1. Preliminaries on pseudofiniteness

1.1. Ultralimits

Let \((X, d)\) be a metric space, and let \(\mathcal{U}\) be a non-principal ultrafilter on \(\mathbb{N}\).

**Definition 1.1.** Let \((x_n)_{n \in \mathbb{N}}\) be a sequence of points in \(X\). The point \(x \in X\) is called the ultralimit of \(x_n\) (relatively to \(\mathcal{U}\)), denoted \(\lim_{\mathcal{U}} x_n\), if for every \(\varepsilon > 0\) we have \(\{n \in \mathbb{N} : d(x_n, x) \leq \varepsilon\} \in \mathcal{U}\).

**Remark 1.2.**

1. If an ultralimit of a sequence of points exists, then it is unique.
2. If \(x = \lim_{n \to \infty} x_n\) in the usual sense of metric limits, then \(x = \lim_{\mathcal{U}} x_n\) (uses that \(\mathcal{U}\) is non-principal).
Fact 1.3. If \((X,d)\) is compact and \(\mathcal{U}\) is a non-principal ultrafilter on \(\mathbb{N}\), then any sequence of points in \(X\) has an ultralimit relatively to \(\mathcal{U}\).

Proof. Let \((x_i : i \in \mathbb{N})\) be a sequence in \(X\) without an ultralimit, then for each \(x \in X\) there is some open set \(U_x \ni x\) such that \(\{i \in \mathbb{N} : x_i \in U_x\} \notin \mathcal{U}\). By compactness, there is a finite sub-covering \(U_1, \ldots, U_n\) of \(X\). But the \(\{i : x_i \notin U_j\} \in \mathcal{U}\) for each \(1 \leq j \leq n\), hence \(\emptyset = \bigcap_{j=1}^n \{i : x_i \notin U_j\} \in \mathcal{U}\), a contradiction. \(\square\)

Corollary 1.4. Any bounded sequence \((x_n : n \in \mathbb{N})\) of real numbers has a well-defined ultralimit in \(\mathbb{R}\) relatively to any non-principal ultrafilter on \(\mathcal{U}\) (as closed intervals are compact).

Of course, this limit depends on the ultrafilter. For example, let \(x_n = 0\) if \(n\) is even and \(x_n = 1\) if \(n\) is odd. Then \(\lim_{\mathcal{U}} x_n = 0\) for any ultrafilter \(\mathcal{U}\) on \(\mathbb{N}\) containing the set of even numbers, and \(\lim_{\mathcal{U}} x_n = 1\) for any ultrafilter on \(\mathbb{N}\) containing the set of odd numbers.

Exercise 1.5. Let \((X,d)\) and \((Y,d')\) be metric spaces, and assume that \(f : X \to Y\) is continuous. Then for any sequence \((a_i)_{i \in \mathbb{N}}\) from \(X\) and any non-principal ultrafilter \(\mathcal{U}\) on \(\mathbb{N}\), we have
\[
\lim_{\mathcal{U}} a_i = a \implies \lim_{\mathcal{U}} f(a_i) = f(a).
\]

1.2. Ultraproducts. For details, see e.g. \[3\].

Let \(\mathcal{L}\) be a language and \(I\) an infinite set. Suppose that \(\mathcal{M}_i\) is an \(\mathcal{L}\)-structure for each \(i \in I\). Let \(\mathcal{U}\) be an ultrafilter on \(I\). Then we have:

Fact 1.6. (Łoś theorem) Let \(\varphi(x_1, \ldots, x_n)\) be an \(\mathcal{L}\)-formula, and let \(\mathcal{M} = \prod_{i \in I} \mathcal{M}_i / \mathcal{U}\) be the ultraproduct of the \(\mathcal{M}_i\) modulo \(\mathcal{U}\). Then for any \([a_1], \ldots, [a_n] \in \mathcal{M}\),
\[
\mathcal{M} \models \varphi([a_1], \ldots, [a_n]) \iff \{i \in I : \mathcal{M}_i \models \varphi(a_1(i), \ldots, a_n(i))\} \in \mathcal{U},
\]
where \([a]\) denotes the class of an element \(a = (a(i) : i \in I) \in \prod_{i \in I} \mathcal{M}_i\) modulo the equivalence relation of equality \(\mathcal{U}\)-almost everywhere.

Corollary 1.7. For each set of sentences \(T\) in \(\mathcal{L}\), every ultraproduct of models of \(T\) is a model of \(T\).

Definition 1.8. Let \(\kappa\) be a cardinal. A structure \(\mathcal{M}\) is \(\kappa\)-saturated if every partial type over a set of parameters of size \(< \kappa\) in \(\mathcal{M}\) is realized in \(\mathcal{M}\).

Fact 1.9. Let \(\mathcal{L}\) be a countable language, \((\mathcal{M}_i : i \in \mathbb{N})\) a sequence of \(\mathcal{L}\)-structures and \(\mathcal{U}\) a non-principal ultrafilter on \(\mathbb{N}\). Then the ultraproduct \(\mathcal{M} = \prod_{i \in \mathbb{N}} \mathcal{M}_i / \mathcal{U}\) is \(\aleph_1\)-saturated (i.e. every partial type over a countable set of parameters is realized in \(\mathcal{M}\)).

Note that every infinite \(\kappa\)-saturated structure \(\mathcal{M}\) has size at least \(\kappa\) (if \(|\mathcal{M}| < \kappa\), then \(\{x \neq a : a \in \mathcal{M}\}\) is a partial type over a set of size \(< \kappa\) which cannot be realized in \(\mathcal{M}\)). If follows from Proposition 1.9 that any ultraproduct relatively to a non-principal ultrafilter in \(\mathbb{N}\) is either finite or of size at least \(\aleph_1\). In fact, more is true.

Fact 1.10. \[3\] Let \(I\) be an arbitrary set and \(\{\mathcal{M}_i : i \in I\}\) all finite. The for any ultrafilter \(\mathcal{U}\) on \(I\), the ultraproduct \(\prod_{i \in I} \mathcal{M}_i / \mathcal{U}\) is either finite or of cardinality \(\geq 2^{\aleph_0}\).
Corollary 1.11. Let \( U \) be a non-principal ultrafilter on \( \mathbb{N} \), and assume that \( M_i, i \in \mathbb{N} \) is a countable \( L \)-structure. Then any ultraproduct \( M = \prod_{i \in \mathbb{N}} M_i/U \) is either finite or of size \( 2^{\aleph_0} \).

Proof. Obviously \( |\prod_{i \in \mathbb{N}} M_i/U| \leq |\prod_{i \in \mathbb{N}} M_i| \leq |\mathbb{N}| = 2^{\aleph_0} \), and \( |M| \geq 2^{\aleph_0} \) by Fact 1.10. \( \square \)

1.3. Pseudofiniteness (of structures, theories, subsets).

Definition 1.12. An \( L \)-structure \( M \) is pseudofinite if for every \( L \)-sentence \( \varphi \), \( M \models \varphi \) implies that there is a finite \( M_0 \) such that \( M_0 \models \varphi \). \( M \) is strictly pseudofinite if \( M \) is pseudofinite and not finite.

Proposition 1.13. Let \( L \) be a language and \( M \) an \( L \)-structure. Then the following are equivalent:

1. \( M \) is pseudofinite.
2. \( M \) is elementarily equivalent to an ultraproduct of finite \( L \)-structures.
3. \( M \models \text{Fin}_L \), where \( \text{Fin}_L := \{ \varphi \in L : \exists M \text{ a finite } L \text{-structure with } M \models \varphi \} \).

Proof. (1) \( \Rightarrow \) (2). Suppose \( M \) is pseudofinite. Let \( I \) be the collection of all finite subsets of \( \text{Th}(M) \). Given \( i = \{ \varphi_1, \ldots, \varphi_n \} \in I \), there exists some finite \( M_i \models \bigwedge_{1 \leq i \leq n} \varphi_i \). For each \( i \in I \), let \( A_i := \{ j \in I : M_j \models \varphi \text{ for all } \varphi \in i \} \), and let \( U_0 := \{ A_i : i \in I \} \). Then \( U_0 \) has the finite intersection property:

\[
A_i \cap A_{i'} = \{ j \in I : M_j \models \varphi \text{ for all } \varphi \in i \} \cap \{ j \in I : M_j \models \varphi \text{ for all } \varphi \in i' \} = \{ j \in I : M_j \models \varphi \text{ for all } \varphi \in i \cup i' \} = A_{i \cup i'} \neq \emptyset,
\]

hence \( U_0 \) can be extended to an ultrafilter \( U \) on \( I \). Then \( M \equiv \prod_{i \in I} M_i/U \). Indeed, if \( M \models \varphi \), then \( \{ i \in I : M_i \models \varphi \} \supseteq A(\varphi) \in U \), hence by Łoś' theorem \( \prod_{i \in U} M_i/U \models \varphi \).

(2) \( \Rightarrow \) (3). Assume \( M \equiv \prod_{i \in I} M_i/U \), where \( \{ M_i : i \in I \} \) are all finite and \( U \) is an ultrafilter on \( I \). Then for every \( \varphi \in \text{Fin}_L \) and \( i \in I \) we have \( M_i \models \varphi \), hence \( \prod_{i \in I} M_i/U \models \varphi \), so \( M \models \varphi \). Hence \( M \models \text{Fin}_L \).

(3) \( \Rightarrow \) (1). Let \( \varphi \in L \) be such that \( M \models \varphi \). If \( \varphi \) has no finite models, then \( M_0 \models \neg \varphi \) for every finite \( L \)-structure \( M_0 \), so \( \neg \varphi \in \text{Fin}_L \), hence \( M \models \neg \varphi \) — a contradiction. \( \square \)

Remark 1.14. In particular, pseudofiniteness is a property of \( \text{Th}(M) \).

Note that not every pseudofinite structure is isomorphic to an ultraproduct of finite structures. For example, if \( L \) is countable and \( M \) is a pseudofinite \( L \)-structure (see Section 1.4 many examples), we can find a countable \( M' \preceq M \), hence \( M' \) is countable and pseudofinite. But any infinite ultraproduct of finite sets has cardinality at least continuum by Fact 1.10.

However, recall:

Fact 1.15. [Keisler-Shelah] \( M \equiv N \iff \text{there exists an ultrafilter } U \text{ on some set } I \text{ such that } M^U = \prod_{i \in I} M_i/U \cong \prod_{i \in I} N_i/U = N^U \).

Hence

Corollary 1.16. A structure \( M \) is pseudofinite if and only if it has an ultrapower isomorphic to an ultraproduct of finite structures.

This follows from Proposition 1.13, Fact 1.15, and the following exercise.
Exercise 1.17. (1) Let $\mathcal{U}$ be an ultrafilter on $I$, and for every $i \in I$ let $\mathcal{V}_i$ be an ultrafilter on $J_i$, and let $K := \{(i,j) : i \in I, j \in J_i\}$. Let $\mathcal{W}$ be the collection of subsets of $K$ of the form

$$A \in \mathcal{W} \iff \{i \in I : \{j \in J_i : (i,j) \in A\} \in \mathcal{V}_i\} \in \mathcal{U}.$$ 

Then $\mathcal{W}$ is an ultrafilter on $K$.  
(2) Every ultraproduct of ultraproducts of finite structures is isomorphic to an ultraproduct of finite structures.

Exercise 1.18. Let $\mathcal{M}$ be a pseudofinite $\mathcal{L}$-structure. 
(1) Let $\mathcal{M}$ be pseudofinite, and assume that $\mathcal{N}$ is interpretable in $\mathcal{M}$ (using formulas with parameters). Then $\mathcal{N}$ is also pseudofinite.  
(2) In particular: any reduct of $\mathcal{M}$ to a sublanguage of $\mathcal{L}$, any expansion of $\mathcal{M}$ by constants and by definable relations, and $\mathcal{M}^{eq}$, are pseudofinite.

Definition 1.19. Let $T$ be a consistent (but possibly incomplete) theory in a language $\mathcal{L}$. 
(1) $T$ is weakly pseudofinite if whenever $T \models \varphi$, then $\varphi$ is true in some finite $\mathcal{L}$-structure (not necessarily a model of $T$).  
(2) $T$ is strongly pseudofinite if whenever $T \cup \{\varphi\}$ is consistent, then there exist some finite $M_0 \models \varphi$.

Example 1.20. The empty $\mathcal{L}$-theory is weakly pseudofinite, but not strongly pseudofinite.

Exercise 1.21. Let $T$ be an $\mathcal{L}$-theory. 
(1) $T$ is weakly pseudofinite if and only if $T$ has some pseudofinite model.  
(2) $T$ is strongly pseudofinite if and only if $T \models \text{Fin}_\mathcal{L}$, if and only if every model of $T$ is pseudofinite.  
(3) If $T$ is complete, then $T$ is weakly pseudofinite if and only if $T$ is strongly pseudofinite.

Definition 1.22. A complete theory $T$ is pseudofinite if it is weakly (equivalently, strongly) pseudofinite.

Definition 1.23. Let $\mathcal{M}$ be an $\mathcal{L}$-structure, and $A$ a subset of $M^n$. We say that a set $A$ is pseudofinite in $\mathcal{M}$ if whenever $\varphi$ is a sentence in the language $\mathcal{L}_P = \mathcal{L} \cup \{P\}$ with an additional predicate symbol $P$ naming $A$ and $(\mathcal{M}, A) \models \varphi$, then there is an $\mathcal{L}$-structure $\mathcal{M}'$ and a finite subset $A'$ of $(\mathcal{M}')^n$ such that $(\mathcal{M}', A') \models \varphi$.

Remark 1.24. 
(1) Pseudofiniteness of $A$ in $\mathcal{M}$ is a property of $\text{Th}_{\mathcal{L}_P}(\mathcal{M}, A)$.  
(2) Suppose that $A \subseteq M^n$ is definable by some $\mathcal{L}$-formula $\varphi(x,b)$. The “$A$ is pseudofinite in $\mathcal{M}$” is equivalent to: for every $\mathcal{L}$-formula $\psi(y) \in \text{tp}_\mathcal{M}(b)$, there is an $\mathcal{L}$-structure $\mathcal{M}'$ and $b' \in \mathcal{M}'$ such that $\mathcal{M} \models \psi(b')$ and $\varphi(M,b')$ is finite.  
(3) So if $A$ is definable by an $\mathcal{L}$-formula $\varphi(x)$ without parameters, then $A$ is pseudofinite in $\mathcal{M}$ if and only if for every $\psi \in \text{Th}_\mathcal{L}(\mathcal{M})$ there exists some $\mathcal{L}$-structure $\mathcal{M}'$ such that $\mathcal{M} \models \psi$ and $\varphi(M')$ is finite.  
Similarly to Proposition 1.13 we have:

Proposition 1.25. Let $\mathcal{M}$ be an $\mathcal{L}$-structure and $A$ a subset of $M^n$. The following are equivalent.
(1) $A$ is pseudofinite in $M$.

(2) $(M, A)$ is elementarily equivalent to some ultraproduct of $L_P$-structures of the form $(M', A')$ with $A'$ finite.

(3) $(M, A) \models \text{Fin}_{L_P}$, where $\text{Fin}_{L_P}$ is the set of all $L_P$-sentences which are true in every $L_P$-structure $(M', A')$ with $A'$ finite.

Exercise 1.26. Assume that $A, B \subseteq M^n$ are pseudofinite in $M$. Is $A \cup B$ pseudofinite in $M$?

Exercise 1.27. Let $A \subseteq M^n$ be pseudofinite in $M$ and let $f$ be a definable function (possibly with parameters in $M$) such that $f(A) \subseteq A$. Then $f$ is injective if and only if it is surjective.

1.4. Some examples of pseudofinite theories.

(1) For any language $L$, the common theory of all $L$-structures is weakly pseudofinite.

(2) Let $L$ be a language and $T$ an $L$-theory. Let $T_{\text{Fin}}$ be the common theory of all finite models of $T$. Then $T_{\text{Fin}}$ is strongly pseudofinite. (Exercise: $T_{\text{Fin}}$ may not be the weakest strongly pseudofinite theory extending $T$).

(3) The theory DLO is not pseudofinite (the sentence given by the conjunction of the axioms of linear order and $\forall x \forall y (x < y \rightarrow \exists z (x < z < y))$ has no finite models).

Let $U$ be a non-principal ultrafilter on $\mathbb{N}$. Let $M_i = (\{0, 1, \ldots, i-1\}, <)$ be a finite linear order on $i$ elements. Let $M := \prod_{i \in \mathbb{N}} M_i/U$, and let $T := \text{Th}(M)$. For any $i \in \mathbb{N}$, $M_i$ has the first and the last elements, and is a discrete linear order (i.e. every element has immediate successor and predecessor) of size $\geq i$. Each of these properties can be expressed by a first-order sentence. Hence, by Łoś theorem, $M$ is an infinite discrete linear order with endpoints, and these properties axiomatize a complete first-order theory (which is then the unique complete pseudofinite theory of linear orders). In fact, $M \cong \mathbb{N} + \sum_{j \in L} \mathbb{Z} + \mathbb{N}^\ast$, where $L$ is a dense (by $\aleph_1$-saturation) linear order without endpoints of cardinality continuum and $\mathbb{N}^\ast$.

(4) The abelian group $(\mathbb{Z}, +)$ is not pseudofinite.

By Exercise 1.27, as the definable map $x \mapsto x + x$ is injective, but not surjective.

(5) Let ACF be the theory of algebraically closed fields (in the language of rings). It is not weakly pseudofinite.

Let $K \models \text{ACF}$. Assume $\text{char}(K) \neq 2$, then the definable map $x \mapsto x^2$ is surjective by algebraic closedness, but not injective (as $1 \neq -1 \mapsto 1$). If $\text{char}(K) \neq 3$, then the definable map $x \mapsto x^3$ has the same property. Let $\varphi$ be the sentence expressing “$K$ is a field, and either the square map or the cube map is surjective, but not injective”. Then $\text{ACF} \models \varphi$, but $\varphi$ has no finite model.

(6) However, we have:

**Proposition 1.28.** Any field has an infinite pseudofinite field extension.

**Proof.** The algebraic closure of a finite field is the directed union of its finite subfields, hence it embeds into an ultraproduct of its finite subfields
(namely, $\mathbb{F}_{alg} = \bigcup_{n \in \omega} \mathbb{F}_p^n$ embeds into $\prod_{n \in \omega} \mathbb{F}_p^n / \mathcal{U}$ for any $\mathcal{U}$ an ultrafilter on $\omega$ containing the filter $\mathcal{F} = \{ S_m : m \in \omega \}$, where $S_m = \{ km : k \in \omega \}$, via the map $f(a) = (b_n)_{n \in \omega} \in \prod_{n \in \omega} \mathbb{F}_p^n$ for all $a \in \mathbb{F}_{alg}$ with $b_n := a$ if $a \in \mathbb{F}_{alg}^n$ and $b_n := 0$ otherwise), and such an ultraproduct is a pseudofinite field. Hence the claim holds for algebraically closed fields of positive characteristic, so for all algebraically closed fields (since $\prod_{p \text{ prime}} \mathbb{F}_p / \mathcal{U} \models \text{ACF}_0$ for any $\mathcal{U}$ a non-principal ultrafilter on the set of prime numbers), and thus for all fields. □

(7) Any vector space over any field $K$ is pseudofinite (viewed as a structure in the language $L_K = \{ +, 0, (r(x))_{r \in K} \}$ of vector spaces).

Take an infinite pseudofinite field extending $K$. Viewing it as a vector space over $K$ (which is a reduct), it remains pseudofinite by Exercise 1.18. Since the $L_K$-theory of infinite vector spaces over $K$ is complete (e.g., by $\kappa$-categoricity for any $\kappa > |K|$), every vector space over $K$ is pseudofinite.

(8) What about vector spaces over division rings?

Classical Wedderburn’s theorem: every finite division ring is a field. Hence every pseudofinite division ring is a field. However if a $K$-vector space $V$ is pseudofinite, it doesn’t imply that $K$ is a pseudofinite ring (since $K$ is not interpretable in $V$ in general, but rather is coded in the language $L_K$).

Fact 1.29. [23]

(a) Suppose $K$ is a division ring that is finite dimensional as a vector space over its center. Then any vector space over $K$ is pseudofinite.

(b) There exist division ring $K$ and a $K$-vector space which is not pseudofinite.

(9) Rado’s random graph is pseudofinite.

Recall that this is a theory in the language $L = \{ E(x,y) \}$ with a single binary relation axiomatized by:

(a) $\forall x \neg E(x,y)$,

(b) $\forall x \forall y E(x,y) \rightarrow E(y,x)$,

(c) For each $n$, the $n^{th}$ extension axiom

$$\varphi_n := \forall x_1 \ldots \forall x_{2^n} \left( \bigwedge_{1 \leq i \neq j \leq 2^n} x_i \neq y_j \right) \rightarrow \exists z \left( \bigwedge_{1 \leq i \leq n} E(z,x_i) \land \bigwedge_{n < i \leq 2^n} \neg E(z,x_i) \right).$$

By an easy back-and-forth, this is a complete theory. A simple probabilistic argument shows: for each $n$, $P(G_m \models \varphi_n) \rightarrow 1$ as $m \rightarrow \infty$, where $G_m$ is a graph on $m$ vertices picked uniformly at random (see e.g. [19] for the details)

(10) There is a unique complete pseudofinite theory of Boolean algebras (in the language $L = \{ \cup, \cap, \neg, 0, 1 \}$). It is axiomatized by a single sentence saying that the Boolean algebra is atomic (i.e. that there is an atom under any element), plus the infinity axiom schema [20].

(11) The following is a deep result in geometric model theory, we will touch on some of the ingredients in this course.

Fact 1.30. [24] [2] Let $T$ be a totally categorical theory (i.e. $\kappa$-categorical for all $\kappa \geq \aleph_0$) in a countable language. Then $T$ is pseudofinite.
In fact, a weaker assumption “$\aleph_0$-stable, $\aleph_0$-categorical” is sufficient. Note also that this fact implies that such a $T$ is not finitely axiomatizable. They proved additionally that such $T$ is quasi-finitely axiomatizable, i.e., it is axiomatized by a single sentence plus an axiom schema expressing that the structure is infinite.

**Exercise 1.31.** (1) Show that every groups embeds into an ultraproduct of its finitely generated subgroups. Hence every locally finite group embeds into a pseudofinite group.

(2) Show that the groups of all permutations of a countably infinite set does not embed into any pseudofinite group.

1.5. **Faux finite theories.** We also consider the following strengthening of an infinite structure being “finite-like”.

**Definition 1.32.** (1) Let $\mathcal{L}$ be a language and let $\mathcal{F}$ be an infinite family of finite $\mathcal{L}$-structures closed under isomorphism. We let $\lim \mathcal{F}$ be the set of all $\mathcal{L}$-sentences which are satisfied by all but finitely many structures in $\mathcal{F}$. We say that $\mathcal{F}$ is convergent if $\lim \mathcal{F}$ is a complete first-order theory. Equivalently, if the theory of a non-principal ultraproduct of structures in $\mathcal{F}$ does not depend on the choice of an ultrafilter.

(2) We say that a complete first-order theory $T$ in a language $\mathcal{L}$ is faux finite if there is an $\mathcal{L}$-sentence $\varphi$ such that the family $\mathcal{F}_\varphi$ of all finite models of $\varphi$ is convergent and $\lim \mathcal{F}_\varphi = T$. We say that an $\mathcal{L}$-structure $\mathcal{M}$ is faux finite if $\text{Th}(\mathcal{M})$ is faux finite.

**Remark 1.33.** (1) Every faux finite theory is obviously pseudofinite.

(2) Every pseudofinite quasi-finitely axiomatizable theory is faux finite (if $T$ is axiomatized by a sentence $\varphi$ and the axiom of infinity, then the family $\mathcal{F}_\varphi$ of all finite models of $\varphi$ is convergent).

**Exercise 1.34.** (1) Which of the pseudofinite theories discussed above are faux finite?

(2) Give an example of a faux-finite theory which is not quasi-finitely axiomatizable.

1.6. **References.** Calculating the saturation or cardinality of an ultraproduct with an arbitrary index set is a difficult problem, even when it is an ultraproduct of finite structures — see for example [22, 13, 14]. Various observations about weak/strong pseudofiniteness for incomplete theories are mostly from [21].

It is a well-known open problem of Cherlin whether the theory of the triangle-free generic countable graph is pseudofinite, see e.g. [4, 16].

Any countably categorial theory with disjoint $n$-amalgamation for all $n \geq 2$ is pseudofinite, and certain theories of parametrized equivalence relations are pseudofinite [15].

For a survey on pseudofinite groups see [18]. Exercise 1.31 is from Theorem 6.4 there.

2. **Pseudofinite dimensions**

2.1. **Nonstandard cardinality of pseudofinite sets.** We introduce an auxiliary construction which provides one possible way to rigorously manipulate the
non-standard cardinalities of pseudofinite sets. We fix a countable language \( \mathcal{L} \), a collection of \( \mathcal{L} \)-structures (\( \mathcal{M}_i : i \in I \)) and let \( \mathcal{U} \) be a non-principal ultrafilter on \( I \).

We enrich the language \( \mathcal{L} \) to a language \( \mathcal{L}^+ \) which contains:

\begin{itemize}
  \item all of the sorts from \( \mathcal{L} \) with the corresponding functions/relations/constants on them;
  \item one additional sort \( R \) with the language of ordered rings and a unary function symbol \( \log \) on it, plus an additional constant symbol \( \infty \);
  \item for each \( \mathcal{L} \)-formula \( \varphi(x,y) \), \( x, y \) tuples of variables, a function symbol \( f_\varphi \) from the sort corresponding to \( y \) to the new sort \( R \).
\end{itemize}

Now every \( \mathcal{L} \)-structure \( \mathcal{M} \) can be canonically expanded to an \( \mathcal{L}^+ \)-structure \( \mathcal{M}^+ \) as follows:

\begin{itemize}
  \item All the \( \mathcal{L} \) sorts are interpreted in the same way as in \( \mathcal{M} \);
  \item We interpret the sort \( R \) as \( (\mathbb{R}, +, \cdot , 0, 1, <, \log) \);
  \item for every \( b \in M_y \) we define \( f_\varphi(b) := |\varphi(M,b)| \) if the set \( \varphi(M,b) \) is finite, and \( f_\varphi := \infty \) otherwise.
\end{itemize}

Finally, we let \( \bar{\mathcal{M}} := \prod_{i \in I} \mathcal{M}_i^+/\mathcal{U} \). This is a structure with sorts corresponding to \( \mathcal{M} := \prod_{i \in I} \mathcal{M}_i/\mathcal{U} \) and \( \mathbb{R}^* := \mathbb{R}^\mathcal{U} \), the sort for the non-standard reals, and each \( \mathcal{L} \)-definable subset \( X = \varphi(M,b) \) in \( \mathcal{M} \) is equipped with its non-standard cardinality \( |X| := f_\varphi(b) \) (which is equal to the size of \( X \) if \( X \) is finite). Note that \( \mathbb{R} \) embeds into \( \mathbb{R}^* \) diagonally and \( \mathbb{R}^* \supseteq \mathbb{R} \). In particular, we are allowed to take sums, products and quotients of non-standard cardinalities, as well as compare them to each other, or to rational numbers, and all this operations and the non-standard \( \log \) satisfy the usual properties by Łoś theorem.

### 2.2. Convex subgroups of the non-standard reals.

**Definition 2.1.** A non-empty set \( S \subseteq \mathbb{R}^* \) is convex if whenever \( s_1, s_2 \in S \) and \( s_1 < r < s_2 \), then also \( r \in S \).

For any \( a < b \in \mathbb{R}^* \cup \{-\infty, +\infty\} \), the interval \( (a,b) := \{x \in \mathbb{R}^* : a < x < b\} \) is convex. For any \( r \in \mathbb{R}^* \), the monad of \( r \) is defined as

\[ \left\{ x \in \mathbb{R}^* : r - \frac{1}{n} < x < r + \frac{1}{n} \text{ for all } n \in \mathbb{N} \right\} \]

is convex (but not an interval).

**Example 2.2.** The following are convex subgroups of \( (\mathbb{R}^*, +) \).

1. The trivial subgroup \( C = \{0\} \).
2. The group of infinitesimals \( C_0 \), namely the monad of 0 in \( \mathbb{R}^* \). (Note: this is the only monad which is also a subgroup of \( (\mathbb{R}^*, +) \).
3. Note that the family of all convex subgroups is closed under intersection. Hence for any non-empty subset \( A \) of \( \mathbb{R}^* \), we let \( C(A) \) be the smallest convex subgroup of \( \mathbb{R}^* \) containing \( A \).

**Remark 2.3.** Note that if \( C \) is a convex proper subgroup of \( \mathbb{R}^* \), then the quotient \( \mathbb{R}^*/C \) is an abelian ordered group with the order given by \( x + C < y + C \) if and only if \( x < y \) in \( \mathbb{R}^* \).

**Proposition 2.4.** Let \( 0 < \alpha \in \mathbb{R}^* \) be arbitrary.

1. There exists the smallest subgroup \( C_\alpha \) of \( (\mathbb{R}^*, +) \) containing \( \alpha \).
(2) There exists a convex subgroup $C_{<\alpha}$ of $(\mathbb{R}^*, +)$ which is the largest convex subgroup of $\mathbb{R}^*$ not containing $\alpha$.

(3) There exists a unique isomorphism of ordered abelian groups (in fact, even ordered $\mathbb{R}$-vector spaces) $\varphi : C_{\alpha}/C_{<\alpha} \to \mathbb{R}$ such that $\varphi (\alpha + C_{<\alpha}) = 1$.

Proof. (1) It exists by the previous remark. More explicitly, let $C_{\alpha} := \{ x \in \mathbb{R}^* : |x| < n\alpha \text{ for some } n \in \mathbb{N} \}.$

Then $\alpha \in C_{\alpha}$ as $0 < \alpha < 2\alpha$ and $C_{\alpha}$ is convex (assume $s_1 < r < s_2$ and $s_1, s_2 \in C_{\alpha}$, let $n$ be such that $|s_1|, |s_2| < n\alpha$, then $|r| < n\alpha$, hence $r \in C_{\alpha}$).

Suppose $\alpha \in C$ and $C$ is a convex subgroup. Then $n\alpha \in C$, hence $C_{\alpha} \subseteq C$.

(2) Define $C_{<\alpha} := \{ x \in \mathbb{R}^* : n \cdot |x| < \alpha \text{ for all } n \in \mathbb{N} \}$.

Then $\alpha \notin C_{<\alpha}$ since $1 \cdot \alpha \notin \alpha$.

If $s_1 < r < s_2$ and $s_1, s_2 \in C_{\alpha}$, we have for every $n \in \mathbb{N}$ that $ns_1 < nr < ns_2$, hence $n|r| < n \cdot \max\{|s_1|, |s_2|\} < \alpha$, so $r \in C_{\alpha}$, hence $C_{\alpha}$ is convex.

Suppose $C_{<\alpha} \subseteq C$, where $C$ is a convex subgroup of $\mathbb{R}^*$. If $x \in C \setminus C_{\alpha}$, then also $|x| \in C$, and by definition $n \cdot |x| \geq \alpha$ for some $n$. But then $0 < \alpha < (n+1) \cdot |x|$, hence $\alpha \in C$ as $C$ is convex. Thus $C_{<\alpha}$ is the largest convex subgroup not containing $\alpha$.

(3) Let $\phi : C_{\alpha} \to \mathbb{R}$ be the map defined by $\phi (\beta) = \sup \{ q \in \mathbb{Q} : q \leq \beta / \alpha \}$. Note that $\frac{\beta}{\alpha} < n$ for some $n \in \mathbb{N}$ by (1), hence $\phi (\beta) \in \mathbb{R}$ for all $\beta \in C_{\alpha}$.

- $\phi$ is a homomorphism of ordered abelian groups: clear from the definition.
- $\phi$ is surjective. If $r \in \mathbb{R}$ then $n \leq r < n+1$ for some $n \in \mathbb{Z}$, hence $n\alpha \leq r\alpha < (n+1)\alpha$, hence $r\alpha \in C_{\alpha}$ by (1). Then $\phi (r\alpha) = \sup \{ q \in \mathbb{Q} : q \leq \frac{r\alpha}{\alpha} = r \} = r$.
- $\ker \phi = \{ x \in C_{\alpha} : \phi (x) = 0 \} = \{ x \in C_{\alpha} : -\frac{1}{n} < \frac{x}{\alpha} < \frac{1}{n} \text{ for all } n \in \mathbb{N} \} = \{ x \in C_{\alpha} : n \cdot |x| < \alpha \text{ for all } n \in \mathbb{N} \} = C_{<\alpha}$ by (2).
- Then, by the groups isomorphism theorem, there is an isomorphism $\varphi : C_{\alpha}/C_{<\alpha} \to \mathbb{R}$ with $\varphi (\alpha + C_{<\alpha}) = \phi (\alpha) = 1$.

Note that all convex subgroups of $(\mathbb{R}^*, +, <)$ are linearly ordered by inclusion, and intuitively correspond to different orders of magnitude: if $C_1 \subseteq C_2$ and $\alpha \in C_1, \beta \in C_2 \setminus C_1$, then $\alpha$ is infinitesimally small compared to $\beta$.

Definition 2.5. Consider $C_1 = \{ r \in \mathbb{R}^* : |r| \leq n \text{ for some } n \in \mathbb{N} \}$. Note that $C_1$ is a convex subring of $\mathbb{R}^*$. Let $C_{<1} = \{ r \in \mathbb{R}^* : \frac{r}{n} \leq 1 \text{ for all } n \in \mathbb{N} \}$, this is the maximal ideal of the ring $C_1$. Then the map $\phi : C_1 \to \mathbb{R}$ defined in (2.4.3) is called the standard part map and is denoted as $\text{st} : C_1 \to \mathbb{R}$. It sends each $r \in C_1$ to the nearest real number $s \in \mathbb{R}$, that is $s \in \mathbb{R}$ and for all rational $q_1, q_2 \in \mathbb{Q}$ if $q_1 \leq r \leq q_2$, then $q_1 \leq s \leq q_2$. By (2.4.3) this is the unique ring isomorphism that respects the ordering, its kernel is the infinitesimals $C_{<1}$ and $C_1/C_{<1} \cong \mathbb{R}$ are isomorphic rings.

Exercise 2.6. Let $\mathcal{U}$ be an ultrafilter on $I$, and let $(r_i)_{i \in I}$ be a sequence of real numbers with $|r_i|$ bounded. Note that by boundness $r := (r_i)_{i \in I} / \mathcal{U} \in \mathbb{R}^*$ is a bounded non-standard real, i.e. $r \in C_1$. Then $\lim_{\mathcal{U}} r_i = \text{st} (r)$.

2.3. Pseudofinite dimensions parametrized by convex subgroups.

Definition 2.7. Let $\tilde{\mathcal{M}} := \prod_{i \in I} \mathcal{M}_i^+/\mathcal{U}$ be as in Section 2.1 and let $C$ be a convex subgroup of $\mathbb{R}^*$ containing $\mathbb{Z}$. Then for any non-empty $L$-definable $\mathcal{U}$-pseudofinite
subset $A$ of $M^n$ (or of some sort of $M$, in the multisorted setting) we define the pseudofinite dimension of $A$ with respect to $C$ as

$$\delta_C (A) := \log |A| + C,$$

i.e. the image of $\log |A|$ under the canonical projection of $\mathbb{R}^*$ onto $\mathbb{R}^*/C$. We define $\delta_C (\emptyset) := -\infty$. Hence $\delta_C$ takes values in $\mathbb{R}^*/C \cup \{-\infty, \infty\}$.

Remark 2.8. If $\varphi (x) \in \mathcal{L} (M)$ is a formula such that the definable set $\varphi (M)$ is pseudofinite, then we write $\delta_C (\varphi (x))$ to denote $\delta_C (\varphi (M))$.

1. The hypothesis that $C$ contains $\mathbb{Z}$ ensures that finite sets have dimension 0, see Proposition 2.3.
2. This dimension in the ordered abelian group $\mathbb{R}^*/C$, rather than the usual integer-valued dimensions. The following proposition is viewed as justifying the term “dimension”.

Proposition 2.9. Let $A, B$ be definable $U$-pseudofinite subsets of $M$. Then the following hold for any convex subgroup $C$ of $\mathbb{R}^*$ containing $\mathbb{Z}$.

1. $\delta_C (A) \geq 0$ for all non-empty $A$.
2. If $A \subseteq B$, then $\delta_C (A) \leq \delta_C (B)$.
3. $A \neq \emptyset$ is finite if and only if $\delta_C (A) = 0$.
4. $\delta_C (A \times B) = \delta_C (A) + \delta_C (B)$.
5. $\delta_C (A \cup B) = \max \{\delta_C (A), \delta_C (B)\}$.
6. If $f : A \rightarrow B$ is a definable function, then $\delta_C (f (A)) \leq \delta_C (B)$.
   In particular, if $f$ is a definable bijection then $\delta_C (A) = \delta_C (B)$.
7. (Subadditivity) Let $f : A \rightarrow B$ be a definable surjective function such that for some $\beta \in \mathbb{R}^*/C$ and for all $b \in B$, $\delta_C (f^{-1}(b)) \leq \beta$. Then $\delta_C (A) \leq \delta_C (B) + \beta$.

Proof. (1) is immediate as log is an increasing function.

2. Note that $\log (m) \leq m \in C$ for all $m \in \mathbb{N}$. If $A = \{a_1, \ldots, a_m\} \subseteq M$ is a finite set, then $\delta_C (A) = \log |A| + C = m + C = C$.

3. Assume $A = \prod A_i/U$ and $B = \prod B_i/U$ are both pseudofinite. Then

$$\{i : \text{both } A_i \text{ and } B_i \text{ are finite} \} \in U.$$

For each such $i$, $\log (|A_i \times B_i|) = \log (|A_i| |B_i|) = \log |A_i| + \log |B_i|$, hence $\delta_C (A \times B) = \log |A \times B| + C = \log |A| + \log |B| + C = \delta_C (A) + \delta_C (B)$.

4. Assume that $\{i : |A_i| \geq |B_i|\} \in U$ (the other case is symmetric). Then $|A_i \cup B_i| \leq 2 |A_i|$ for $U$-almost $i$, hence $\log |A_i| \leq \log |A_i \cup B_i| \leq \log (2 |A_i|) = \log 2 + \log |A_i|$, hence $\log |A| \leq \log |A \cup B| \leq \log 2 + \log |A|$, so $\log |A| + C \leq \log |A \cup B| + C \leq \log 2 + \log |A| + C = \log |A| + C$, so $\delta_C (A) \leq \delta_C (A \cup B) \leq \delta_C (A)$ because $\log 2 \in C$.

5. Let $f = \prod f_i/U$. By Łoś, for $U$-almost $i$ we have that $f_i$ is a function, hence $|f_i (A_i)| \leq |A_i|$, hence $|f (A)| \leq |A|$ which implies $\delta_C (f (A)) = \log |f (A)| + C \leq \log |A| + C = \delta_C (A)$.

6. Say $\beta = r + C$ for $r \in \mathbb{R}^*$. By Łoś, for $U$-almost $i$ we have $f_i : A_i \rightarrow B_i$ is a surjective function. Then we can choose $b_i \in B_i$ such that $|f_i^{-1} (b_i)|$ is maximal among all $b_i \in B_i$. Then $|A_i| = \bigcup_{b_i \in B_i} |f_i^{-1} (b_i)| = \sum_{b_i \in B_i} |f_i^{-1} (b_i)| \leq |f_i^{-1} (b_i)| \cdot |B_i|$. Let $b := (b_i) \in B$. By hypothesis $\delta_C (f^{-1} (b)) \leq \beta$, hence there exists $c \in C$ such that $\log |f^{-1} (b)| \leq r + c$. Then $|A| \leq |f^{-1} (b)| |B|$, so $\log |A| \leq \log |f^{-1} (b)| + \log |B|$.


\[
\log |B| \leq r + \log |B| + c, \text{ so } \delta_C (A) = \log |A| + C \leq (r + C) + (\log |B| + C) = \beta + \delta_C (B). \]

So for each non-infinitesimal convex subgroup of \((\mathbb{R}^+, +)\) there is a corresponding notion of “dimension”, and varying \(C\) allows to distinguish between different degrees of graininess.

### 2.4. Coarse and fine pseudofinite dimensions

Two natural choices for a convex subgroup \(C\) are the smallest convex non-trivial subgroup \(C_{\text{fin}}\) given by the convex hull of \(Z\); and for a given \(\alpha \in \mathbb{R}^*\), the largest convex subgroup not containing it.

**Definition 2.10.** We let \(C_{\text{fin}}\) be the convex hull of \(Z\), and we define \(\delta_{\text{fin}} := \delta_{C_{\text{fin}}}.\)

**Remark 2.11.** Asymptotically, given two pseudofinite sets \(Y = \prod Y_i/\mathcal{U} \subseteq X = \prod X_i/\mathcal{U}\), \(Y\) has the same dimension as \(X\) if for some \(k \in \mathbb{N}\), \(|X_i| \leq k|Y_i|\) for \(\mathcal{U}\)-almost all \(i\).

The characteristic feature of \(\delta_{\text{fin}}\) is that every possible value \(\alpha \in \mathbb{R}^*/C_{\text{fin}}\) for the dimension comes with a corresponding real-valued measure \(\mu_\alpha\) defined up to a scalar multiple.

It is characterized (up to a scalar multiple) by \(\mu_\alpha (X) = 0\) if and only if \(\delta_{\text{fin}} (X) < \alpha\), \(\mu_\alpha (X) = \infty\) if and only if \(\delta_{\text{fin}} (X) > \alpha\), and given any \(X, Y\) such that \(\delta_{\text{fin}} (X) = \delta_{\text{fin}} (Y) = \alpha\), we have \(\mu_\alpha (X) = st \left(\frac{|X|}{|Y|}\right) \mu_\alpha (Y)\), where \(st : \mathbb{R}_{\geq 0} \to \mathbb{R}_\infty\) is the standard part homomorphism (if we fix any definable set \(X\), we may define measure \(\mu_X\) on all definable subsets by \(\mu_X (Y) = st \left(\frac{|X|}{|Y|}\right)\) so that \(\delta_M (Y) = \delta_M (X)\) if and only if \(\mu_X (Y) \in (0, \infty))\). Hence to every set we can attach a pair \((\delta_{\text{fin}} (X), \mu_{\delta_{\text{fin}}(X)})\).

**Proposition 2.12.** For definable sets \(X, Y\) in \(\mathcal{M}\) we have \(\delta_{\text{fin}} (X) = \delta_{\text{fin}} (Y)\) if and only if \(\frac{1}{n} \leq \frac{|X|}{|Y|} \leq n\) for some \(n \in \mathbb{N}_{>0}\).

**Proof.** Indeed, if \(|X| \geq |Y|\), then \(\delta_{\text{fin}} (X) = |X|/|Y| \leq \log |X| - \log |Y| \in C_{\text{fin}} \iff \log \left(\frac{|X|}{|Y|}\right) \in C_{\text{fin}} \iff \frac{|X|}{|Y|} \in C_{\text{fin}}. \)

**Definition 2.13.** Let \(\alpha \in \mathbb{R}^*\).

1. The coarse pseudofinite dimension on \(\mathcal{M}\) normalized by \(\alpha\) and denoted \(\delta_\alpha\) is defined to be \(\delta_{C_{\alpha}}\), and we restrict our attention to definable sets \(Y\) with \(\log |Y| \in C_{\alpha}\).
2. The corresponding dimension can be viewed as real valued, identifying \(C_{\alpha}/C_{<\alpha}\) with \(\mathbb{R}\) via the unique isomorphism sending \(\alpha\) to 1 (See Proposition 2.4(3)).
3. When \(\alpha = \log |X|\) for some pseudofinite set \(X\), we can also write \(\delta_X\) instead of \(\delta_\alpha\), and call \(\delta_X\) the coarse dimension with respect to \(X\).

**Remark 2.14.** By Exercise 2.6, for any definable pseudofinite set \(A \subseteq M^n\) we have \(\delta_\alpha (A) = st \left(\frac{\log |A|}{\alpha}\right)\), and \(\delta_X (A) = \lim_{\mathcal{U}} \left(\frac{\log |A|}{\log |X|}\right)\).

**Remark 2.15.** Asymptotically, given two pseudofinite sets \(Y = \prod Y_i/\mathcal{U} \subseteq X = \prod X_i/\mathcal{U}\), \(Y\) has the same dimension as \(X\) if for any \(\varepsilon \in \mathbb{R}_{>0}\), for \(\mathcal{U}\)-almost all \(i\) we have \(|Y_i| \geq |X_i|^{1-\varepsilon}\). And if \(|Y_i| \approx |X_i|^{\beta}\), then \(\delta_X (Y) \approx \beta\).
Remark 2.16. Typically, it is used in the following situation: \( \mathcal{M} \) is an ultraproduct of finite structures, we normalize by the non-standard cardinality of the model, i.e., consider \( \delta = \delta_M \) (so we want to compare our sets to the fixed set). For finite dimension, we have various sets in the picture with different powers, and we want to be able to compare between all of the simultaneously.

Example 2.17. Let \( \mathcal{M}_i := (\mathbb{R}, +, <) \), let \( X_i := \{(p, q) \in \mathbb{N}^2 : p + q < i\} \), \( Y_i := \{1, 2, \ldots, i^2\} \) and \( \alpha_i := i \) for all \( i \geq 1 \). Let \( \alpha := (\alpha_i)/U \), then \( \delta_{\alpha}(X) = 2 \) and \( \delta_{\alpha}(Y) = \infty \).

2.5. Completions of ordered abelian monoids. Let \((G, \leq)\) be a linearly ordered set. \( G \) is (Dedekind) complete if every non-empty subset of \( G \) which has a lower bound has a largest lower bound. For \( X \subseteq G \), let

\[
L(X) := \{ s \in G : s \leq x \text{ for all } x \in X \},
\]

\[
U(X) := \{ s \in G : s \geq x \text{ for all } x \in X \}.
\]

If \( L(X) \) has a largest element, it is denoted by \( \inf X \), and if \( U(X) \) has a smallest element, it is denoted by \( \sup X \).

Note that \( L(X) \) is downwards closed in \( G \), \( U(X) \) is upwards closed in \( G \), and \( l \leq u \) for all \( l \in L(X), u \in U(X) \).

Let \( C(X) := L(U(X)) \). If \( X \subseteq Y \subseteq G \), then \( L(X) \subseteq L(Y) \) and \( U(X) \supseteq U(Y) \), hence \( C(X) \subseteq C(Y) \). Moreover \( C(X) \supseteq X \) and \( C(C(X)) = C(X) \), thus \( C \) is a closure operation on \( 2^G \).

For \( s \in G \), \( C(\{s\}) = C(\{s\}) = G^\leq s \).

Fact 2.18. [17] The set \( G^\leq := \{ X \subseteq G : X, U(X) \neq \emptyset \land C(X) = X \} \) is ordered by inclusion \( \leq^G \) is called the (Dedekind-Mac Neille) completion of \( G \).

1. The linear order \((G^\leq, \leq^G)\) is linear and complete; if \( F \subseteq G^\leq \) with a lower bound, then \( \inf F = \bigcap \{ X : X \in F \} \).

2. The map \( s \mapsto C(\{s\}) = G^\leq s : G \to G^\leq \) is an embedding of ordered sets; identifying \( G \) with its image, for every \( s \in G^\leq \) there are subsets \( X, Y \) of \( G \) with \( \sup X = \inf Y = s \).

Let now \( G = (G, +, 0, \leq) \) be an ordered abelian monoid (i.e. the operation \(+\) is associative, commutative and \( x \leq y \) implies \( x + z \leq y + z \) for all \( x, y, z \in G \)).

Let \( G^\leq \) be the completion of \((G, \leq)\) given by Fact 2.18. We define a binary operation \( +^G \) on \( G^\leq \) as follows: for \( A, B \in G^\leq \) let

\[
A +^G B := C(A + B) \in G^\leq,
\]

where \( A + B = \{ a + b : a \in A, b \in B \} \).

Note that \( G \) is equipped with the order topology which is generated by a sub-base of open sets of the form \((a, \infty)\) and \((\infty, b)\) for all \( a, b \in G \).

Definition 2.19. (1) \( G \) is upper semi-continuous if for each \( a, b, g \in G \) with \( g > a + b \) there are open neighborhoods \( U, V \) of \( a, b \), respectively, so that \( g > u + v \) for all \( u \in U \) and \( v \in V \).

(2) \( G \) is lower semi-continuous if for each \( a, b, g \in G \) with \( g < a + b \) there are open neighborhoods \( U, V \) of \( a, b \), respectively, so that \( g < u + v \) for all \( u \in U \) and \( v \in V \).

(3) \( G \) is continuous if it is both upper and lower semi-continuous.

Exercise 2.20. Every ordered abelian group is continuous.
Exercise 2.21. $G$ is upper (lower) semi-continuous if and only if for any set $A, B \subseteq G$ such that $\inf A$ and $\inf B$ both exist, then $\inf (A + B) = \inf A + \inf B$ (respectively, if both $\sup A$ and $\sup B$ both exist, then $\sup (A + B) = \sup A + \sup B$).

Fact 2.22. \cite[Ch. XI, §77]{7} If $G = (G, +, 0, \leq)$ is a lower semi-continuous ordered abelian monoid, then $(G^c, +^c, \leq^c)$ is a complete lower semicontinuous ordered abelian monoid with the identity element $G^{\leq 0}$, and identifying $G$ with an ordered subset of $G^c$ via the map $s \mapsto C(\{s\})$ we have that $G$ is a submonoid of $G^c$.

Corollary 2.23. If $G = (G, +, 0, \leq)$ is an upper semi-continuous ordered abelian monoid, then there exists a complete upper semi-continuous ordered abelian monoid $G^u$ such that $G$ embeds into $G^u$ as an ordered submonoid via $s \mapsto S^{\geq s}$, and for every $s \in G^u$ there are subsets $X, Y$ of $G$ with $\sup X = \inf Y = s$.

Proof. If $G$ is upper semi-continuous, then $G'$ obtained from $G$ by reversing the ordering is a lower semi-continuous ordered abelian monoid, and the rest follows by Fact 2.22.

Remark 2.24. If $G$ is an ordered abelian group, then it is continuous, hence has both a lower completion $G^c$ and an upper completion $G^u$. They are non-isomorphic in general (see \cite[Ch. XI, §77]{7}).

Fact 2.25. \cite{7} If $G$ is an ordered abelian group, then for $C \in G^c$ the following are equivalent:

1. $C$ is invertible in $G^c$;
2. $U(L(-C) + C) = G^{\geq 0}$;
3. $L(-C + U(C)) = G^{\leq 0}$;
4. For all $g \in G$, if $U(C) + g \subseteq U(C)$, then $g \in G^{\geq 0}$.

In this case $L(-C)$ is the inverse of $C$ in $G^c$.

Using this, the following can be demonstrated.

Fact 2.26. (1) Let $G$ be a complete archimedean ordered abelian group. Then $G$ is isomorphic to one of $\{0\}, \mathbb{Z}, \mathbb{R}$.

(2) Let $G$ be a complete ordered abelian group. Then any subgroup $H$ of $G$ is archimedean.

(3) If $G$ is an archimedean ordered abelian group, then so is $G^c$.

2.6. Extending pseudofinite dimensions to type-definable sets. Assume that $\mathcal{L}$ is countable, and that $\mathcal{M}$ is given by an ultraproduct over a countable index set. Then $\mathcal{M}$ is $\aleph_1$-saturated (Proposition 1.9). By a type-definable set, or $\Lambda$-definable set, we mean a subset of $M^n$ given by an arbitrary conjunction of formulas over a countable set $A \subseteq M$ of parameters.

Definition 2.27. For any type-definable set $X \subseteq M^n$ and $C$ a convex subgroup of $\mathbb{R}^*$, we define

$$\delta_C(X) := \inf \{\delta_C(D) : X \subseteq D \text{ and } D \text{ is definable}\},$$

where the infimum is evaluated in the complete ordered abelian monoid $(\mathbb{R}^*/C)^u$ (see Section 2.5).

Remark 2.28. If $X = \bigcap_{n \in \mathbb{N}} X_n$ with $X_n$ definable and such that $X_0 \supseteq X_1 \supseteq \ldots$, then $\delta(X) = \inf \{\delta(X_n)\}$. Indeed, $\delta(X) \leq \inf \{\delta(X_n)\}$ is clear. On the other hand, by $\aleph_1$-saturation of $\mathcal{M}$ for any definable set $D$ with $X \subseteq D$ we must have
$X_n \subseteq D$ for all $n$ large enough, hence $\delta(X_n) \leq \delta(D)$, so $\inf \{ \delta(X_n) \} \leq \delta(X)$.
(The same is true if we only assume the $X_n$’s to be type-definable).

Lemma 2.29 holds for type-definable sets as well, under a mild definability assumption on $C$.

**Proposition 2.29.** Let $X, Y$ be type-definable subsets of some sorts in $\mathcal{M}$.

1. If $X \subseteq Y$, then $\delta_C(X) \leq \delta_C(Y)$.
2. $X \neq \emptyset$ is finite then $\delta_C(X) = 0$.
3. $\delta_C(X \times Y) = \delta_C(X) + \delta_C(Y)$.
4. $\delta_C(X \cup Y) = \max \{ \delta_C(X), \delta_C(Y) \}$.
5. (Subadditivity) Assume additionally that $C$ is a countable union of definable subsets of $\mathbb{R}^*$.

Let $f$ be a definable function such that for some $\gamma \in (\mathbb{R}^*/C)^n$ and for all $a$ in $f(X)$ we have $\delta_C(f^{-1}(a) \cap X) \leq \gamma$. Then $\delta_C(X) \leq \delta_C(f(X)) + \gamma$.

**Proof.** By $\aleph_1$-saturation any definable set $Z \supseteq X \times Y$ must contain $X' \times Y'$ for some definable $X' \supseteq X, Y' \supseteq Y$. Hence, using upper semicontinuity of $(\mathbb{R}^*/C)^c$ and Proposition 2.29(4), we have

\[
\delta_C(X \times Y) = \inf \{ \delta_C(X' \times Y'): X \subseteq X', Y \subseteq Y' \text{ and $X', Y'$ are definable} \} = \inf \{ \delta_C(X') + \delta_C(Y'): X \subseteq X', Y \subseteq Y' \text{ and $X', Y'$ are definable} \} \leq \delta_C(X) + \delta_C(Y).
\]

(4) similar to (3).

(5) As $X$ is type-definable, it can be written as $X = \bigcap_{n \in \mathbb{N}} X_n$ with $X_n$ a descending sequence of definable sets. Then $f(X) = \bigcap_{n \in \mathbb{N}} f(X_n)$ by $\aleph_1$-saturation of $\mathcal{M}$.

**Claim.** For every $\beta \in \mathbb{R}^*/C$ with $\beta > \gamma$ there is some $n(\beta) \in \mathbb{N}$ such that $\delta(f^{-1}(a) \cap X_{n(\beta)}) \leq \beta$ for all $a \in f(X_{n(\beta)})$.

**Proof.** Say $\beta = \beta' + C$ for some $\beta' \in \mathbb{R}^*$. Assume that the claim doesn’t hold, then for each $n$ there exists some $a_n \in f(X_n)$ such that $\delta(f^{-1}(a_n) \cap X_n) > \beta$.

Assume that $C = \bigcup_{k \in \mathbb{N}} C_k$, with $C_1 \subseteq C_2 \subseteq \ldots$ definable subsets of $\mathbb{R}^*$. Note that

\[
\delta(f^{-1}(a_n) \cap X_n) > \beta \iff \log(|f^{-1}(a_n) \cap X_n|) > \beta' + C \iff \bigwedge_{k \in \mathbb{N}} \forall c \in C_k \left( \log(|f^{-1}(a_n) \cap X_n|) > \beta' + c \right).
\]

Consider the $\mathcal{L}^+$-partial type in $\mathcal{M}^+$ (see Section 2.1) over a countable set of parameters given by

\[
\pi(y) = \bigwedge_{n \in \mathbb{N}} \bigwedge_{k \in \mathbb{N}} y \in f(X_n) \land \forall c \in C_k \left( \log(|f^{-1}(y) \cap X_n|) > \beta' + c \right).
\]

Then the $a_n$’s witness that it is finitely consistent, hence can be realized by some $a \in M_y$ by saturation of $\mathcal{M}^+$, hence $a \in f(X)$ and $\delta(f^{-1}(a) \cap X_n) > \beta$ for all
n ∈ N simultaneously, hence \( \delta (f^{-1}(a) \cap X) = \inf \{ \delta (f^{-1}(a) \cap X_n) \} \geq \beta > \gamma \) — contradicting the assumption on \( f \).

So for each \( \beta \in B \) we have \( \delta (X_{n(\beta)}) \leq \delta (f(X_{n(\beta)})) + \beta \) by Proposition 2.9(7). Thus, using upper semi-continuity of \((\mathbb{R}^n/C)^n\), we have \( \delta (X) = \inf \{ \delta (X_n) : n \in \mathbb{N} \} \leq \inf \{ \delta (X_{n(\beta)}) : \beta \in B \} \leq \inf \{ \delta (f(X_{n(\beta)})) + \beta : \beta \in B \} = \inf \{ \delta (f(X_{n(\beta)})) : \beta \in B \} + \inf \{ \beta : \beta \in B \} = \delta (f(X)) + \gamma \).

**Example 2.30.** Note that \( C_{\text{fin}} = C_1 = \bigcup_{n \in \mathbb{N}} \{ x \in \mathbb{R}^n : |x| < n \} \) is a countable union of definable subsets of \( \mathbb{R}^n \), while \( C_{\leq \alpha} = \bigcap_{n \in \mathbb{N}} \{ x \in \mathbb{R}^n : n \cdot |x| < \alpha \} \) is a countable intersection of definable subsets of \( \mathbb{R}^n \), hence the lemma applies to both fine \( C_{\text{fin}} \) (and we give a proof for \( C_\alpha \) later).

**Problem 2.31.** Does subadditivity hold for an arbitrary convex subgroup \( C \) without any definability assumptions on it?

**Definition 2.32.** If \( a \) is a finite tuple and \( B \subseteq M \) is countable, we define

\[
\delta_C (a/B) := \delta_C (\text{tp}(a/B)) = \inf \{ \delta_C (D) : a \in D, D \text{ definable over } B \}.
\]

We will write \( \delta_C (a) \) for \( \delta_C (a/\emptyset) \).

Note that if \( B_1 \subseteq B_2 \), then \( \delta_C (a/B_2) \leq \delta_C (a/B_1) \). If \( X \) is type definable over \( B \) then \( \delta_C (a/B) \leq \delta_C (X) \) for every \( a \in X \). Saturation allows to always find a tuple of full dimension:

**Proposition 2.33.** (Existence of independent realizations) If \( X \subseteq M^n \) is \( \bigwedge \)-definable over \( B \), then \( X \) contains some element \( a \) with \( \delta_C (a/B) = \delta_C (X) \).

**Proof.** For any \( a \in X \) by definition we have \( \delta_C (a/B) < \delta_C (X) \) if and only if there is some \( B \)-definable set \( Z \) with \( a \in Z \) and \( \delta (Z) < \delta (X) \) (evaluated in \((\mathbb{R}^n/C)^n\)). Consider the family of all \( B \)-definable subsets of \( Z \) with \( \delta_C (Z) < \delta_C (X) \). It is enough to show that their union does not contain \( X \). If it did, by \( \aleph_1 \)-saturation \( X \) would be contained in the union of finitely many of them, say \( Z_1, \ldots, Z_m \), so \( \delta_C (\bigcup_{i=1}^m Z_i) \geq \delta_C (X) \) by monotonicity. But \( \delta_C (\bigcup_{i=1}^m Z_i) = \max \{ \delta_C (Z_i) \} \geq \delta_C (X) \), a contradiction.

**Proposition 2.34.** For a tuple \( a = (a_1, \ldots, a_n) \in M^n \) and a countable set \( B \), \( \delta_C (a/B) \) depends only on the set of the coordinates \( \{a_1, \ldots, a_n\} \subseteq M \).

**Proof.** Indeed \( \delta_C (a/B) \) is invariant under permutation of the coordinates of \( a \) because these induce bijections of \( M^n \), and thus preserve \( \delta_C \)-dimension by Proposition 2.9(6).

If \( X \) is a definable set in \( M^n \) such that the last two coordinates \( x_{n-1} \) and \( x_n \) coincide for all \( x \in X \), then \( \delta_C (X) = \delta_C (\pi(X)) \) where \( \pi(X) \) is the projection onto the first \( n - 1 \) coordinates which is a bijection in this case, again by 2.9(6) (and this claim can be iterated).

2.7. Continuity and additivity of pseudofinite dimensions.

**Definition 2.35.** (1) We say that \( \delta_C \) is invariant if for every formula \( \varphi (x,y) \) and every \( b \in M_y \), \( \delta_C (\varphi (x,b)) \) depends only on \( \text{tp}(b) \) (this holds for example if \( \delta_C \) is Aut \((M)\)-invariant).
Exercise 2.36. Let \( W \) satisfying the required condition. Indeed, given an \( \alpha \) for some set of parameters \( \delta \). Namely, if in Exercise 2.36(3)

\[
\delta = \delta_\alpha \text{ for some } \alpha \in \mathbb{R}^*.
\]

Then the following are equivalent.

1. \( \delta_\alpha \) is invariant and continuous in \( \mathcal{M} \).
2. For any \( Y \) an \( \emptyset \)-definable subset of \( M^n \times M^m \) and \( \beta < \gamma \in \mathbb{R} \), there is some \( \emptyset \)-definable set \( W \subseteq M^m \) such that \( \{ b \in M^m : \delta (Y_b) \leq \beta \} \subseteq W \subseteq \{ b \in M^m : \delta (Y_b) < \gamma \} \).
3. For any \( n, m \geq 1, \beta \in \mathbb{R}, \varepsilon \in \mathbb{R}_{> 0} \) and an \( \emptyset \)-definable set \( Y \subseteq M^n \times M^m \) there is an \( \emptyset \)-definable set \( W \subseteq M^m \) such that

\[
\{ b \in M^m : \delta (Y_b) \geq \beta + \varepsilon \} \subseteq W \subseteq \{ b \in M^m : \delta (Y_b) \geq \beta \},
\]

where \( Y_b := \{ a \in M^m : (a, b) \in Y \} \) is the fiber of \( Y \) at \( b \).

Exercise 2.37. \( \delta_C \) is definable if and only if for every \( \varphi (x, y) \in \mathcal{L} \) and \( b \in M_b \), there is some \( \theta (y) \in \text{tp} (b) \) such that \( \mathcal{M} \models \theta (a) \iff \delta_C (\varphi (x, b)) = \delta_C (\varphi (x, a)) \) for all \( a \in M_y \).

Proposition 2.38. Let \( \delta = \delta_\alpha, \alpha \in \mathbb{R}^* \) be a coarse dimension. Given any \( \mathcal{M} = \prod_{i \in \mathbb{N}} \mathcal{M}_i \) in a countable language \( \mathcal{L} \), there exists an expansion \( \mathcal{M}' = \prod_{i \in \mathbb{N}} \mathcal{M}'_i \) in a countable language \( \mathcal{L}' \supseteq \mathcal{L} \) such that \( \delta \) is continuous in \( \mathcal{M}' \), and \( \mathcal{M}'_i \) is an expansion of \( \mathcal{M}_i \).

Proof. Write \( \alpha = (\alpha_i)_i / \mathcal{U}_i, \alpha_i \in \mathbb{R} \). Let \( \mathcal{L}_0 := \mathcal{L} \), and let \( \mathcal{L}_{i+1} \) be obtained from \( \mathcal{L}_i \) by adding a new predicate \( \psi_{\varphi(x,y),q} (y) \) for each formula \( \varphi (x, y) \in \mathcal{L}_i \) and each \( q \in \mathbb{Q} \). Let \( \mathcal{L}' := \bigcup_{i \in \mathbb{N}} \mathcal{L}_i, |\mathcal{L}'| = |\mathcal{L}| + \aleph_0 \). For each \( i \), we define an \( \mathcal{L}' \)-expansion \( \mathcal{M}'_i \) of \( \mathcal{M}_i \) by interpreting \( \psi_{\varphi(x,y),q} (M_i) := \{ b \in (M_i)_y : |\varphi (M, b)|^q \geq \alpha_i \} \). Then in the ultraproduct \( \mathcal{M}' \) we have \( \psi_{\varphi(x,y),q} (M') = \{ b : |\varphi (M', b)|^q \geq \alpha \} \).

We claim that \( \delta \) is continuous in \( \mathcal{M}' \). Let \( \alpha \in \mathbb{R}, \varepsilon \in \mathbb{R}_{> 0} \) be arbitrary. Pick a rational \( q \in (\alpha, \alpha + \varepsilon) \). Then if \( b \in \psi_{\varphi(x,y),q} (M') \) then \( |\varphi (M, b)|^q \geq \alpha \), so \( \delta (\varphi (M, b)) \geq q > \alpha \). And if \( \delta (\varphi (M, b)) \geq q > \alpha \), then \( \delta (\varphi (M, b)) \geq \delta (\varphi (M', b)) \geq q \) and \( b \in \psi_{\varphi(x,y),q} (M), \) hence condition (3) in Exercise 2.36 is satisfied.

Exercise 2.39. Show that for \( \delta = \delta_X \) with \( X \) an \( \mathcal{L} \)-definable set, we can alternatively achieve continuity by adding cardinality comparison predicates, i.e. for each formula \( \varphi (x,y) \) add a new predicate \( \theta (y,y') \) interpreted in \( \mathcal{M}_i \) as

\[
\{ (a, a') \in (M_i)_y \times (M_i)_y : |\varphi (M_i, a)| \leq |\varphi (M_i, a')| \}
\]

(closing under these in countably many steps).

Remark 2.40. The continuity of \( \delta = \delta_\alpha \) automatically extends to definable sets with parameters. Namely, if in Exercise 2.36(3) \( Y \) is assumed to be \( A \)-definable for some set of parameters \( A \subseteq M \) and \( \delta \) is continuous, we may find a \( A \)-definable \( W \) satisfying the required condition. Indeed, given an \( A \)-definable \( Y \subseteq M^n \times M^m \),
there exist some $l$, some $∅$-definable set $Y^0 \subseteq M^{a+m+l}$ and a tuple $a_0 \in A^l$ so that $Y = Y^0_{a_0} = \{(x, y) : (x, y, a_0) \in Y^0\}$. By continuity of $δ$, there exists some $∅$-definable set $W^0 \subseteq M^m$ such that

$$\{(b, a) \in M^{m+l} : δ(Y_{b,a}) ≥ β + ε\} \subseteq W^0 \subseteq \{(b, a) \in M^{m+l} : δ(Y_{b,a}) ≥ β\}.$$  

But then $W := W^0_{a_0}$ satisfies the same condition with respect to the fibers of $Y$.

The following result strengthens sub-additivity of $δ$ from Proposition 2.29 and is a desirable characteristic of a dimension function (shared by dimension in vector spaces, transference degree, Morley rank in strongly minimal theories, etc).

**Proposition 2.41.** If $δ = δ_α$ is continuous, then it is additive: $δ(ab/B) = δ(b/B) + δ(a/bB)$.

**Proof.** Given any $ε \in \mathbb{R}_{>0}$, by definition of $δ_α$ for types there exist some $B$-definable sets $Y, Y' \subseteq M^b \times M^m$ and $Z \subseteq M^m$ such that $δ_α(ab/B) ≤ δ_α(Y) ≤ δ_α(ab/B) + ε$ and $δ_α(a/bB) ≤ δ_α(Y_b) ≤ δ_α(a/bB) + ε$, and $δ_α(b/B) ≤ δ_α(Z) ≤ δ(b/B) + ε$. Replacing both $Y, Y'$ by $Y \cap Y' \cap π_2^{-1}(Z)$, we may assume that $Y = Y'$ and $Z = π_2(Y)$. Now by continuity of $δ_α$ there exists a $B$-definable set $W \ni b$ such that $|δ(Y_{b'}) - δ(Y_b)| < ε$ for all $b' \in W$. Further replacing $Y$ by $Y \cap π_2^{-1}(W)$ we may assume $δ(ab/B) ≤ δ(Y) ≤ δ(ab/B) + ε$, $δ(b/B) ≤ δ(π_2(Y)) ≤ δ(b/B) + ε$ and all fibers $Y_{b'}$ with $b' \in π_2(Y)$ satisfy $δ(a/bB) - ε ≤ δ(Y_{b'}) ≤ δ(a/bB) + ε$. Thus $|δ(ab/B) - δ(b/C) - δ(a/bC)| ≤ 3ε$, as desired. □

**Exercise 2.42.** Show that additivity implies subadditivity (as in Proposition 2.29).

### 2.8. Independence relations arising from pseudofinite dimensions.

**Definition 2.43.** We write $a \downarrow^{δ} B b$ if $δ(a/bB) = δ(a/B)$.

**Exercise 2.44.** $a \downarrow^{δ} B b \iff$ there is a formula $θ(x) \in tp(a/bB)$ such that for all $ψ(x) \in tp(a/B)$ we have $δ(θ(x)) < δ(ψ(x))$.

**Proposition 2.45.** (Properties of coarse independence) Let $δ = δ_α$ for some $α ∈ \mathbb{R}^*$.

1. Symmetry (assuming additivity): $a \downarrow^{δ} A b \iff b \downarrow^{δ} A a$.
2. Transitivity: if $A \subseteq D \subseteq B$, then $a \downarrow^{δ} A B \iff \left(a \downarrow^{δ} A D \text{ and } a \downarrow^{δ} D B\right)$.
3. Extension: assume $a \downarrow^{δ} A b$. Then for any $c$ there exists $a'$ with $tp(a'/Ab) = tp(a/Ab)$ and $a' \downarrow^{δ} A bc$.

**Proof.** Transitivity: immediate from definitions.

Symmetry: it suffices to show that $a \downarrow^{δ_α} A b \implies b \downarrow^{δ_α} A a$. Suppose $a \downarrow^{δ_α} A b$, that is $δ_α(a/bA) = δ(a/A)$. By additivity and invariance under permutation (propositions 2.34 and 2.41) we have $δ(b/A) + δ(a/bA) = δ(ab/A) = δ(a/A) + δ(b/aA)$, hence $δ(b/aA) = δ(b/A)$ as required.

Extension: same as existence (see Proposition 2.33). □

**Exercise 2.46.** Show that 3-amalgamation fails.
2.9. References. Pseudofinite dimensions were introduced in [12], and further investigated in [10, Section 5] and [11] — most of the material here is based on these papers. The extension of $\delta_C$ to type-definable sets is from [10, Section 5]. I thank Matthias Aschenbrenner for clarifying completions of ordered abelian groups and providing the references in Section 2.5. I also used [8]. Proposition 2.4 has a nice general treatment in the context of Hahn spaces [11, Section 2].

For more on connections of forking and fine pseudofinite dimension see [9]. Coarse dimension is particularly well-behaved in sufficiently fast growing pseudofinite difference fields [25].


Main applications to asymptotic combinatorics stem from establishing some additional properties of $\delta$ restricting to a tame class of theories (such as strongly minimal, stable, NIP, etc.) or just tame formulas, and the results are usually in the form of comparing the dimension $\delta$ ($\delta$-independence) with some natural notion of dimension (respectively, independence relation) in the corresponding context.

3.1. Erdős-Hajnal conjecture. By a graph $G$ we mean, as usual, a pair $(V,E)$, where $E$ is a symmetric subset of $V \times V$ not intersecting the diagonal. If $G$ is a graph then a clique in $G$ is a set of vertices all pairwise adjacent, and an anti-clique in $G$ is a set of vertices such that any two different vertices from it are non-adjacent.

As usual, for a graph $H$ we say that a graph $G$ is $H$-free if $G$ does not contain an induced subgraph isomorphic to $H$ (i.e. a substructure in the language).

It is well-known that every graph on $n$ vertices contains either a clique or an anti-clique of size $\frac{1}{2} \log n$, and that this is optimal in general. However, the following famous conjecture of Erdős and Hajnal says that one can do much better in a family of graphs omitting a certain fixed graph $H$.

Conjecture 3.1. (Erdős-Hajnal conjecture) For every finite graph $H$ there is a real number $\delta = \delta(H) > 0$ such that every finite $H$-free graph $G = (V,E)$ contains either a clique or an anti-clique of size at least $|V|^\delta$.

Remark 3.2. It is known to hold for some choices of $H$, but is widely open in general. A variation of this conjecture starts with a finite set of finite graphs $\mathcal{H} = \{H_1, \ldots, H_k\}$ and asks for the existence of a real constant $\delta = \delta(\mathcal{H}) > 0$ such that every finite graph $G$ which is $\mathcal{H}$-free (that is, omits all of the $H_i \in \mathcal{H}$ simultaneously), contains either a clique or an anti-clique of size at least $|V|^\delta$.

Definition 3.3. (1) Given $m \in \mathbb{N}$, sets $V_1, V_2$ and a relation $R \subseteq V_1 \times V_2$, we say that $R$ has the $m$-order property if there are some vertices $a_1, \ldots, a_m \in V_1, b_1, \ldots, b_m \in V_2$ such that $a_i R b_j$ holds if and only if $i < j$.

(2) A graph $G = (V,E)$ has the $m$-order property if the relation $E \subseteq V \times V$ does.

(3) A relation is stable if it doesn’t have the $m$-order property for some $m \in \mathbb{N}$.

The aim of this section is to prove the following theorem.

Theorem 3.4. For every $m \in \mathbb{N}$ there is a constant $\delta = \delta(m) \in \mathbb{R}_{>0}$ such that every finite graph $G = (V,E)$ without the $m$-order property contains either a clique or an anti-clique of size at least $|V|^\delta$. 

Theorem 3.4 implies an instance of Conjecture 3.1 for certain $H$. We consider the following graphs, for each $m \in \mathbb{N}$.

1. Let $H_m$ be the half-graph on $2m$ vertices. Namely, the vertices of $H_m$ are \{a_1, \ldots, a_m, b_1, \ldots, b_m\}, and the edges are \{(a_i, b_j) : i < j\}.
2. Let $H_m'$ be the complement graph of $H_m$. Namely, the vertices of $H_m'$ are \{a_1, \ldots, a_m, b_1, \ldots, b_m\}, and the edges are \{(a_i, b_j) : i \geq j\} \cup \{(a_i, a_j) : i \neq j\}.
3. Let $H_m''$ have \{a_1, \ldots, a_m, b_1, \ldots, b_m\} as its vertices, and \{(a_i, b_j) : i < j\} \cup \{(a_i, a_j) : i \neq j\}$ as its edges.

Finally, let $H_m = \{H_m, H_m', H_m''\}$.

Corollary 3.5. For every $m \in \mathbb{N}$, the Erdős-Hajnal conjecture holds for the family of all $H_m$-free graphs.

Proof. In view of Theorem 3.4, it is enough to show that for every $m \in \mathbb{N}$ there is some $m' \in \mathbb{N}$ such that if a finite graph $G$ is $H_m$-free, then it doesn’t have the $m'$-order property. Assume that $G$ has the $m'$-order property. That is, there are some vertices $a_1, \ldots, a_{m'}, b_1, \ldots, b_{m'}$ in $V$ such that $a_i b_j$ holds if and only if $i < j$. If $m'$ is large enough with respect to $m$, by Ramsey theorem we can find some subsequences $A = \{a_{i_1}, \ldots, a_{i_{m+1}}\}$ and $B = \{b_{j_1}, \ldots, b_{j_{m+1}}\}$, $1 \leq i_1 < \cdots < i_{m+1} \leq m'$, $1 \leq j_1 < \cdots < j_{m+1} \leq m'$, such that each of $A, B$ is either a clique or an anti-clique. If both are anti-cliques, then the graph induced on $(A \cup B) \setminus \{a_{i_{m+1}}, b_{j_{m+1}}\}$ is isomorphic to $H_m$. If both are cliques, let $a_k' := b_{j_{k+1}}$ and $b_k' := a_{i_k}$ for $1 \leq k \leq m$. Then the graph induced on $\{a_{i_1}', \ldots, a_{i_{m-1}}', b_{j_1}', \ldots, b_{j_m}'\}$ is isomorphic to $H_m$. If $A$ is a clique and $B$ is an anti-clique, then the graph induced on $(A \cup B) \setminus \{a_{i_{m+1}}, b_{j_{m+1}}\}$ is isomorphic to $H_m'$. Finally, if $A$ is an anti-clique and $B$ is a clique, let $a_k' := b_{j_{m+1-k}}$ and $b_k' := a_{i_{m+1-k}}$ for $1 \leq k \leq m$. Then the graph induced on $\{a_{i_1}', \ldots, a_{i_{m-1}}', b_{j_1}', \ldots, b_{j_m}'\}$ is again isomorphic to $H_m'$. In any of the cases, $G$ is not $H_m$-free. \hfill \square

3.2. Stable relations, Shelah’s 2-rank and definability of types. We review some basic facts from local stability theory. A partitioned formula formula $\phi(x, y)$ has the $m$-order property (is stable) if the relation that it defines on $M_x \times M_y$ is.

Exercise 3.6. Let $\phi(x, y), \psi(x, z)$ be stable formulas (where $y, z$ are not necessarily disjoint tuples of variables). Then:

1. Let $\phi^*(y, x) := \phi(x, y)$, i.e. we switch the roles of the variables. Then $\phi^*(y, x)$ is stable.
2. $\neg \phi(x, y)$ is stable.
3. $\theta(x, yz) := \phi(x, y) \land \psi(x, z)$ and $\theta'(x, yz) := \phi(x, y) \lor \psi(x, z)$ are stable.
4. If $y = wu$ and $c \in M_x$ then $\theta(x, u) := \phi(x, wu)$ is stable.

Definition 3.7. We define Shelah’s local 2-rank taking values in $\{-\infty\} \cup \omega \cup \{+\infty\}$ by induction on $n \in \omega$ (there are many other related ranks). Let $\Delta$ be a set of $L$-formulas, and $\theta(x)$ a partial type over $M$.

- $R_\Delta(\theta(x)) \geq 0$ iff $\theta(x)$ is consistent (and $-\infty$ otherwise).
- $R_\Delta(\theta(x)) \geq n + 1$ if for some $\phi(x, y) \in \Delta$ and $a \in M_y$ we have both $R_\Delta(\theta(x) \land \phi(x, a)) \geq n$ and $R_\Delta(\theta(x) \land \neg \phi(x, a)) \geq n$.
- $R_\Delta(\theta(x)) = n$ if $R_\Delta(\theta(x)) \geq n$ and $R_\Delta(\theta(x)) \not\geq n + 1$, and $R_\Delta(\theta(x)) = \infty$ if $R_\Delta(\theta(x)) \geq n$ for all $n \in \omega$. 

If $\phi(x,y)$ is a formula, we write $R_\phi$ instead of $R\{\phi\}$.

**Proposition 3.8.** $\phi(x,y)$ is stable if and only if $R_\phi(x = x)$ is finite (and so also $R_\phi(\theta(x))$ is finite for any partial type $\theta$). Here $x = (x_i : i \in I)$ is a tuple of variables, and $x = x$ is an abuse of notation for $\bigwedge_{i \in I} x_i = x_i$.

**References**


