Lower Bounds for the Polynomial Calculus via the “Pigeon Dance”

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Overview

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- Ideas behind the proof and its structure

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- The proof in more detail

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- We use multilinear polynomials $S_n(\mathbb{K})$ $(xy + xz + v \equiv x^2y + x^3z^5 + v)$

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- We construct polynomials such that their zeroes correspond to satisfying assignments

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Definition ($\neg\mathcal{PHP}^m_n$)

$$Q_i := 1 - \sum_{j \in [n]} x_{ij} \qquad \text{for each } i \in [m]$$

$$Q_{i_1,i_2,j} := x_{i_1 j} x_{i_2 j} \qquad \text{for each } i_1 \neq i_2 \in [m], j \in [n]$$

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- Strategy: pick some pigeon i, and show it can not fit regardless of other assignments
- Start with some Q_i, multiply with all other $x_{i',j}$, and remove all terms

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- Pigeonhole principle is locally consistent
- Polynomial calculus preserves local validity
- Only large terms are always cancellable

Technical details

- $\prec$ orders variables and terms degree lexicographic $(x_{3,1} \prec x_{2,5} \prec x_{1,1}x_{1,2})$

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- Important: R tells us what can not be proved ($R \neq 0 \Leftrightarrow V$ refutable)

Proof structure

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- Show the different operators are identical

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- Polynomials are evaluated to 0 if they allow the assignment

$$\delta(1 - x_{1,1} - x_{1,2} - x_{1,3} - x_{1,4}) = 0$$
$$\delta(x_{1,1}x_{3,1}) = \delta(x_{1,2}x_{2,2}) = 0$$

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$\Rightarrow$ V_I are all polynomials identically zero on M_I

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- Set $V_d := \bigcup_{|I| \le d} V_I$ and R_d accordingly
- Does this definition actually work?
- Yes it does! But only if $R_I(t) = R_{\mathrm{dom}(t)}(t)$

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- We will only show the broad steps

Example

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Formalization

- The first pigeon flies to an unoccupied hole to its right
- Repeat until all pigeons have moved once
- If a pigeon can not find an empty hole, the dance is aborted
- Define Δ_I to be the set of terms that let pigeons complete the dance
- $R_I(t) = R_{\mathrm{dom}(t)}(t)$ since pigeons not in the dance do not affect it

Defining R_I

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- Otherwise we use $Q_{i_1} = 0$ to derive

$$t = x_{i_2 j_2} \cdots x_{i_d j_d} - \sum_{j' < j_1} x_{i_1 j'} x_{i_2 j_2} \cdots x_{i_d j_d} - \sum_{j' > j_1} x_{i_1 j'} x_{i_2 j_2} \cdots x_{i_d j_d} \mod V_I.$$

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- The first two summands are $\prec t$ and can be ignored
- Any terms with $j' \in \{j_2, \ldots, j_d\}$ are 0 and can be ignored

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- Process terminates with $f \prec t$ and $t = f \mod V_I$

The Kill operator

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- $\mathrm{Kill}(x_{i_1,j_1} \cdots x_{i_d,j_d}) = x_{i_2,j'_2} \cdots x_{i_d,j'_d}$ with

$$j'_k := \begin{cases} j_k + 1, & \text{if } j_k < j_1 \\ j_k, & \text{if } j_k > j_1. \end{cases}$$

Properties of Kill

Theorem

$x_{i_1,j_1}\cdots x_{i_d,j_d}\in\Delta_I$ *if and only if there is a* $j'>j_1$ *such that* $\mathrm{Kill}(x_{i_1,j'}\cdots x_{i_d,j_d})\in\Delta_I$.

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Proof

This operator effectively moves the first pigeon to an empty hole and then kills it. This is the same as each step in the dance, where the first pigeon flies to some free hole to its right and then occupies it. $\square$

Properties of Kill (cont.)

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Proof

If $t \in \Delta_I$ then the pigeons can complete their dance. During this the first pigeon will start at j and fly to j'. Killing the pigeon frees up j' so any other pigeon that wanted to use j can use it instead. $\square$

The lower bound

Theorem

If $|I| \leq (n+1)/2, t \in D_I$ *and the minimal element* i *of* I *is not in* $\mathrm{dom}(t)$*, then there exists a* $j \in [n]$ *such that* $\mathrm{Kill}(x_{ij}t) \in \Delta_I$.

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Proof

At most

$$|\operatorname{dom}(t)| \leq |I \setminus \{i\}| \leq \frac{n-1}{2}$$

pigeons involved in the dance, each occupying two holes. Thus the total number of holes is $n-1$ and one hole j remains free. For the purposes of the dance, $\mathrm{Kill}(x_{ij} \cdot t)$ is the same as t since the only difference is j being moved to the left. $\square$

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- Equivalent to Δ_I being linearly independent as functions $M_I \to \mathbb{K}$
- Induction on $|I|$ gives us assignment $a \in M_{I \setminus \{i\}}$ with $a(f') \neq 0$
- Pick a j such that $\mathrm{Kill}(x_{i,j}t) \in \Delta_I$
- Extend assignment to I with $a'(f) \neq 0$

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- Pigeons not in the dance do not affect its success, so $R_I(t) = R_{\mathrm{dom}(t)}(t)$
- V_d is precisely polynomials identically zero on M_I
- $R_d \neq 0$
- There is no refutation of $\neg\mathcal{PHP}_n^m$ with $d \leq n/2+1$