

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

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ABSTRACT. [1] computed a bound $2n + 1$ for the VC function in p-adic numbers, but it is not known to be optimal. I investigate a C-minimal additive reduct of p-adic numbers and using techniques of [2] I compute an optimal bound n for that structure.

VC density was introduced in [1] by Aschenbrenner, Dolich, Haskell, MacPherson, and Starchenko as a natural notion of dimension for NIP theories. In a NIP theory we can define the VC function

$$\text{vc} : \mathbb{N} \longrightarrow \mathbb{N}$$

where $\text{vc}(n)$ measures complexity of the definable sets in an n -dimensional space. The simplest possible behavior is $\text{vc}(n) = n$ for all n . [1] computes an upper bound for this function to be $2n + 1$, and it is not known whether it is optimal. This same bound would hold in any reduct of p-adic numbers, so one may hope that the simplified structure of the reduct would allow a better bound. In [2], Leenknegt provides a cell decomposition result for the C-minimal additive reduct of p-adic numbers. Using that I'm able to improve the bound for the VC function, showing that $\text{vc}(n) = n$.

1. CELL DECOMPOSITION

We work with the reduct of p-adic numbers in the language $\mathcal{L}_R = \{\mathbb{Q}_p, \{Q_{n,m}\}_{n,m \in \mathbb{N}}, +, -, \{\bar{c}\}_{c \in K}\}$, where \bar{c} is a scalar multiplication by c , and $Q_{n,m}$ is a unary predicate.

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

[2] provides a cell decomposition result for this structure. Any formula $\phi(t, x)$ with t singleton decomposes as the union of the following cells:

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

where D is a cell of a smaller dimension, a_1, a_2, c are linear polynomials in x , \square is $<$ or no condition, $\lambda \in \mathbb{Q}_p$.

Lemma 1.1. *For a formula $\phi(x)$ with $x = (t, \bar{x})$ there exists a family of formulas $\Psi'(x)$*

$$\begin{aligned} \text{val}(q_i(x)) &< \text{val}(q_j(x)) & i, j \in I \\ \text{val}(q_i(x)) &\in \lambda_k Q_{n,m} & i \in I, k \in K \\ \bar{x} &\in D_l & l \in L \end{aligned}$$

with I, K, L finite, D_l cells, q_i linear polynomials, $\lambda_k \in \mathbb{Q}_p$, and $Q = Q_{n,m}$ for some n, m . Moreover we have that if $a, a' \in Q_p^{|x|}$ agree on all the formulas from Ψ' then they agree on ϕ .

Proof. To see that, apply cell decomposition theorem to $\phi(t, \bar{x})$. Let q_i enumerate all of the polynomials $a_1(\bar{x}), a_2(\bar{x}), t - c(\bar{x})$ that show up in the cells. Let D_l be the smaller cells for the \bar{x} components that appear in the cells. Choose n, m large enough to cover all n', m' that come up in the cells for $Q_{n', m'}$. Choose λ_k to go over all the cosets of $Q_{n,m}$. \square

Applying this lemma inductively to smaller cells, we obtain a family $\Psi(x)$

$$\begin{aligned} \text{val}(q_i(x)) &< \text{val}(q_j(x)) & i, j \in I \\ \text{val}(q_i(x)) &\in \lambda_k Q_{n,m} & i \in I, k \in K \end{aligned}$$

with I, K finite, q_i linear polynomials, $\lambda_k \in \mathbb{Q}_p$, and $Q = Q_{n,m}$ for some n, m . Moreover whenever $a, a' \in Q_p^{|x|}$ agree on all the formulas from Ψ then they agree on ϕ .

Now fix a formula $\phi(x; y)$ for finding an upper bound of its VC-density. Using the result above we can construct a family of formulas $\Psi(x; y)$ which can be now written as

$$\begin{aligned} \text{val}(p_i(x) - c_i(y)) &< \text{val}(p_j(x) - c_j(y)) & i, j \in I \\ \text{val}(p_i(x) - c_i(y)) &\in \lambda_k Q & i \in I, k \in K \end{aligned}$$

where I, K finite, p_i a homogeneous linear polynomials in x , c_i is a linear polynomial in y , $\lambda_k \in \mathbb{Q}_p$, and $Q = Q_{n,m}$ for some n, m (to do this we simply split the polynomial q_i into its x part and into its y part including the constant term). Now for any parameter set B we have that if a, a' have the same Ψ -type over B then they have the same ϕ -type over B . Thus it suffices to bound VC-density for Ψ .

2. KEY LEMMAS AND DEFINITIONS

Definition 2.1. A tuple $p \in \mathbb{Q}_p^{|x|}$ can be viewed as a vector \vec{p} , treating $\mathbb{Q}_p^{|x|}$ as a vector space over \mathbb{Q}_p .

We may rewrite our collection of formulas $\Psi(x, y)$ as

$$\begin{aligned} \text{val}(\vec{p}_i \cdot \vec{x}) - c_i(y) &< \text{val}(\vec{p}_j \cdot \vec{x}) - c_j(y) & i, j \in I \\ \text{val}(\vec{p}_i \cdot \vec{x}) - c_i(y) &\in \lambda_k Q & i \in I, k \in K \end{aligned}$$

Lemma 2.2. *Suppose we have a collection of vectors $\{\vec{p}_i\}_{i \in I}$ with each $\vec{p}_i \in \mathbb{Q}_p^{|x|}$. Pick a subset $J \subset I$ and $j \in I$ such that*

$$\vec{p}_j \in \text{span} \{\vec{p}_i\}_{i \in J}$$

Suppose we have $\vec{x} \in \mathbb{Q}_p^{|x|}, \alpha \in \mathbb{Z}$ with

$$\text{val}(\vec{p}_i \cdot \vec{x}) > \alpha \text{ for all } i \in J$$

Then

$$\text{val}(\vec{p}_j \cdot \vec{x}) > \alpha - \gamma$$

for some $\gamma \in \mathbb{Z}^{\geq 0}$. Moreover γ can be chosen independently from J, j, \vec{x}, α depending only on $\{\vec{p}_i\}_{i \in I}$, independent of their order.

Proof. Fix some i, J . For some c_i

$$\begin{aligned} \vec{p}_j &= \sum_{i \in J} c_i \vec{p}_i \\ \vec{p}_j \cdot \vec{x} &= \sum_{i \in J} c_i \vec{p}_i \cdot \vec{x} \end{aligned}$$

We have

$$\text{val}(c_i \vec{p}_i \cdot \vec{x}) = \text{val}(c_i) + \text{val}(\vec{p}_i \cdot \vec{x}) > \text{val}(c_i) + \alpha$$

Pick $\gamma = -\max \text{val}(c_i)$ or 0 if all those values are positive. Then we have

$$\begin{aligned} \text{val}(c_i \vec{p}_i \cdot \vec{x}) &> \alpha - \gamma & \text{for all } i \in J \\ \sum_{i \in J} c_i \vec{p}_i \cdot \vec{x} &> \alpha - \gamma \end{aligned}$$

This shows that we can pick such γ for a given choice of i, J , but independent from α, \vec{x} . To get a choice independent from i, J , go over all such eligible choices (of which there are finitely many as I is finite), pick γ for each, and then take the maximum of those values. \square

Definition 2.3. For $c \in \mathbb{Q}_p, \alpha \in \mathbb{Z}$ we define an open ball

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

Definition 2.4. Suppose we have a finite $T \subset \mathbb{Q}_p$. We view it as a tree as follows. Branches through the tree are elements of T . With this tree we associate open balls $B(t_1, \text{val}(t_1 - t_2))$ for all $t_1, t_2 \in T$. An interval is two balls $B(t_1, v_1) \supset B(t_2, v_2)$ with no balls in between. An element $a \in \mathbb{Q}_p$ belongs to this interval if $a \in B(t_1, v_1) \setminus B(t_2, v_2)$. There are at most $2|T|$ different intervals and they partition the entire space.

Fix a parameter set B of size N .

Consider a tree $T = \{c_i(b) \mid b \in B, i \in I\}$ It has at most $O(N) = N \cdot |I|$ many intervals. Denote the set of all intervals as Pt . For the remainder of the paper we work with this tree.

Definition 2.5. Let $c \in \mathbb{Q}_p$. It lies in the tree in one of the unique intervals $B(c_L, \alpha_L) \setminus B(c_U, \alpha_U)$. Define $F(c)$, the floor of c to be α_L .

Definition 2.6. We say $a, a' \in \mathbb{Q}_p^{[x]}$ have the same Ψ -type if they have the same Ψ type over B .

Definition 2.7. We say $x, x' \in \mathbb{Q}_p$ have the same tree type if

- $\text{val}(x - c_i(b)) < \text{val}(x - c_j(b))$ iff $\text{val}(x' - c_i(b)) < \text{val}(x' - c_j(b))$ for all $i, j \in I, b \in B$
- $x + c_i(b)$ is in the same Q -coset as $x' + c_i(b)$ for all $i \in I, b \in B$

Lemma 2.8. Let $a, a' \in \mathbb{Q}_p^{[x]}$. If $p_i(a), p_i(a')$ have the same tree type for all $i \in I$, then a, a' have the same Ψ -type.

Proof. Clear from the construction. \square

Definition 2.9. For $c \in \mathbb{Q}_p$ and $\alpha, \beta \in \mathbb{Z}$ let $c \upharpoonright [\alpha, \beta] \in (\mathbb{Z}/p\mathbb{Z})^{\beta-\alpha}$ be the record of coefficients of c for the valuations between α, β . More precisely write c in its power series form

$$c = \sum_{\gamma \in \mathbb{Z}} c_\gamma p^\gamma \text{ with } c_\gamma \in \mathbb{Z}/p\mathbb{Z}$$

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

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

Lemma 2.10. For n, m there exists $D = D(n, m) \in \mathbb{Z}$ such that for any $x, y, a \in \mathbb{Q}_p$ if

$$\text{val}(x - c) = \text{val}(y - c) < \text{val}(x - y) - D$$

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

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

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

If a, b are similar then

$$Q_{n,m}a \leftrightarrow Q_{n,m}b$$

Moreover for any $\lambda \in \mathbb{Q}_p$, if a, b are similar we would also have $a/\lambda, b/\lambda$ are similar. Thus if a, b are similar, then they belong in the same coset of $Q_{n,m}$. If we pick $D = n + m$ then conditions of the lemma force $x - c, y - c$ to be similar. \square

The following construction is along the lines of lemma 7.5 of [1].

Definition 2.11. Let the distance between two balls $B(a, \alpha), B(b, \beta)$ be $|\alpha - \beta|$. In \mathbb{Q}_p value group is discrete and residue field is finite, so there are finitely many balls at a fixed distance from a given ball. Near balls of $B(a, \alpha)$ are defined to be balls with distance $\leq D$ from $B(a, \alpha)$. Enumerate those as:

$$B_1(c, \alpha), B_2(c, \alpha), \dots, B_{N_D}(c, \alpha)$$

Definition 2.12. Let $c \in \mathbb{Q}_p$. It lies in our tree in one of the intervals $B(c_L, \alpha_L) \setminus B(c_U, \alpha_U)$. Suppose c lies in one of the near balls of $B(c_L, \alpha_L)$ or $B(c_U, \alpha_U)$. Then define its interval type to be the index of that near ball. Otherwise define its interval type to be the coset of $c - c_U$ of Q . Denote the space of all the possible branch types Bt. We have

$$|\text{Bt}| = N_D + \text{number of cosets of } Q$$

finite, depending only on Ψ , independent from B .

Lemma 2.13. If a, a' are in the same interval and have the same interval type then they have the same tree type.

Proof. First part of the tree type definition is satisfied as a, a' are in the same interval, so we only need to demonstrate that the corresponding Q -cosets match. Pick any element of our tree $c_i(b)$. We want to show that $a - c_i(b), a' - c_i(b)$ are in the same Q -coset.

Suppose a is in one of the near balls. As a' has the same interval type, it has to be in the same near ball. By definition of the near ball we then have $\text{val}(a - c_i(b)) = \text{val}(a' - c_i(b)) < \text{val}(a - a') - D$. Thus by Lemma ?? we have $a - c_i(b), a' - c_i(b)$ in the same Q -coset.

Now, suppose both a, a' aren't in any near balls. Label their interval as $B(c_L, \alpha_L) \setminus B(c_U, \alpha_U)$. Then we have

$$\alpha_L + D < \text{val}(a - c_U) < \alpha_U - D$$

$$\alpha_L + D < \text{val}(a' - c_U) < \alpha_U - D$$

as otherwise one (both) of them would be in one of the near balls. We have either $\text{val}(c_U - c_i(b)) \geq \alpha_U$ or $\text{val}(c_U - c_i(b)) \leq \alpha_L$ as otherwise it would contradict the definition of an interval.

Suppose it is the first case $\text{val}(c_U - c_i(b)) \geq \alpha_U$. Then

$$\text{val}(a - c_i(b)) = \text{val}(a - c_U) < \alpha_U - D \leq \text{val}(c_U - c_i(b)) - D$$

so by Lemma ?? we have $a - c_i(b), a - c_U$ are in the same Q -coset. By a parallel argument we have $a' - c_i(b), a' - c_U$ are in the same Q -coset. As we are assuming a, a' have the same tree type it implies that $a - c_U, a' - c_U$ 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 $\text{val}(c_U - c_i(b)) \leq \alpha_L$. Then

$$\text{val}(a - c_i(b)) = \text{val}(c_U - c_i(b)) \leq \alpha_L < \text{val}(a - c_U) - D$$

so by Lemma ?? we have $a - c_i(b), c_U - c_i(b)$ are in the same Q -coset. By a parallel argument we have $a' - c_i(b), c_U - c_i(b)$ 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. \square

3. MAIN PROOF

Fix γ corresponding to $\{\tilde{p}_i\}_{i \in I}$ according to Lemma 2.2.

Definition 3.1. Denote $\mathbb{Z}/p\mathbb{Z}^\gamma$ as Ct.

Definition 3.2. Let $f : \mathbb{Q}_p^{[x]} \longrightarrow \mathbb{Q}_p^I$ with $f(\tilde{c}) = (p_i(\tilde{c}))_{i \in I}$. 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 floors $\{F(a_i)\}_{i \in I}$. Those are ordered as elements of \mathbb{Z} . Partition the segment space by order type of $\{F(a_i)\}$. Work in a fixed partition Sg' . After relabeling we may assume that

$$F(a_1) \geq F(a_2) \geq \dots$$

Consider the (relabelled) sequence of vectors $\tilde{p}_1, \tilde{p}_2, \dots, \tilde{p}_I$. 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.

Now, we define the following function

$$g : \text{Sg}' \longrightarrow \text{Bt}^I \times \text{Pt}^J \times \text{Ct}^{I-J}$$

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

For all a_i record its interval type $\in \text{Bt}$, giving the first component.

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

For the third component do the following computation. Pick a_i with i dependent. Let j be the largest independent index with $j < i$. Record $a_i \upharpoonright [F(a_j) - \gamma, F(a_j)]$.

Lemma 3.3. For $\tilde{a}, \tilde{a}' \in \text{Sg}'$ if $g(\tilde{a}) = g(\tilde{a}')$ then a_i, a'_i have the same tree type for all $i \in I$.

Proof. For each i we show that a_i, a'_i are in the same interval and have the same interval type, so the conclusion follows by Lemma 2.12. Bt records the interval type of each element, so if $g(\tilde{a}) = g(\tilde{a}')$ then a_i, a'_i have the same interval type for all $i \in I$. Thus it remains to show that a_i, a'_i lie in the same interval for all $i \in I$. Suppose i is an independent index. Then by construction, Pt records the interval for a_i, a'_i , so those have to belong to the same interval. 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 they are mapped to the same interval (using the earlier part of the argument as j is independent).

Claim 3.4. $\text{val}(a_i - a'_i) > F(a_j) - \gamma$

Proof. Let $\tilde{x}, \tilde{x}' \in \mathbb{Q}_p^{[x]}$ be some elements with

$$\tilde{p}_k \cdot \tilde{x} = a_k$$

$$\tilde{p}_k \cdot \tilde{x}' = a'_k \text{ for all } k \in I$$

It is always possible to do that as $\tilde{a}, \tilde{a}' \in \text{Sg}'$. Let J' be the set of the independent indices less than i . We have

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

as for the independent indices a_k, a'_k lie in the same interval.

$$\begin{aligned} \text{val}(a_k - a'_k) &> F(a_j) \text{ for all } k \in J' \text{ by monotonicity of } F(a_k) \\ \text{val}(\tilde{p}_k \cdot \tilde{x} - \tilde{p}_k \cdot \tilde{x}') &> F(a_j) \text{ for all } k \in J' \\ \text{val}(\tilde{p}_k \cdot (\tilde{x} - \tilde{x}')) &> F(a_j) \text{ for all } k \in J' \end{aligned}$$

J' and i match the requirements of Lemma 2.2 so we conclude

$$\begin{aligned} \text{val}(\tilde{p}_i \cdot (\tilde{x} - \tilde{x}')) &> F(a_j) - \gamma \\ \text{val}(\tilde{p}_i \cdot \tilde{x} - \tilde{p}_i \cdot \tilde{x}') &> F(a_j) - \gamma \\ \text{val}(a_i - a'_i) &> F(a_j) - \gamma \end{aligned}$$

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

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

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

As $F(a_i) \leq F(a_j)$, a_i, a'_i have to lie in the same interval. \square

Corollary 3.5. $\Psi(x, y)$ has 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 $p_i(c)$ has the same tree type as $p_i(c')$ for all $i \in I$. Then by Lemma 2.8 c, c' have the same Ψ -type. Thus the number of possible Ψ -types is bounded by the size of the range of g times the number of possible partitions

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

We have

$$\begin{aligned} |Pt| &\leq N \cdot I^2 \text{ (the only component dependent on } N) \\ |Ct| &= p^\gamma \end{aligned}$$

and there are at most $|I|!$ many partitions of Sg. This gives us a bound

$$|I|! \cdot |Bt|^{|I|} \cdot (N \cdot |I|^2)^{|J|} \cdot p^{\gamma|I-J|} = O(N^{|J|})$$

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 3.6. In the language \mathcal{L}_R we have $\text{vc}(n) = n$.

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

REFERENCES

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