

VC-DENSITY IN AN ADDITIVE REDUCT OF THE P -ADIC NUMBERS

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ABSTRACT. Aschenbrenner et. al. computed a bound $\text{vc}(n) \leq 2n - 1$ for the vc-density function in the field of p -adic numbers, but it is not known to be optimal. In this paper we investigate a certain P -minimal additive reduct of the field of p -adic numbers and use a cell decomposition result of Leenknegt to compute an optimal bound $\text{vc}(n) = n$ for that structure.

VC-density was studied in model theory in [1] by Aschenbrenner, Dolich, Haskell, MacPherson, and Starchenko as a natural notion of dimension for definable families of sets in NIP theories. In a complete NIP theory T we can define the vc-function

$$\text{vc}^T = \text{vc} : \mathbb{N} \longrightarrow \mathbb{R} \cup \{\infty\}$$

where $\text{vc}(n)$ measures the worst-case complexity of families of definable sets in an n -fold cartesian power of the underlying set of a model of T (see 1.13 below for a precise definition of vc^T). The simplest possible behavior is $\text{vc}(n) = n$ for all n , satisfied, for example, if T is o-minimal. For $T = \text{Th}(\mathbb{Q}_p)$, the paper [1] computes an upper bound for this function to be $2n - 1$, and it is not known whether this is optimal. This same bound holds in any reduct of the field of p -adic numbers, but one may expect that the simplified structure of the reduct would allow a better bound. In [2], Leenknegt provides a cell decomposition result for a certain P -minimal additive reduct of the field of p -adic numbers. Using this result, in this paper we improve the bound for the vc-function, showing that in Leenknegt's structure $\text{vc}(n) = n$.

Section 1 defines vc-density and states some basic lemmas about it. A more in depth exposition of vc-density can be found in [1]. Section 2 defines and states some

basic facts about the theory of p -adic numbers. Here we also introduce the reduct which we will be working with. Section 3 sets up basic definitions and lemmas that will be needed for the proof. We define trees and intervals and show how they help with vc-density calculations. Section 4 concludes the proof.

Throughout the paper, variables and tuples of elements will be simply denoted as x, y, a, b, \dots . We will occasionally write \vec{a} instead of a for a tuple in \mathbb{Q}_p^n to emphasize it as an element of \mathbb{Q}_p -vector space \mathbb{Q}_p^n . We denote the arity of a tuple x of variables by $|x|$.

1. VC-DIMENSION AND VC-DENSITY

Throughout this section we work with a collection \mathcal{F} of subsets of a set X . We call the pair (X, \mathcal{F}) a set system.

Definition 1.1.

- Given a subset A of X , we define the set system $(A, A \cap \mathcal{F})$ where $A \cap \mathcal{F} = \{A \cap F \mid F \in \mathcal{F}\}$.
- For $A \subset X$ we say that \mathcal{F} shatters A if $A \cap \mathcal{F} = \mathcal{P}(A)$ (the power set of A).

Definition 1.2. We say (X, \mathcal{F}) has VC-dimension n if the largest subset of X shattered by \mathcal{F} is of size n . If \mathcal{F} shatters arbitrarily large subsets of X , we say that (X, \mathcal{F}) has infinite VC-dimension. We denote the VC-dimension of (X, \mathcal{F}) by $\text{VC}(X, \mathcal{F})$.

Note 1.3. We may drop X from the $\text{VC}(X, \mathcal{F})$, as the VC-dimension doesn't depend on the base set and is determined by $(\bigcup \mathcal{F}, \mathcal{F})$.

Set systems of finite VC-dimension tend to have good combinatorial properties, and we consider set systems with infinite VC-dimension to be poorly behaved.

Another natural combinatorial notion is that of a dual system:

Definition 1.4. For $a \in X$ define $X_a = \{F \in \mathcal{F} \mid a \in F\}$. Let $\mathcal{F}^* = \{X_a \mid a \in X\}$. We call $(\mathcal{F}, \mathcal{F}^*)$ the dual system of (X, \mathcal{F}) . The VC-dimension of the dual system of

(X, \mathcal{F}) is referred to as the dual VC-dimension of (X, \mathcal{F}) and denoted by $\text{VC}^*(\mathcal{F})$.
(As before, this notion doesn't depend on X .)

Lemma 1.5. *A set system (X, \mathcal{F}) has finite VC-dimension if and only if its dual system has finite VC-dimension. More precisely*

$$\text{VC}^*(\mathcal{F}) \leq 2^{1+\text{VC}(\mathcal{F})}.$$

For a more refined notion of complexity of (X, \mathcal{F}) we look at the traces of our family on finite sets:

Definition 1.6. Define the shatter function $\pi_{\mathcal{F}}: \mathbb{N} \longrightarrow \mathbb{N}$ and the dual shatter function $\pi_{\mathcal{F}}^*: \mathbb{N} \longrightarrow \mathbb{N}$ of \mathcal{F} by

$$\pi_{\mathcal{F}}(n) = \max \{ |A \cap \mathcal{F}| \mid A \subset X \text{ and } |A| = n \}$$

$$\pi_{\mathcal{F}}^*(n) = \max \{ \text{atoms}(B) \mid B \subset \mathcal{F}, |B| = n \}$$

where $\text{atoms}(B)$ = number of atoms in the Boolean algebra of sets generated by B . Note that the dual shatter function is precisely the shatter function of the dual system: $\pi_{\mathcal{F}}^* = \pi_{\mathcal{F}^*}$.

A simple upper bound is $\pi_{\mathcal{F}}(n) \leq 2^n$ (same for the dual). If the VC-dimension of \mathcal{F} is infinite then clearly $\pi_{\mathcal{F}}(n) = 2^n$ for all n . Conversely we have the following remarkable fact:

Theorem 1.7 (Sauer-Shelah '72). *If the set system (X, \mathcal{F}) has finite VC-dimension d then $\pi_{\mathcal{F}}(n) \leq \binom{n}{\leq d}$ for all n , where $\binom{n}{\leq d} = \binom{n}{d} + \binom{n}{d-1} + \dots + \binom{n}{1}$.*

Thus the systems with a finite VC-dimension are precisely the systems where the shatter function grows polynomially. Define the *vc-density* of \mathcal{F} to quantify the growth of the shatter function of \mathcal{F} :

Definition 1.8. Define vc-density and dual vc-density of \mathcal{F} as

$$\begin{aligned} \text{vc}(\mathcal{F}) &= \limsup_{n \rightarrow \infty} \frac{\log \pi_{\mathcal{F}}(n)}{\log n} \in \mathbb{R}^{\geq 0} \cup \{+\infty\}, \\ \text{vc}^*(\mathcal{F}) &= \limsup_{n \rightarrow \infty} \frac{\log \pi_{\mathcal{F}}^*(n)}{\log n} \in \mathbb{R}^{\geq 0} \cup \{+\infty\}. \end{aligned}$$

Generally speaking a shatter function that is bounded by a polynomial doesn't itself have to be a polynomial. Proposition 4.12 in [1] gives an example of a shatter function that grows like $n \log n$ (so it has vc-density 1).

So far the notions that we have defined are purely combinatorial. We now adapt VC-dimension and vc-density to the model theoretic context.

Definition 1.9. Work in a first-order structure M . Fix a finite collection of formulas $\Phi(x, y)$.

- For $\phi(x, y) \in \mathcal{L}(M)$ and $b \in M^{|y|}$ let

$$\phi(M^{|x|}, b) = \{a \in M^{|x|} \mid \phi(a, b)\} \subseteq M^{|x|}.$$

- Let $\Phi(M^{|x|}, M^{|y|}) = \{\phi(M^{|x|}, b) \mid \phi \in \Phi, b \in M^{|y|}\} \subseteq \mathcal{P}(M^{|x|})$.
- Let $\mathcal{F}_{\Phi} = \Phi(M^{|x|}, M^{|y|})$, giving rise to a set system $(M^{|x|}, \mathcal{F}_{\Phi})$.
- Define the VC-dimension of Φ , $\text{VC}(\Phi)$ to be the VC-dimension of $(M^{|x|}, \mathcal{F}_{\Phi})$, similarly for the dual.
- Define the vc-density of Φ , $\text{vc}(\Phi)$ to be the vc-density of $(M^{|x|}, \mathcal{F}_{\Phi})$, similarly for the dual.

We will also refer to the vc-density and VC-dimension of a single formula ϕ viewing it as a one element collection $\Phi = \{\phi\}$.

Counting atoms of a Boolean algebra in a model theoretic setting corresponds to counting types, so it is instructive to rewrite the shatter function in terms of types.

Definition 1.10.

$$\pi_{\Phi}^*(n) = \max \{\text{number of } \Phi\text{-types over } B \mid B \subset M, |B| = n\}$$

Here a Φ -type over B is a maximal consistent collection of functions of the form $\phi(x, b)$ or $\neg\phi(x, b)$ where $\phi \in \Phi$ and $b \in B$.

Lemma 1.11.

$$\text{vc}^*(\Phi) = \text{degree of polynomial growth of } \pi_\Phi^*(n) = \limsup_{n \rightarrow \infty} \frac{\log \pi_\Phi^*(n)}{\log n}$$

Proof.

$$\begin{aligned} \pi_{\mathcal{F}_\Phi}^*(n) &\leq \pi_\Phi^*(n) \leq \pi_{\mathcal{F}_\Phi}^*(|\Phi|n) \\ \text{vc}^*(\Phi) &\leq \limsup_{n \rightarrow \infty} \frac{\log \pi_\Phi^*(n)}{\log n} \leq \limsup_{n \rightarrow \infty} \frac{\log \pi_{\mathcal{F}_\Phi}^*(|\Phi|n)}{\log n} = \\ &= \limsup_{n \rightarrow \infty} \frac{\log \pi_{\mathcal{F}_\Phi}^*(|\Phi|n)}{\log |\Phi|n} \frac{\log |\Phi|n}{\log n} = \limsup_{n \rightarrow \infty} \frac{\log \pi_{\mathcal{F}_\Phi}^*(|\Phi|n)}{\log |\Phi|n} \leq \\ &\leq \limsup_{n \rightarrow \infty} \frac{\log \pi_{\mathcal{F}_\Phi}^*(n)}{\log n} = \text{vc}^*(\Phi) \end{aligned}$$

□

One can check that the shatter function and hence VC-dimension and vc-density of a formula are elementary notions, so they only depend on the first-order theory of the structure.

NIP theories are a natural context for studying vc-density. In fact we can take the following as the definition of NIP:

Definition 1.12. Define ϕ to be NIP if it has finite VC-dimension. A theory T is NIP if all the formulas are NIP.

In a general combinatorial context for arbitrary set systems, vc-density can be any real number in $0 \cup [1, \infty)$. Less is known if we restrict our attention to NIP theories. Proposition 4.6 in [1] gives examples of formulas that have non-integer rational vc-density in an NIP theory, however it is open whether one can get an irrational vc-density in this model-theoretic setting.

Instead of working with a theory formula by formula, we can look for a uniform bound for all formulas:

Definition 1.13. For a given NIP structure M , define the vc-function

$$\begin{aligned} \text{vc}^M(n) &= \sup\{\text{vc}^*(\phi(x, y)) \mid \phi \in \mathcal{L}(M), |x| = n\} \\ &= \sup\{\text{vc}(\phi(x, y)) \mid \phi \in \mathcal{L}(M), |y| = n\} \end{aligned}$$

As before this definition is elementary, so it only depends on the theory of M . We omit the superscript M if it is understood from the context. One can easily check the following bounds:

Lemma 1.14 (Lemma 3.22 in [1]). *We have $\text{vc}(1) \geq 1$ and $\text{vc}(n) \geq n \text{vc}(1)$.*

However, it is not known whether the second inequality can be strict or even whether $\text{vc}(1) < \infty$ implies $\text{vc}(n) < \infty$.

2. P -ADIC NUMBERS

The field \mathbb{Q}_p of p -adic numbers is often studied in the language of Macintyre

$$\mathcal{L}_{Mac} = \{0, 1, +, -, \cdot, |, \{P_n\}_{n \in \mathbb{N}}\}$$

which is a language $\{0, 1, +, -, \cdot\}$ of fields together with unary predicates P_n interpreted in \mathbb{Q}_p so as to satisfy

$$P_n x \leftrightarrow \exists y \, y^n = x$$

and a divisibility relation where $a|b$ holds in \mathbb{Q}_p when $\text{val } a \leq \text{val } b$.

Note that $P_n \setminus \{0\}$ is a multiplicative subgroup of \mathbb{Q}_p with finitely many cosets.

Theorem 2.1 (Macintyre '76). *The \mathcal{L}_{Mac} -structure \mathbb{Q}_p has quantifier elimination.*

There is also a cell decomposition result:

Definition 2.2. Define k -cell recursively as follows. 0-cell is a singleton subset of \mathbb{Q}_p . A $(k+1)$ -cell is a subset of \mathbb{Q}_p^{k+1} of the following form:

$$\{(x, t) \in D \times \mathbb{Q}_p \mid \text{val } a_1(x) \square_1 \text{val}(t - c(x)) \square_2 \text{val } a_2(x), t - c(x) \in \lambda P_n\}$$

where D is a k -cell, $a_1(x), a_2(x), c(x)$ are definable functions $D \rightarrow \mathbb{Q}_p$, \square_i is $<, \leq$ or no condition, and $\lambda \in \mathbb{Q}_p$.

Theorem 2.3 (Denef '84). *Any definable subset of \mathbb{Q}_p^n defined by an \mathcal{L}_{Mac} -formula decomposes into a finite disjoint union of n -cells.*

In [1], Aschenbrenner, Dolich, Haskell, Macpherson, and Starchenko show that this structure satisfies $\text{vc}(n) \leq 2n - 1$, however it is not known whether this bound is optimal.

In [2], Leenknegt analyzes the reduct of \mathbb{Q}_p to the language

$$\mathcal{L}_{aff} = \left\{ 0, 1, +, -, \{\bar{c}\}_{c \in \mathbb{Q}_p}, |, \{Q_{m,n}\}_{m,n \in \mathbb{N}} \right\}$$

where \bar{c} denotes a scalar multiplication by c , $a|b$ as above stands for $\text{val } a \leq \text{val } b$, and $Q_{m,n}$ is a unary predicate interpreted as

$$Q_{m,n} = \bigcup_{k \in \mathbb{Z}} p^{km} (1 + p^n \mathbb{Z}_p).$$

Note that $Q_{m,n} \setminus \{0\}$ is a subgroup of the multiplicative group of \mathbb{Q}_p with finitely many cosets. One can check that these extra relation symbols are definable in the \mathcal{L}_{Mac} -structure \mathbb{Q}_p . The paper [2] provides a cell decomposition result with the following cells:

Definition 2.4. A 0-cell is a singleton subset of \mathbb{Q}_p . A $(k+1)$ -cell is a subset of \mathbb{Q}_p^{k+1} of the following form:

$$\{(x, t) \in D \times \mathbb{Q}_p \mid \text{val } a_1(x) \square_1 \text{val}(t - c(x)) \square_2 \text{val } a_2(x), t - c(x) \in \lambda Q_{m,n}\}$$

where D is a k -cell, called the base of the cell, $a_1(x), a_2(x), c(x)$ are polynomials of degree ≤ 1 , called the defining polynomials \square_1, \square_2 is $<$ or no condition, and $\lambda \in \mathbb{Q}_p$. We call $\mathbb{Q}_{m,n}$ the defining predicate.

Theorem 2.5 (Leenknecht '12). *Any definable subset of \mathbb{Q}_p^n defined by an \mathcal{L}_{aff} -formula decomposes into a finite disjoint union of n -cells.*

Moreover, [2] shows that $(\mathbb{Q}_p, \mathcal{L}_{aff})$ is a P -minimal reduct, that is, the one-dimensional definable sets of $(\mathbb{Q}_p, \mathcal{L}_{aff})$ coincide with the one-dimensional definable sets in the full structure $(\mathbb{Q}_p, \mathcal{L}_{Mac})$.

The main result of this paper is the computation of the vc-function for this structure:

Theorem 2.6. *$(\mathbb{Q}_p, \mathcal{L}_{aff})$ has $vc(n) = n$.*

3. KEY LEMMAS AND DEFINITIONS

To show that $vc(n) = n$ it suffices to bound $vc^*(\phi) \leq |x|$ for every \mathcal{L}_{aff} -formula $\phi(x; y)$. Fix such a formula $\phi(x; y)$. Instead of working with it directly, we simplify it using quantifier elimination. The required quantifier elimination result can be easily obtained from cell decomposition:

Lemma 3.1. *Any formula $\phi(x; y)$ in $(\mathbb{Q}_p, \mathcal{L}_{aff})$ can be written as a boolean combination of formulas from the following collection*

$$\begin{aligned} \Phi(x; y) = & \{ \text{val}(p_i(x) - c_i(y)) < \text{val}(p_j(x) - c_j(y)) \}_{i,j \in I} \cup \\ & \{ p_i(x) - c_i(y) \in \lambda_k \mathbb{Q}_{m,n} \}_{i \in I, k \in K} \end{aligned}$$

where I, K are finite index sets, each p_i is a degree ≤ 1 polynomial in x without a constant term, each c_i is a degree ≤ 1 polynomial in y , and $\lambda_k \in \mathbb{Q}_p$.

Proof. Let $l = |x| + |y|$. Partition the subset of \mathbb{Q}_p^l defined by ϕ to obtain \mathcal{D}^l , a collection of l -cells. Let \mathcal{D}^{l-1} be the collection of the bases of the cells in \mathcal{D}^l . Similarly, construct by induction \mathcal{D}^j for each $0 \leq j < l$, where \mathcal{D}^j is the collection

of j -cells which are the bases of cells in \mathcal{D}^{j+1} .

$$m = \prod \{m' \mid Q_{m',n'} \text{ is the defining predicate of a cell in } \mathcal{D}^j \text{ for } 0 \leq j \leq l\}$$

$$n = \max \{n' \mid Q_{m',n'} \text{ is the defining predicate of a cell in } \mathcal{D}^j \text{ for } 0 \leq j \leq l\}$$

This way if a, a' are in the same coset of $Q_{m',n'}$ then they are in the same coset of $Q_{m,n}$. Choose $\{\lambda_k\}_{k \in K}$ to go over all the cosets of $Q_{m,n}$. Let $q_i(x, y)$ enumerate all of the defining polynomials $a_1(x), a_2(x), t - c(x)$ that show up in the cells of \mathcal{D}^j for any j . All if those are all polynomials of degree ≤ 1 in variables x, y . We can split each of them as $q_i(x, y) = p_i(x) - c_i(y)$ where the constant term goes into c_i . This gives us the appropriate finite collection of formulas Φ . From the cell decomposition it is easy to see that when a, a' have the same Φ -type, then they have the same ϕ -type. Thus ϕ can be written as a boolean combination of formulas from Φ . \square

Lemma 3.2. *Let $\Phi(x; y)$ be a finite collection of formulas. If ϕ can be written as a boolean combination of formulas from Φ then*

$$\text{vc}^*(\Phi) \leq r \implies \text{vc}^*(\phi) \leq r \text{ for all } r \in \mathbb{R}$$

Proof. If a, a' have the same Φ -type over B , then they have the same ϕ -type over B , where B is some parameter set. Therefore the number of ϕ -types is bounded by the number of Φ -types. The bound follows from Lemma 1.11. \square

For the remainder of the paper fix $\Phi(x; y)$ to be the collection of formulas defined by Lemma 3.1. By the previous lemma, to show that $\text{vc}^*(\phi) \leq |x|$, it suffices to bound $\text{vc}^*(\Phi) \leq |x|$. More precisely, it is sufficient to show that if there is a parameter set B of size N then the number of Φ -types over B is $O(N^{|x|})$. Fix such a parameter set B and work with it from now on. We will compute a bound for the number of Φ -types over B .

Consider a set $T = T(\Phi, B) = \{c_i(b) \mid b \in B, i \in I\} \subset \mathbb{Q}_p$. In this definition B is the parameter set that we have fixed and $c_i(b)$ come from the collection of formulas Φ from the quantifier elimination above. View T as a tree as follows:

Definition 3.3.

- For $c \in \mathbb{Q}_p, \alpha \in \mathbb{Z}$ define a ball

$$B(c, \alpha) = \{c' \in \mathbb{Q}_p \mid \text{val}(c' - c) > \alpha\}.$$

We also let $B(c, -\infty) = \mathbb{Q}_p$ and $B(c, +\infty) = \emptyset$.

- Define a collection of balls $\mathcal{B} = \{B(t_1, \text{val}(t_1 - t_2))\}_{t_1, t_2 \in T}$. Note that \mathcal{B} is a (directed) boolean algebra of sets in \mathbb{Q}_p . We refer to the atoms in that algebra as intervals. Note that the intervals partition \mathbb{Q}_p so any element $a \in \mathbb{Q}_p$ belongs to a unique interval.
- Let's introduce some notation for the intervals. For $t \in T$ and $\alpha_L, \alpha_U \in \mathbb{Z} \cup \{-\infty, +\infty\}$ define

$$I(t, \alpha_L, \alpha_U) = B(t, \alpha_L) \setminus \bigcup \{B(t', \alpha_U) \mid t' \in T, \text{val}(t' - t) \geq \alpha_U\}$$

(this is sometimes referred to as the swiss cheese construction). One can check that every interval is of the form $I(t, \alpha_L, \alpha_U)$ for some values of t, α_L, α_U . Quantities α_L, α_U are uniquely determined by the interval, while t might not be.

- Intervals are a natural construction for trees, however we will require a more refined notion to make Lemma 3.12 below work. Define a larger collection of balls

$$\mathcal{B}' = \mathcal{B} \cup \{B(c_i(b), \text{val}(c_j(b) - c_k(b)))\}_{i,j,k \in I, b \in B}.$$

Similar to the previous definition, we define a subinterval to be an atom of the boolean algebra generated by \mathcal{B}' . Subintervals refine intervals. Moreover, as before, each subinterval can be written as $I(t, \alpha_L, \alpha_U)$ for some

values of t, α_L, α_U . As before, α_L, α_U are uniquely determined by the subinterval, while t might not be.

Subintervals are fine enough to make Lemma 3.12 below work while coarse enough to be $O(N)$ small:

Lemma 3.4.

- *There are at most $2|T| = 2N|I| = O(N)$ different intervals.*
- *There are at most $2|T| + |B| \cdot |I|^3 = O(N)$ different subintervals.*

Proof. Each new element in the tree T adds at most two intervals to the total count, so by induction there can be at most $2|T|$ many intervals. Each new ball in $\mathcal{B}' \setminus \mathcal{B}$ adds at most one subinterval to the total count, so by induction there are at most $|\mathcal{B}' \setminus \mathcal{B}|$ more subintervals than there are intervals. \square

Definition 3.5. Suppose $a \in \mathbb{Q}_p$ lies in an interval $I(t, \alpha_L, \alpha_U)$. Define the T-valuation of a to be $\text{T-val}(a) = \text{val}(a - t)$.

This is a natural notion having the following properties:

Lemma 3.6.

- (a) $\text{T-val}(a)$ is well-defined, independent of choice of t to represent the interval.
- (b) If $a \in \mathbb{Q}_p$ lies in a subinterval $I(t, \alpha_L, \alpha_U)$, then $\text{T-val}(a) = \text{val}(a - t)$.
- (c) If $a \in \mathbb{Q}_p$ lies in a (sub)interval $I(t, \alpha_L, \alpha_U)$ then $\alpha_L < \text{T-val}(a) \leq \alpha_U$.
- (d) For any $a \in \mathbb{Q}_p$ lying in a (sub)interval $I(t, \alpha_L, \alpha_U)$ and $t' \in T$
 - If $\text{val}(t - t') \geq \alpha_U$, then $\text{val}(a - t') = \text{T-val}(a)$.
 - If $\text{val}(t - t') \leq \alpha_L$, then $\text{val}(a - t') = \text{val}(t - t') (\leq \alpha_L < \text{T-val}(a))$.

Proof. (a)-(c) are clear. For (d) fix $t' \in T$ and suppose $a \in \mathbb{Q}_p$ lies in a subinterval $I(t, \alpha'_L, \alpha'_U)$. This subinterval lies inside of an interval $I(t, \alpha_L, \alpha_U)$ for some choice of α_L, α_U and by the definition of intervals (or more specifically \mathcal{B})

$$\text{val}(t - t') \geq \alpha_U \iff \text{val}(t - t') \geq \alpha'_U$$

$$\text{val}(t - t') \geq \alpha_L \iff \text{val}(t - t') \geq \alpha'_L.$$

Therefore without loss of generality we may assume that $a \in \mathbb{Q}_p$ lies in an interval $I(t, \alpha_L, \alpha_U)$. By (c) and the definition of intervals one of the three following cases has to hold.

Case 1: $\text{val}(t - t') \geq \alpha_U$ and $\text{T-val}(a) < \alpha_U$. Then

$$\text{val}(t - t') \geq \alpha_U > \text{T-val}(a) = \text{val}(a - t),$$

thus $\text{val}(a - t') = \text{val}(a - t) = \text{T-val}(a)$ as needed.

Case 2: $\text{val}(t - t') \geq \alpha_U$ and $\text{T-val}(a) = \alpha_U$. Then

$$\text{T-val}(a) = \text{val}(a - t) = \text{val}(t - t') \geq \alpha_U,$$

thus $\text{val}(a - t') \geq \alpha_U$. The interval $I(t, \alpha_L, \alpha_U)$ is disjoint from the ball $B(t', \alpha_U)$, so $a \notin B(t', \alpha_U)$, that is, $\text{val}(a - t') \leq \alpha_U$. Combining this with the previous inequality we get that $\text{val}(a - t') = \alpha_U = \text{T-val}(a)$ as needed.

Case 3: $\text{val}(t - t') \leq \alpha_L$. Then

$$\text{val}(t - t') \leq \alpha_L < \text{T-val}(a) = \text{val}(a - t),$$

thus $\text{val}(a - t') = \text{val}(t - t')$ as needed. □

Definition 3.7. Suppose $a \in \mathbb{Q}_p$ lies in a subinterval $I(t, \alpha_L, \alpha_U)$. We say that a is far from the boundary (of $I(t, \alpha_L, \alpha_U)$) if

$$\alpha_L + n \leq \text{T-val}(a) \leq \alpha_U - n.$$

Here n is from the Lemma 3.1. Otherwise we say that it is close to the boundary.

Definition 3.8. Suppose $a_1, a_2 \in \mathbb{Q}_p$ lie in the same subinterval $I(t, \alpha_L, \alpha_U)$. We say a_1, a_2 have the same subinterval type if one of the following holds:

- Both a_1, a_2 are far from the boundary and $a_1 - t, a_2 - t$ are in the same $Q_{m,n}$ -coset. ($Q_{m,n}$ is from the Lemma 3.1.)

- Both a_1, a_2 are close to the boundary and

$$\text{T-val}(a_1) = \text{T-val}(a_2) \leq \text{val}(a_1 - a_2) - n.$$

Definition 3.9. For $c \in \mathbb{Q}_p$ and $\alpha, \beta \in \mathbb{Z}, \alpha < \beta$ define $c \upharpoonright [\alpha, \beta) \in (\mathbb{Z}/p\mathbb{Z})^{\beta-\alpha}$ to be the record of the coefficients of c for the valuations between $[\alpha, \beta)$. More precisely write c in its power series form

$$c = \sum_{\gamma \in \mathbb{Z}} c_\gamma p^\gamma \text{ with } c_\gamma \in \{0, 1, \dots, p-1\}$$

Then $c \upharpoonright [\alpha, \beta)$ is just $(c_\alpha, c_{\alpha+1}, \dots, c_{\beta-1})$.

The following lemma is an adaptation of Lemma 7.4 in [1].

Lemma 3.10. Fix $m, n \in \mathbb{N}$. For any $x, y, c \in \mathbb{Q}_p$, if

$$\text{val}(x - c) = \text{val}(y - c) \leq \text{val}(x - y) - n,$$

then $x - c, y - c$ are in the same coset of $Q_{m,n}$.

Proof. Call $a, b \in \mathbb{Q}_p$ similar if $\text{val } a = \text{val } b$ and

$$a \upharpoonright [\text{val } a, \text{val } a + n) = b \upharpoonright [\text{val } b, \text{val } b + n)$$

If a, b are similar then

$$a \in Q_{m,n} \iff b \in Q_{m,n}$$

Moreover for any $\lambda \in \mathbb{Q}_p^\times$, if a, b are similar then so are $\lambda a, \lambda b$. Thus if a, b are similar, then they belong to the same coset of $Q_{m,n}$. Conditions of the lemma force $x - c, y - c$ to be similar, thus belonging to the same coset. \square

Lemma 3.11. For each subinterval there are at most $K = K(Q_{m,n})$ many subinterval types (with K not depending on B or on the subinterval).

Proof. Let $a, a' \in \mathbb{Q}_p$ lie in the same subinterval $I(t, \alpha_L, \alpha_U)$.

Suppose a, a' are far from the boundary. Then they have the same subinterval type if $a - t, a' - t$ are in the same $Q_{m,n}$ -coset. The number of such subinterval types is bounded by the number of $Q_{m,n}$ -cosets.

Suppose a, a' are close to the boundary and

$$\text{T-val}(a) - \alpha_L = \text{T-val}(a') - \alpha_L < n \text{ and}$$

$$a \upharpoonright [\text{T-val}(a), \text{T-val}(a) + n] = a' \upharpoonright [\text{T-val}(a'), \text{T-val}(a') + n]$$

Then a, a' have the same subinterval type. Such a subinterval type is thus determined by $\text{T-val}(a) - \alpha_L$ and $a \upharpoonright [\text{T-val}(a), \text{T-val}(a) + n]$, therefore there are at most np^n many such types.

A similar argument works for a with $\alpha_U - \text{T-val}(a) \leq n$.

Adding those up we get that there are at most

$$K = (\text{number of } Q_{m,n} \text{ cosets}) + 2np^n$$

many subinterval types. □

The following critical lemma relates tree notions to Φ -types.

Lemma 3.12. *Suppose $d, d' \in \mathbb{Q}_p^{|x|}$ satisfy the following three conditions:*

- *For all $i \in I$ $p_i(d)$ and $p_i(d')$ are in the same subinterval.*
- *For all $i \in I$ $p_i(d)$ and $p_i(d')$ have the same subinterval type.*
- *For all $i, j \in I$, $\text{T-val}(p_i(d)) > \text{T-val}(p_j(d))$ iff $\text{T-val}(p_i(d')) > \text{T-val}(p_j(d'))$.*

Then d, d' have the same Φ -type over B .

Proof. There are two kinds of formulas in Φ (see Lemma 3.1). First we show that d, d' agree on formulas of the form $p_i(x) - c_i(y) \in \lambda_k Q_{m,n}$. It is enough to show that for every $i \in I, b \in B$, $p_i(d) - c_i(b), p_i(d') - c_i(b)$ are in the same $Q_{m,n}$ -coset. Fix such i, b . For brevity let $a = p_i(d), a' = p_i(d')$ and $Q = Q_{m,n}$. We want to show that $a - c_i(b), a' - c_i(b)$ are in the same Q -coset.

Suppose a, a' are close to the boundary. Then $\text{T-val}(a) = \text{T-val}(a') \leq \text{val}(a - a') - n$. Using Lemma 3.6d, we have

$$\text{val}(a - c_i(b)) = \text{val}(a' - c_i(b)) \leq \text{T-val}(a) \leq \text{val}(a - a') - n.$$

Lemma 3.10 shows that $a - c_i(b), a' - c_i(b)$ are in the same Q -coset.

Now, suppose both a, a' are far from the boundary. Label their interval as $I(t, \alpha_L, \alpha_U)$. Then we have

$$\alpha_L + n \leq \text{val}(a - t) \leq \alpha_U - n$$

$$\alpha_L + n \leq \text{val}(a' - t) \leq \alpha_U - n$$

(as being far from the subinterval's boundary also makes a, a' far from interval's boundary). We have either $\text{val}(t - c_i(b)) \geq \alpha_U$ or $\text{val}(t - c_i(b)) \leq \alpha_L$ (as otherwise it would contradict the definition of intervals, or more specifically \mathcal{B}).

Suppose it is the first case $\text{val}(t - c_i(b)) \geq \alpha_U$. Then using Lemma 3.6d

$$\text{val}(a - c_i(b)) = \text{val}(a - t) \leq \alpha_U - n \leq \text{val}(t - c_i(b)) - n.$$

So by Lemma 3.10 $a - c_i(b), a - t$ are in the same Q -coset. By an analogous argument, $a' - c_i(b), a' - t$ are in the same Q -coset. As a, a' have the same subinterval type, $a - t, a' - t$ are in the same Q -coset. Thus by transitivity we get that $a - c_i(b), a' - c_i(b)$ are in the same Q -coset.

For the second case, suppose $\text{val}(t - c_i(b)) \leq \alpha_L$. Then using Lemma 3.6d

$$\text{val}(a - c_i(b)) = \text{val}(t - c_i(b)) \leq \alpha_L \leq \text{val}(a - t) - n,$$

so by Lemma 3.10, $a - c_i(b), t - c_i(b)$ are in the same Q -coset. Similarly $a' - c_i(b), t - c_i(b)$ are in the same Q -coset. Thus by transitivity we get that $a - c_i(b), a' - c_i(b)$ are in the same Q -coset.

Next, we need to show that d, d' agree on formulas of the form $\text{val}(p_i(x) - c_i(y)) < \text{val}(p_j(x) - c_j(y))$ (again, referring to the presentation in Lemma 3.1). Fix $i, j \in I, b \in B$. We would like to show the following equivalence:

(3.1)

$$\text{val}(p_i(d) - c_i(b)) < \text{val}(p_j(d) - c_j(b)) \iff \text{val}(p_i(d') - c_i(b)) < \text{val}(p_j(d') - c_j(b))$$

Suppose $p_i(d), p_i(d')$ are in the subinterval $I(t_i, \alpha_i, \beta_i)$ and $p_j(d), p_j(d')$ are in the subinterval $I(t_j, \alpha_j, \beta_j)$. Lemma 3.6d yields the following four cases.

Case 1:

$$\begin{aligned} \text{val}(p_i(d) - c_i(b)) &= \text{val}(p_i(d') - c_i(b)) = \text{val}(t_i - c_i(b)) \\ \text{val}(p_j(d) - c_j(b)) &= \text{val}(p_j(d') - c_j(b)) = \text{val}(t_j - c_j(b)) \end{aligned}$$

Then it is clear that the equivalence (3.1) holds.

Case 2:

$$\begin{aligned} \text{val}(p_i(d) - c_i(b)) &= \text{T-val}(p_i(d)) \text{ and } \text{val}(p_i(d') - c_i(b)) = \text{T-val}(p_i(d')) \\ \text{val}(p_j(d) - c_j(b)) &= \text{T-val}(p_j(d)) \text{ and } \text{val}(p_j(d') - c_j(b)) = \text{T-val}(p_j(d')) \end{aligned}$$

Then the equivalence (3.1) holds by the third hypothesis of the lemma (that order of T-valuations is preserved).

Case 3:

$$\begin{aligned} \text{val}(p_i(d) - c_i(b)) &= \text{val}(p_i(d') - c_i(b)) = \text{val}(t_i - c_i(b)) \\ \text{val}(p_j(d) - c_j(b)) &= \text{T-val}(p_j(d)) \text{ and } \text{val}(p_j(d') - c_j(b)) = \text{T-val}(p_j(d')) \end{aligned}$$

If $p_j(d), p_j(d')$ are close to the boundary, then $\text{T-val}(p_j(d)) = \text{T-val}(p_j(d'))$ and the equivalence (3.1) clearly holds. Suppose then that $p_j(d), p_j(d')$ are far from the

boundary.

$$\alpha_j + n \leq \text{T-val}(p_j(d)), \text{T-val}(p_j(d')) \leq \beta_j - n$$

$$\alpha_j < \text{T-val}(p_j(d)), \text{T-val}(p_j(d')) < \beta_j$$

and $\text{val}(t_i - c_i(b))$ lies outside of the (α_j, β_j) by the definition of subinterval (more specifically definition of \mathcal{B}'). Therefore (3.1) has to hold. (Note that we always have $\text{T-val}(p_j(d)), \text{T-val}(p_j(d')) \in (\alpha_j, \beta_j]$ by Lemma 3.6c, so we only need the far from the boundary condition to avoid the edge case of equality to β_j .)

Case 4:

$$\text{val}(p_i(d) - c_i(b)) = \text{T-val}(p_i(d)) \text{ and } \text{val}(p_i(d') - c_i(b)) = \text{T-val}(p_i(d'))$$

$$\text{val}(p_j(d) - c_j(b)) = \text{val}(p_j(d') - c_j(b)) = \text{val}(t_j - c_j(b))$$

Similar to case 3 (switching i, j). □

Note 3.13. The previous lemma gives us an upper bound on the number of types - there are at most $|2I|!$ many choices for the order of T-val, $O(N)$ many choices for the subinterval for each p_i , and K many choices for the subinterval type for each p_i (where K is as in Lemma 3.11), giving a total of $O(N^{|I|}) \cdot K^{|I|} \cdot |I|! = O(N^{|I|})$ many types. This implies $\text{vc}^*(\Phi) \leq |I|$. The biggest contribution to this bound are the choices among the $O(N)$ many subintervals for each p_i with $i \in I$. Are all of those choices realized? Intuitively there are $|x|$ many variables and $|I|$ many equations, so once we choose a subinterval for $|x|$ many p_i 's, the subintervals for the rest should be determined. This would give the required bound $\text{vc}^*(\Phi) \leq |x|$. The next section outlines this idea formally.

4. MAIN PROOF

An alternative way to write $p_i(c)$ is as a scalar product $\vec{p}_i \cdot \vec{c}$, where \vec{p}_i and \vec{c} are vectors in $\mathbb{Q}_p^{|x|}$ (as $p_i(x)$ is homogeneous linear).

Lemma 4.1. *Suppose we have a finite collection of vectors $\{\vec{p}_j\}_{j \in J}$ with each $\vec{p}_j \in \mathbb{Q}_p^{|x|}$. Suppose $\vec{p} \in \mathbb{Q}_p^{|x|}$ satisfies $\vec{p} \in \text{span}\{\vec{p}_j\}_{j \in J}$, and we have $\vec{c} \in \mathbb{Q}_p^{|x|}, \alpha \in \mathbb{Z}$ with $\text{val}(\vec{p}_j \cdot \vec{c}) > \alpha$ for all $j \in J$. Then $\text{val}(\vec{p} \cdot \vec{c}) > \alpha - \gamma$ for some $\gamma \in \mathbb{N}$. Moreover γ can be chosen independently from \vec{c}, α depending only on $\{\vec{p}_j\}_{j \in J}$.*

Proof. For some $c_j \in \mathbb{Q}_p$ for $j \in J$ we have $\vec{p} = \sum_{j \in J} c_j \vec{p}_j$, hence $\vec{p} \cdot \vec{c} = \sum_{j \in J} c_j \vec{p}_j \cdot \vec{c}$.

Thus

$$\text{val}(c_j \vec{p}_j \cdot \vec{c}) = \text{val}(c_j) + \text{val}(\vec{p}_j \cdot \vec{c}) > \text{val}(c_j) + \alpha.$$

Let $\gamma = \max(0, -\max_{j \in J} \text{val}(c_j))$. Then we have

$$\begin{aligned} \text{val}(\vec{p} \cdot \vec{c}) &= \text{val}\left(\sum_{j \in J} c_j \vec{p}_j \cdot \vec{c}\right) \geq \\ &\geq \min_{j \in J} \text{val}\left(\sum_{j \in J} c_j \vec{p}_j \cdot \vec{c}\right) > \min_{j \in J} \text{val}(c_j) + \alpha \geq \alpha - \gamma \end{aligned}$$

□

Corollary 4.2. *Suppose we have a finite collection of vectors $\{\vec{p}_i\}_{i \in I}$ with each $\vec{p}_i \in \mathbb{Q}_p^{|x|}$. Suppose $J \subset I$ and $i \in I$ satisfy $\vec{p}_i \in \text{span}\{\vec{p}_j\}_{j \in J}$, and we have $\vec{c} \in \mathbb{Q}_p^{|x|}, \alpha \in \mathbb{Z}$ with $\text{val}(\vec{p}_j \cdot \vec{c}) > \alpha$ for all $j \in J$. Then $\text{val}(\vec{p}_i \cdot \vec{c}) > \alpha - \gamma$ for some $\gamma \in \mathbb{N}$. Moreover γ can be chosen independently from J, j, \vec{c}, α depending only on $\{\vec{p}_i\}_{i \in I}$.*

Proof. The previous lemma shows that we can pick such γ for a given choice of i, J , but independent from α, \vec{c} . To get a choice independent from i, J , go over all such eligible choices (i ranges over I and J ranges over subsets of I), pick γ for each, and then take the maximum of those values. □

Fix γ according to Corollary 4.2 corresponding to $\{\vec{p}_i\}_{i \in I}$ given by our collection of formulas Φ . (The lemma above is a general result, but we only use it applied to the vectors given by Φ .)

Definition 4.3. Suppose $a \in \mathbb{Q}_p$ lies in the subinterval $I(t, \alpha_L, \alpha_U)$. Define T -floor of a to be $F(a) = \alpha_L$.

Definition 4.4. Let $f : \mathbb{Q}_p^{|x|} \rightarrow \mathbb{Q}_p^I$ with $f(c) = (p_i(c))_{i \in I}$. Define the segment space Sg to be the image of f .

Given a tuple $(a_i)_{i \in I}$ in the segment space, look at the corresponding T -floors $\{F(a_i)\}_{i \in I}$ and T -valuations $\{\text{T-val}(a_i)\}_{i \in I}$. Partition the segment space by the order types of $\{F(a_i)\}_{i \in I}$ and $\{\text{T-val}(a_i)\}_{i \in I}$ (as subsets of \mathbb{Z}).

Work in a fixed set Sg' of the partition. After relabeling we may assume that

$$F(a_1) \geq F(a_2) \geq \dots \text{ for all } a_i \in \text{Sg}'$$

Consider the (relabelled) sequence of vectors $\vec{p}_1, \vec{p}_2, \dots, \vec{p}_I$. There is a unique subset $J \subset I$ such that all vectors with indices in J are linearly independent, and all vectors with indices outside of J are a linear combination of preceding vectors. For any index $i \in I$ we call it independent if $i \in J$ and we call it dependent otherwise.

Definition 4.5.

- Denote $\mathbb{Z}/p\mathbb{Z}^\gamma$ as Ct. Note that $|\text{Ct}| = p^\gamma$.
- Let Tp be the space of all subinterval types. By Lemma 3.11 $|\text{Tp}| \leq K$.
- Let Sub be the space of all subintervals. By Lemma 3.4 $|\text{Sub}| \leq 3|I|^2 \cdot N = O(N)$.

Definition 4.6. Now, we define the following function

$$g_{\text{Sg}'} : \text{Sg}' \rightarrow \text{Tp}^I \times \text{Sub}^J \times \text{Ct}^{I \setminus J}$$

Let $a = (a_i)_{i \in I} \in \text{Sg}'$. To define $g_{\text{Sg}'}(a)$ we need to specify where it maps a in each individual component of the product.

For each a_i record its subinterval type, giving the first component Tp^I .

For a_j with $j \in J$, record the subinterval of a_j , giving the second component Sub^J .

For the third component $\text{Ct}^{I \setminus J}$ do the following computation. Pick a_i with i dependent. Let j be the largest independent index with $j < i$. Record $a_i \upharpoonright [F(a_j) - \gamma, F(a_j))$.

Combine $g_{\text{Sg}'}$ for all the partitions to get a function

$$g : \text{Sg} \longrightarrow \text{Tp}^I \times \text{Sub}^J \times \text{Ct}^{I \setminus J}.$$

Lemma 4.7. *Suppose we have $c, c' \in \mathbb{Q}_p^{|x|}$ such that $f(c), f(c')$ are in the same partition and $g(f(c)) = g(f(c'))$. Then c, c' have the same Φ -type over B .*

Proof. Let $a_i = \vec{p}_i \cdot \vec{c}$ and $a'_i = \vec{p}_i \cdot \vec{c}'$ so that

$$\begin{aligned} f(c) &= (p_i(c))_{i \in I} = (\vec{p}_i \cdot \vec{c})_{i \in I} = (a_i)_{i \in I} \\ f(c') &= (p_i(c'))_{i \in I} = (\vec{p}_i \cdot \vec{c}')_{i \in I} = (a'_i)_{i \in I} \end{aligned}$$

For each i we show that a_i, a'_i are in the same subinterval and have the same subinterval type, so the conclusion follows by Lemma 3.12 ($f(c), f(c')$ are in the same partition ensuring the proper order of T-valuations for the 3rd condition of the lemma). Tp records the subinterval type of each element, so if $g(\bar{a}) = g(\bar{a}')$ then a_i, a'_i have the same subinterval type for all $i \in I$. Thus it remains to show that a_i, a'_i lie in the same subinterval for all $i \in I$. Suppose i is an independent index. Then by construction, Sub records the subinterval for a_i, a'_i , so those have to belong to the same subinterval. Now suppose i is dependent. Pick the largest $j < i$ such that j is independent. We have $F(a_i) \leq F(a_j)$ and $F(a'_i) \leq F(a'_j)$. Moreover $F(a_j) = F(a'_j)$ as a_j, a'_j lie in the same subinterval (using the earlier part of the argument as j is independent).

Claim 4.8. $\text{val}(a_i - a'_i) > F(a_j) - \gamma$

Proof. Let K be the set of the independent indices less than i . Note that by the definition for dependent indices we have $\vec{p}_i \in \text{span}\{\vec{p}_k\}_{k \in K}$. We also have

$$\text{val}(a_k - a'_k) > F(a_k) \text{ for all } k \in K$$

as a_k, a'_k lie in the same subinterval (using the earlier part of the argument as k is independent).

$$\text{val}(a_k - a'_k) > F(a_j) \text{ for all } k \in K \text{ by monotonicity of } F(a_k)$$

$$\text{val}(\vec{p}_k \cdot \vec{c} - \vec{p}_k \cdot \vec{c}') > F(a_j) \text{ for all } k \in K$$

$$\text{val}(\vec{p}_k \cdot (\vec{c} - \vec{c}')) > F(a_j) \text{ for all } k \in K$$

$K \subset I, i \in I, \vec{c} - \vec{c}' \in \mathbb{Q}_p^{|x|}, F(a_j) \in \mathbb{Z}$ satisfy the requirements of Lemma 4.2, so we apply it to conclude

$$\text{val}(\vec{p}_i \cdot (\vec{c} - \vec{c}')) > F(a_j) - \gamma$$

$$\text{val}(\vec{p}_i \cdot \vec{c} - \vec{p}_i \cdot \vec{c}') > F(a_j) - \gamma$$

$$\text{val}(a_i - a'_i) > F(a_j) - \gamma$$

as needed, finishing the proof of the claim. \square

Additionally a_i, a'_i have the same image in Ct component, so we have

$$\text{val}(a_i - a'_i) > F(a_j)$$

We now would like to show that a_i, a'_i lie in the same subinterval. As $F(a_i) \leq F(a_j)$, $F(a'_i) \leq F(a'_j)$ and $F(a_j) = F(a'_j)$ we have that $\text{val}(a_i - a'_i) > F(a_i)$ and $\text{val}(a_i - a'_i) > F(a'_i)$. Suppose that a_i lies in the subinterval $I(t, F(a_i), \alpha_U)$ and that a'_i lies in the subinterval $I(t', F(a'_i), \alpha'_U)$. Without loss of generality assume that

$F(a_i) \leq F(a'_i)$. As $\text{val}(a_i - a'_i) > F(a'_i)$, this implies that

$$a_i \in B(a'_i, F(a'_i))$$

$$a_i \in B(t', F(a'_i))$$

$$B(t, F(a_i)) \cap B(t', F(a'_i)) \neq \emptyset$$

$$B(t, F(a_i)) \subset B(t', F(a'_i))$$

For the subintervals to be disjoint we need $I(t, F(a_i), \alpha_U) \cap B(t', F(a'_i)) = \emptyset$. But $\text{val}(t' - a_i) > F(a'_i)$ implying that $a_i \in I(t, F(a_i), \alpha_U) \cap B(t', F(a'_i))$ giving a contradiction. Therefore the subintervals coincide finishing the proof. \square

Corollary 4.9. $\Phi(x, y)$ has dual vc-density $\leq |x|$.

Proof. Suppose we have $c, c' \in \mathbb{Q}_p^{|x|}$ such that $f(c), f(c')$ are in the same partition and $g(f(c)) = g(f(c'))$. Then by the previous lemma c, c' have the same Φ -type. Thus the number of possible Φ -types is bounded by the size of the range of g times the number of possible partitions

$$(\text{number of partitions}) \cdot |\text{Tp}|^{|I|} \cdot |\text{Sub}|^{|J|} \cdot |\text{Ct}|^{|I-J|}$$

There are at most $(|2I|!)^2$ many partitions of Sg, so in the product above, the only component dependent on B is

$$|\text{Sub}|^{|J|} \leq (N \cdot 3|I|^2)^{|J|} = O(N^{|J|})$$

Every p_i is an element of a $|x|$ -dimensional vector space, so there can be at most $|x|$ many independent vectors. Thus we have $|J| \leq |x|$ and the bound follows. \square

Corollary 4.10 (Theorem 2.6). $\mathcal{L}_{aff}\text{-structure } \mathbb{Q}_p$ has $\text{vc}(n) = n$.

Proof. The previous lemma implies that $\text{vc}^*(\phi) \leq \text{vc}^*(\Phi) \leq |x|$. As choice of ϕ was arbitrary, this implies that the vc-density of any formula is bounded by the arity of x . \square

This proof relies heavily on the linearity of functions a_1, a_2, c in the cell decomposition result (see Definition 2.4). Linearity is used to separate x and y variables as well as for Corollary 4.2 to reduce the number of independent factors from $|I|$ to $|x|$. The paper [2] has cell decomposition results for more expressive reducts of \mathbb{Q}_p , including, for example, restricted multiplication. While our results don't apply to it directly, it is this author's hope that similar techniques can be used to compute $\text{vc}(n)$ function for those structures.

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