah, see Corollary 17.21 below.

17.7 Proposition *Let $\mathcal{C} \subseteq \mathcal{U}^{|\mathbf{y}\mathbf{z}|}$ be approximated from below by the formula $\varphi(\mathbf{x}; \mathbf{y}\mathbf{z})$. Then $\mathcal{D} = \{\mathbf{z} : \exists \mathbf{y} (\mathbf{y}\mathbf{z} \in \mathcal{C})\}$ is approximated from below by the formula $\exists \mathbf{y} \varphi(\mathbf{x}; \mathbf{y}\mathbf{z})$.*

Proof Let $B \subseteq \mathcal{U}$ be finite. We want $\mathbf{a} \in \mathcal{U}^{|\mathbf{x}|}$ such that

$$\text{a.} \quad \exists \mathbf{y} (\mathbf{y}\mathbf{b} \in \mathcal{C}) \leftrightarrow \exists \mathbf{y} \varphi(\mathbf{a}; \mathbf{y}\mathbf{b}) \quad \text{for every } \mathbf{b} \in B^{|\mathbf{z}|}$$

$$\text{b.} \quad \forall \mathbf{z} \left[\exists \mathbf{y} \varphi(\mathbf{a}; \mathbf{y}\mathbf{z}) \rightarrow \exists \mathbf{y} (\mathbf{y}\mathbf{z} \in \mathcal{C}) \right]$$

Let $D \subseteq \mathcal{U}$ be a finite set such that

$$\text{c.} \quad \exists \mathbf{y} \in D^{|\mathbf{y}|} (\mathbf{y}\mathbf{b} \in \mathcal{C}) \leftrightarrow \exists \mathbf{y} (\mathbf{y}\mathbf{b} \in \mathcal{C}) \quad \text{for every } \mathbf{b} \in B^{|\mathbf{z}|}$$

As \mathcal{C} is approximable from below, there is an \mathbf{a} such that

$$\text{a'.} \quad d\mathbf{b} \in \mathcal{C} \leftrightarrow \varphi(\mathbf{a}; d\mathbf{b}) \quad \text{for every } d\mathbf{b} \in (D \cup B)^{|\mathbf{y}\mathbf{z}|}$$

$$b'. \quad \forall yz \left[\varphi(a; yz) \rightarrow yz \in \mathcal{C} \right]$$

We obtain b from b' simply by logic. Implication \rightarrow in a follows from a' and c . Implication \leftarrow follows from b . \square

17.8 Corollary *If $p \in S_x(\mathcal{U})$ is honestly definable then the family of sets externally definable by p is closed under quantifiers and Boolean combinations.*

Proof The sets externally definable by $p(x)$ are always closed under Boolean operations. By the proposition above, they are closed under quantifiers. \square

2 Ladders and definability

Partitioned formulas have been introduced in Definition 1.14. Here we write $\varphi(x; z)^*$ for the partitioned formula where the order of the two tuples is inverted (i.e. it is the opposite of what displayed).

Let $\varphi(x; z) \in L(\mathcal{U})$ be a partitioned formula. We say that $\langle a_i; b_i : i < \alpha \rangle$ is a **ladder sequence** for $\varphi(x; z)$ if

$$\# \quad i < j \Leftrightarrow \varphi(a_i; b_j) \quad \text{for all } 0 \leq i, j \leq \alpha$$

We say that $\varphi(x; z)$ is **stable** if all ladders have length $\alpha < \omega$. Otherwise we say it is **unstable**. Note that by compactness the ladder sequences of a stable formula cannot have unbounded finite length.

It is evident that $\varphi(x; z)$ is stable if and only if $\varphi(x; z)^*$ is stable.

Suppose $\varphi(x; z)$ is unstable as witnessed by the ladder $\langle a_i; b_i : i < \omega \rangle$. By padding redundant variables, we can read $\varphi(x; z)$ as a formula $\varphi(xz; yw)$. Then $\varphi(xz; yw)$ defines the order of the sequence $\langle a_i b_i : i < \omega \rangle$. For this reason it is also common to say that $\varphi(x; z)$ has the **order property**, this simply means that it is unstable.

The following is arguably one of the most important fact about stable formulas.

17.9 Theorem *Any $\mathcal{D} \subseteq \mathcal{U}^{[z]}$ approximated by a stable formula is definable. Precisely, if $\varphi(x; z)$ is a stable formula that approximates \mathcal{D} then there are $a_{1,1}, \dots, a_{n,m} \in \mathcal{U}^{[x]}$ such that*

$$z \in \mathcal{D} \Leftrightarrow \bigvee_{i=1}^n \bigwedge_{j=1}^m \varphi(a_{i,j}; z)$$

Proof The theorem follows immediately from the the three lemmas below. \square

The converse of the theorem above holds and is proved separately in Theorem 17.14.

17.10 Remark Theorem 17.9 is often stated in the following apparently more general form. For every $\mathcal{A} \subseteq \mathcal{U}$ there are $a_{1,1}, \dots, a_{n,m} \in \mathcal{A}^{[x]}$ such that

$$z \in \mathcal{D} \Leftrightarrow \bigvee_{i=1}^n \bigwedge_{j=1}^m \varphi(a_{i,j}; z) \quad \text{for every } z \in \mathcal{A}^{[z]}$$

Note that the equivalence above is restricted to \mathcal{A} .

The proof is exactly the same, in fact elementarity and saturation are never used (to a great extent, no model theory is used either, just finite combinatorics). This contrast to the proof of Theorem 17.14 for which compactness is essential. \square

17.11 Lemma If \mathcal{D} is approximated from below by a stable formula $\varphi(\mathbf{x}; \mathbf{z})$ then there are $a_1, \dots, a_n \in \mathcal{U}^{|\mathbf{x}|}$ such that

$$\mathbf{z} \in \mathcal{D} \leftrightarrow \bigvee_{i=1}^n \varphi(a_i; \mathbf{z})$$

Proof Choose $a_n \in \mathcal{U}^{|\mathbf{x}|}$ such that $b_0, \dots, b_{n-1} \in \varphi(a_n; \mathcal{U}) \subseteq \mathcal{D}$. Then, if possible, choose b_n such that

$$b_n \in \mathcal{D} \setminus \bigvee_{i=0}^n \varphi(a_i; \mathcal{U})$$

and iterate the procedure. By stability, the procedure has to stop at some n , yielding the required a_1, \dots, a_n . \square

17.12 Lemma If \mathcal{D} is approximated by a stable formula $\varphi(\mathbf{x}; \mathbf{z})$ with ladder order m . Then the formula

$$\psi(x_1, \dots, x_m; \mathbf{z}) = \bigwedge_{j=1}^m \varphi(x_j; \mathbf{z})$$

approximates \mathcal{D} from below.

Proof Let $B \subseteq \mathcal{D}$ be finite. It suffices to prove that there are some a_1, \dots, a_m such that $B \subseteq \psi(a_1, \dots, a_m; \mathcal{U}) \subseteq \mathcal{D}$. Choose $a_n \in \mathcal{U}^{|\mathbf{x}|}$ such that

$$B \subseteq \varphi(a_n; \mathcal{U}) \subseteq \mathcal{U}^{|\mathbf{z}|} \setminus \{b_0, \dots, b_{n-1}\}.$$

Then, if possible, let b_n such that

$$b_n \in \bigwedge_{i=0}^n \varphi(a_i, \mathcal{U}) \setminus \mathcal{D}$$

and iterate the procedure. The procedure has to stop at some $n \leq m$. Hence the required parameters are $a_1, \dots, a_n = a_{n+1} = \dots = a_m$. \square

17.13 Lemma If $\varphi(\mathbf{x}; \mathbf{z})$ is a stable formula then for every m the formula

$$\psi(x_1, \dots, x_m; \mathbf{z}) \leftrightarrow \bigwedge_{j=1}^m \varphi(x_j; \mathbf{z})$$

is stable.

Proof For legibility, we only prove that $\varphi(x_1; \mathbf{z}) \wedge \varphi(x_2; \mathbf{z})$ is stable. Suppose not and let $a_i^1, a_i^2 \in \mathcal{U}^{|\mathbf{x}|}$ and $b_i \in \mathcal{U}^{|\mathbf{z}|}$ be such that

$$i < j \Leftrightarrow \varphi(a_i^1; b_j) \wedge \varphi(a_i^2; b_j) \quad \text{for all } i, j < \omega$$

For $n = 1, 2$ let $H_n \subseteq \binom{\omega}{2}$ contain those pairs $j < i$ such that $\neg \varphi(a_i^n; b_j)$. By the equivalence above $H_1 \cup H_2 = \binom{\omega}{2}$. By the Ramsey Theorem there is an infinite set H such that $\binom{H}{2} \subseteq H_n$ for at least one of $n = 1, 2$. Suppose H_1 for definiteness. So, we obtain an infinite sequence a_i^1, b_i such that

$$j < i \Leftrightarrow \neg \varphi(a_i^1; b_j) \quad \text{for all } i, j < \omega$$

which contradicts the stability of $\varphi(\mathbf{x}; \mathbf{z})$. \square

This last lemma concludes the proof of Theorem 17.9.

17.14 Theorem If every subset of $\mathcal{U}^{|\mathbf{z}|}$ that is externally definable by $\varphi(\mathbf{x}; \mathbf{z})$ is definable, then

$\varphi(x; z)$ is stable.

Proof Suppose $\varphi(x; z)$ is unstable. By compactness there is a ladder sequence $\langle a_i; b_i : i \in I \rangle$ where $I, <_I$ a saturated dense linear order of cardinality κ . For every downward Dedekind cut $c \subseteq I$ we pick a global type

$$p_c(x) \supseteq \{ \varphi(x; b_i) \leftrightarrow i \in c : i \in I \}$$

Clearly sets $\mathcal{D}_{p_c, \varphi}$ are all distinct. As there are 2^κ Dedekind cuts not every $\mathcal{D}_{p_c, \varphi}$ is definable. \square

17.15 Exercise The following is a version of Harrington's mysterious Lemma (cfr. [1, Lemma 8.3.4]). Let $\varphi(x; z) \in L$ be a stable formula and suppose $\mathcal{B} \subseteq \mathcal{U}^{[z]}$ and $\mathcal{A} \subseteq \mathcal{U}^{[x]}$ are approximated by $\varphi(x; z)$ and $\varphi(x; z)^*$, respectively. Then at least one of the conditions 1 and 2 below occurs

1. a. $\varphi(x; z) \wedge x \in \mathcal{A}$ approximates \mathcal{B} and
b. $\varphi(x; z)^* \wedge z \in \mathcal{B}$ approximates \mathcal{A} .
2. a. $\varphi(x; z) \wedge x \notin \mathcal{A}$ approximates \mathcal{B} and
b. $\varphi(x; z)^* \wedge z \notin \mathcal{B}$ approximates \mathcal{A} .

Hint: Note that at least one of 1a or 2a occurs. Hence it suffices to prove that $1a \Rightarrow 1b$ and $2a \Rightarrow 2b$. The two implications are essentially equivalent.

3 Vapnik-Chevronenkis dimension

We say that the formula $\varphi(x; z) \in L$ has **Vapnik-Chevronenkis dimension n** if this is the largest finite cardinality of a set $A \subseteq \mathcal{U}^{[x]}$ such that $|S_\varphi(A)| = 2^n$. If such n does not exist, we say that we say that $\varphi(x; z)$ has **infinite VC-dimension**.

Note that the condition $|S_\varphi(A)| = 2^n$ is equivalent to saying that every subset of A is the trace of some definable set of sort $\varphi(x; z)$.

For instance, the formula $z_1 < x < z_2$ in T_{dlo} has VC-dimension 1.

Arguing by compactness we obtain the following proposition whose proof is left as an exercise for the reader.

17.16 Proposition *The following are equivalent*

1. $\varphi(x; z) \in L$ has finite VC-dimension;
2. there is no infinite set $A \subseteq \mathcal{U}^{[x]}$ such that every subset of A is the trace of some definable set of sort $\varphi(x; z)$. \square

From the proposition above and Proposition 17.29 below it follows that all stable formulas have finite VC-dimension.

We say that the a sequence of sentences $\langle \varphi_i : i < \omega \rangle$ **converges** if the truth value of φ_i is eventually constant.

17.17 Lemma *The following are equivalent*

1. $\varphi(x; z) \in L$ has finite VC-dimension;
2. $\langle \varphi(a_i; b) : i < \omega \rangle$ converges for any b and any indiscernible sequence $\langle a_i : i < \omega \rangle$.

Proof $1 \Rightarrow 2$ Assume $\neg 2$. It suffices to prove that for every $I \subseteq \omega$ the type that says

$$\varphi(a_i; z) \Leftrightarrow i \in I$$

is finitely consistent. Let $\psi_{I \upharpoonright n}(x_0, \dots, x_{n-1})$ the formula that says that there is a z such that

$$\varphi(x_i; z) \Leftrightarrow i \in I \text{ for all } i < n.$$

is finitely consistent we need to prove that $\psi_{I \upharpoonright n}(a_0, \dots, a_{n-1})$ is true. If there is a b such that the truth value of $\langle \varphi(a_i; b) : i < \omega \rangle$ oscillates at least n times, then we can find $k_0 < \dots < k_{n-1}$ such that

$$\varphi(a_{k_i}; b) \Leftrightarrow i \in I.$$

This proves that $\psi_{I \upharpoonright n}(a_{k_0}, \dots, a_{k_{n-1}})$ is true. By indiscernibility, also $\psi_{I \upharpoonright n}(a_0, \dots, a_{n-1})$ holds true.

$2 \Rightarrow 1$ Let $I \subseteq \omega$ be the set of even integers. Assume $\neg 1$ and let $\langle c_i : i < \omega \rangle$ be an infinite sequence that is shattered by $\varphi(x; z)$. Let $\langle a_i : i < \omega \rangle$ be an indiscernible sequence with the same EM-type as $\langle c_i : i < \omega \rangle$. Then $\langle a_i : i < \omega \rangle$ satisfies $\psi_{I \upharpoonright n}(x_0, \dots, x_{n-1})$ for all n . By compactness there is a b such that

$$\varphi(a_i; z) \Leftrightarrow i \text{ is even.}$$

This proves $\neg 2$. □

In the next section we need the following corollary.

17.18 Corollary *If $\mathcal{C} \subseteq \mathcal{U}^{[x]}$ is a set approximable by a formula with finite VC-dimension, then $\langle a_i \in \mathcal{C} : i < \omega \rangle$ converges for any indiscernible sequence $\langle a_i : i < \omega \rangle$.* □

4 Honest definitions

In this section we present a beautiful theorem of Chernikov and Simon [1] and their alternative proof of a famous quantifier elimination result of Shelah.

We write \neg^n for $\neg \neg$. We abbreviate $\neg^n(\cdot \in \cdot)$ as \notin^n .

17.19 Lemma *Let \mathcal{C} be a set approximable by a formula with finite VC-dimension and let A be any (small) set of parameters. Then every global A -invariant type $p(x)$ contains a formula $\psi(x)$ such that either $\psi(x) \rightarrow x \in \mathcal{C}$ or $\psi(x) \rightarrow x \notin \mathcal{C}$. Moreover, for every sufficiently saturated model M containing A , we can require that $\psi(x) \in L(M)$*

Proof The property we want to prove is elementary in $L(\mathcal{C})$ therefore, by Remark 16.2 we can assume that \mathcal{C} is saturated. By Corollary 17.18, there is no infinite sequence $\langle a_i : i < \omega \rangle$

$$a_i \models p_{A, a \upharpoonright i}(x) \cup \{x \notin^i \mathcal{C}\}$$

Let n be the largest integer such that $\langle a_i : i < n \rangle$ satisfies the condition above. Then

$$p_{A, a \upharpoonright n}(x) \rightarrow x \notin^n \mathcal{C}$$

and the first claim of the lemma follows by compactness.

Now let M be a model that contains A and such that $\langle M, \mathcal{C} \rangle \preceq \langle \mathcal{U}, \mathcal{C} \rangle$. Assume also that $\langle M, \mathcal{C} \rangle$ is saturated, we can further require that all $a_i \in M^{[x]}$. Hence $\psi(x) \in L(M)$. □

17.20 Theorem Let \mathcal{C} be a set approximable by a formula with finite VC-dimension. Then \mathcal{C} is approximable from above and from below.

Proof Let $A \subseteq \mathcal{C}$ be any non empty (small) set. As above, by Remark 16.2 we can assume that \mathcal{C} is saturated. Let M be a saturated elementary substructure of \mathcal{U} , in the language $L(\mathcal{C})$. Define

$$q(x) = \{\varphi(x) \in L(M) : A \subseteq \varphi(\mathcal{U})\}.$$

By compactness, it suffices to prove that $q(x) \rightarrow x \in \mathcal{C}$. Suppose not and fix some $a \models q(x) \wedge x \notin \mathcal{C}$. Let $p(x) = \text{tp}(a/M)$. As $p(x)$ is finitely satisfied in A and M is saturated, from Lemma 17.19 yields a formula $\psi(x) \in p(x)$ such that either $\psi(x) \rightarrow x \in \mathcal{C}$ or $\psi(x) \rightarrow x \notin \mathcal{C}$. But the first contradicts $a \models \psi(x)$ and the second cannot hold because $\psi(x)$ is satisfied in $A \subseteq \mathcal{C}$. \square

When all formulas have finite VC-dimension, we say that the theory T has the **non-independence property** or, for short, that T **is nip**.

Let $\langle \mathcal{D}_i : i < \lambda \rangle$ be the collection of all subsets of \mathcal{U} , of arbitrary finite arity, that are externally definable. The expansion of \mathcal{U} to the language $L(\mathcal{X}_i : i < \lambda)$ is called the **Shelah expansion** of \mathcal{U} and is denoted by \mathcal{U}^{Sh} .

From Theorem 17.20 and Proposition 17.7 we obtain the following.

17.21 Corollary If T is nip then \mathcal{U}^{Sh} has L -elimination of quantifiers. (I.e. every formula is Boolean combination of formulas in L and formulas of the form $z \in \mathcal{D}_i$.) \square

5 Stable theories

We say that T is a **stable theory** if every formula is stable. By Theorem 17.9 and 17.14 this is equivalent to requiring that all externally definable sets are definable.

If $p(x) \in S(\mathcal{U})$ is a global type, a **canonical base** of $p(x)$ is a definably closed set $\text{Cb}(p) \subseteq \mathcal{U}^{\text{eq}}$ such that an automorphism $f \in \text{Aut}(\mathcal{U})$ fixes $p(x)$ if and only if it fixes $\text{Cb}(p)$ pointwise. When they exist, canonical bases are unique, see Exercise 17.28.

Clearly, all definable types (Definition 17.3) have a canonical base, namely

$$\text{Cb}(p) = \text{dcl}^{\text{eq}}\left(\{\mathcal{D}_{p,\varphi} : \varphi(x;z) \in L\}\right).$$

Therefore if T is stable, all global types have a canonical base.

We now turn to Lascar invariance. Quite interestingly when T is stable this reduces to a more manageable kind of invariance.

17.22 Proposition Let T be stable and let $p(x) \in S(\mathcal{U})$. Then the following are equivalent

1. $p(x)$ is Lascar invariant over A ;
2. $p(x)$ is definable over $\text{acl}^{\text{eq}} A$;
3. $\mathcal{D}_{p,\varphi} \in \text{acl}^{\text{eq}} A$ for all $\varphi(x;z) \in L$.

Proof $3 \Rightarrow 2 \Rightarrow 1$ are clear (stability is not required).

$1 \Rightarrow 3$ The sets $\mathcal{D}_{p,\varphi}$ are externally definable therefore, by Theorem 17.9, definable

(over \mathcal{U}). As $p(x)$ is Lascar invariant over A , so are the sets $\mathcal{D}_{p,\varphi}$. Hence they belong to $\text{acl}^{\text{eq}}A$ by Theorem 13.10. \square

A type $q(x) \subseteq L(A)$ is **stationary** if it has a unique global extension that is Lascar invariant over A . The following proposition says that in a stable theory with elimination of imaginaries types over algebraically closed sets are stationary.

17.23 Proposition *If T is stable then every type $q(x) \in S(\text{acl}^{\text{eq}}A)$ is stationary.*

Proof Let $p_i(x) \in S(\mathcal{U}^{\text{eq}})$, for $i = 1, 2$, be two global types that extend $q(x)$ and are invariant over $\text{acl}^{\text{eq}}A$. To prove that $p_1(x) = p_2(x)$, it suffices to show that for every formula $\varphi(x; z) \in L$

$$\# \quad \mathcal{D}_{p_1, \varphi} = \mathcal{D}_{p_2, \varphi}$$

Note that, by Proposition 17.22 both sets belong to $\text{acl}^{\text{eq}}A$. Clearly, for $i = 1, 2$, the formula $\forall z [\varphi(x; z) \leftrightarrow z \in \mathcal{D}_{p_i, \varphi}]$ belongs to $p_i(x)$. Then both formulas belong to $q(x)$ and $\#$ follows. \square

17.24 Corollary *If T is stable then the following are equivalent*

1. $a \stackrel{L}{\equiv}_A b$, see Definition 16.10;
2. $a \stackrel{\text{Sh}}{\equiv}_A b$, see Definition 13.12.

Proof $1 \Rightarrow 2$. This is left as an exercise to the reader (stability is not required).

$2 \Rightarrow 1$. Assume $a \stackrel{\text{Sh}}{\equiv}_A b$. By Proposition 13.13 this is equivalent to $a \equiv_{\text{acl}^{\text{eq}}A} b$. Let $q(x) = \text{tp}(a/\text{acl}^{\text{eq}}A) = \text{tp}(b/\text{acl}^{\text{eq}}A)$. Let $p(x) \in S(\mathcal{U}^{\text{eq}})$ be the unique global type that is invariant over $\text{acl}^{\text{eq}}A$ and extends $q(x)$ which we obtain from by Proposition 17.23. Let $\bar{c} = \langle c_i : i < \omega \rangle$ be such that $c_i \models p \upharpoonright \text{acl}^{\text{eq}}(A), a, b, c_{\upharpoonright i}$. Then a, \bar{c} and b, \bar{c} are A -indiscernible sequences, which proves 1, see Exercise 16.13. \square

We end this section with a characterization of stability which is not directly related with the properties discussed above.

17.25 Proposition *The following are equivalent*

1. T is stable;
2. every A -indiscernible sequence is totally A -indiscernible.

Proof $2 \Rightarrow 1$. Assume $\neg 1$ and let $\varphi(x; z)$ be an unstable formula witnessed by the ladder sequence $\langle a_i; b_i : i < \omega \rangle$. Let $\langle a'_i; b'_i : i < \omega \rangle$ be indiscernible sequence with the same Ehrenfeucht-Mostowski type as $\langle a_i; b_i : i < \omega \rangle$. This is not totally indiscernible because $\varphi(a'_i; b'_j)$ if and if $i < j$.

$1 \Rightarrow 2$. Assume $\neg 2$ and let $\langle a_i : i < \omega \rangle$ be an A -indiscernible sequence, which is not totally A -indiscernible. Then there is a formula $\varphi(x, y) \in L(A)$ and some $i < j$ such that $\varphi(a_i, a_j) \wedge \neg \varphi(a_j, a_i)$. By indiscernibility $\varphi(a_i, a_j)$ holds if and only if $i \leq j$. Hence $\varphi(x; y)$ is not stable. \square

17.26 Exercise Prove that if every formula $\varphi(x; z) \in L$ with $|x| = 1$ is stable then T is stable. Hint: by compactness, if all sets approximable by $\varphi(x; y, z)$ are definable, so are the sets approximable by $\varphi(x, y; z)$. \square

17.27 Exercise Prove that strongly minimal theories are stable. \square

17.28 Exercise Let $p(x) \in S(\mathcal{U})$. Prove that there is at most one definably closed set $A \subseteq \mathcal{U}^{\text{eq}}$ such that $\text{Aut}(\mathcal{U}/A)$ is the set of automorphisms that fix $p(x)$. \square

6 Stability and the number of types

The following proposition highlights the connection between stability and the cardinality of types.

Binary trees of formulas have been introduced in Definition 12.18. Here we restrict to trees $\langle \psi_s : s \in 2^{<\lambda} \rangle$ of a particular form. Namely, $\psi_\emptyset = \top$ and for every $s \in 2^{<\lambda}$ we have $\psi_{s1} = \varphi(x; b_s)$ and $\psi_{s0} = \neg\varphi(x; b_s)$. When such a binary tree of height ω exists, we say that $\varphi(x; z)$ has the **binary tree property**.

17.29 Proposition *The following are equivalent*

1. $\varphi(x; z)$ is a stable formula;
2. $|S_\varphi(A)| = |A|$ for all infinite sets A ;
3. $|S_\varphi(A)| < 2^{|A|}$ for all infinite sets A ;
4. $\varphi(x; z)$ does not have the binary tree property.

Proof $2 \Leftrightarrow 3 \Leftrightarrow 4$. This is proved as in Lemma 12.19.

$3 \Rightarrow 1$. Assume $\neg 1$. Let $I, <_I$ be a dense linear order of cardinality $|A|$. Let x_i and z_i , for $i \in I$, be a tuples of variables. The type that says that

$$i < j \Leftrightarrow \varphi(x_i; z_j) \quad \text{for all } i, j \in I$$

is finitely consistent by $\neg 1$. If a_i, b_i is a realization of this type, then for every $<_I$ -upward closed set $C \subseteq I$ the type

$$\{\varphi(x; b_j) : j \in C\} \cup \{\neg\varphi(x; b_j) : j \notin C\}$$

is a finitely consistent. Any two such types are mutually inconsistent. As there are $2^{|A|}$ Dedekind's cuts in I , $\neg 3$ follows.

$1 \Rightarrow 4$ Assume $\varphi(x; z)$ has the binary tree property witnessed, say, by $\langle b_s : s \in 2^{<\omega} \rangle$. We show that there is a ladder sequence of length n . For $i = 0, \dots, n$ abbreviate b_{1^i} by b_i . Let a_j be such that

$$a_j \models \neg\varphi(x; b_j) \wedge \bigwedge_{i=0}^{j-1} \varphi(x; b_i).$$

Then

$$i < j \Leftrightarrow \varphi(a_i; b_j),$$

so $\langle a_i; b_i : i < n \rangle$ is a ladder sequence of length n . \square

17.30 Theorem *The following are equivalent*

1. T is stable;
2. $|S(A)| \leq |A|$ some infinite cardinal λ , and all sets A of cardinality $\leq \lambda$.
3. $|S(A)| \leq |A|$ for every set A such that $|L| < \text{cf}(A)$.

Proof $2 \Rightarrow 1$. Suppose a formula $\varphi(x; z)$ is unstable. Let $\langle z_s : s \in 2^{<\lambda} \rangle$ be a sequence variables of length $|z|$. Let $p(z_s : s \in 2^{<\lambda})$ be the type that says that $\langle z_s : i < 2^{<\lambda} \rangle$ witnesses a binary tree of height λ . As $\varphi(x; z)$ is unstable, p is finitely consistent. As λ is an arbitrary infinite cardinal, this contradicts 2.

$3 \Rightarrow 2$. Trivial.

$1 \Rightarrow 3$. Proposition 17.29 implies that $|S(A)| \leq |A|^{|L|}$. Therefore, when $|L| < \text{cf}(A)$, we obtain $|S(A)| \leq |A|$. \square

17.31 Exercise Prove that $\varphi(x; z)$ is stable if and only if $|S_\varphi(\mathcal{U})| \leq 2^\kappa$. \square

17.32 Exercise Prove that $\varphi(x; z)$ is stable if and only if every set approximated by $\varphi(x; z)$ is definable. \square

7 Notes and references

- [1] Artem Chernikov and Pierre Simon, *Externally definable sets and dependent pairs*, Israel J. Math. **194** (2013), no. 1, 409–425, [arXiv:1007.4468](https://arxiv.org/abs/1007.4468).
- [2] Katrin Tent and Martin Ziegler, *A course in model theory*, Lecture Notes in Logic, vol. 40, Association for Symbolic Logic, Cambridge University Press, 2012.

Chapter 18

Keisler measures

1 T.b.c.