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Separation of Multilinear Circuit and Formula Size

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Abstract: An arithmetic circuit or formula is multilinear if the polynomial computed at each of its wires is multilinear. We give an explicit polynomial $f(x_1,\ldots,x_n)$ with coefficients in $\{0,1\}$ such that over any field:

1. f can be computed by a polynomial-size multilinear circuit of depth $O(\log^2 n)$.
2. Any multilinear formula for f is of size $n^{\Omega(\log n)}$.

This gives a superpolynomial gap between multilinear circuit and formula size, and separates multilinear NC_1 circuits from multilinear NC_2 circuits.

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1 Introduction

An outstanding open problem in arithmetic circuit complexity is to understand the relative power of circuits and formulas. Surprisingly, any arithmetic circuit of size s for a polynomial of degree d can be

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translated into an arithmetic formula of size quasi-polynomial in s and d [3, 8].[1] Can such a circuit be translated into a formula of size *polynomial* in s and d ?

In this paper, we answer this question for *multilinear* circuits and formulas. An arithmetic circuit (or formula) is *multilinear* if the polynomial computed at each of its wires is multilinear (as a formal polynomial), that is, in each of its monomials the exponent of every input variable is at most one.

A preliminary version of this paper appeared in FOCS 2004. The title was "Multilinear-$NC_1 \neq$ Multilinear-NC_2" [6].

1.1 Multilinear Circuits

Let F be a field, and let $\{x_1, \ldots, x_n\}$ be a set of input variables. An *arithmetic circuit* is a directed acyclic graph with nodes of in-degree 0 or 2. We refer to the in-neighbors of a node as its "children." Every *leaf* of the graph (i. e., a node of in-degree 0) is labelled with either an input variable or a field element. Every other node of the graph is labelled with either $+$ or $\times$ (in the first case the node is a *sum gate* and in the second case a *product gate*). We assume that there is only one node of out-degree zero, called the *root*. The circuit is a *formula* if its underlying graph is a (binary) tree (with edges directed from the leaves to the root).

An arithmetic circuit computes a polynomial in the ring $\mathrm{F}[x_1, \ldots, x_n]$ in the following way. A leaf just computes the input variable or field element that labels it. A sum gate computes the sum of the two polynomials computed by its children. A product gate computes the product of the two polynomials computed by its children. The *output* of the circuit is the polynomial computed by the root. For a circuit Φ, we denote by $\hat{\Phi}$ the output of the circuit, that is, the polynomial computed by the circuit. The *size* of a circuit Φ is defined to be the number of nodes in the graph, and is denoted by $|\Phi|$. The *depth* of a circuit is defined to be the maximal distance between the root and a leaf in the graph.

A polynomial in the ring $\mathrm{F}[x_1, \ldots, x_n]$ is *multilinear* if in each of its monomials the exponent of every input variable is at most one. An arithmetic circuit (or formula) is *multilinear* if the polynomial computed by each gate of the circuit is multilinear.

1.2 Background

Multilinear circuits (and formulas) were formally defined by Nisan and Wigderson in [5]. Obviously, multilinear circuits can only compute multilinear functions. Moreover, multilinear circuits are restricted, as they do not allow the intermediate use of higher powers of variables in order to finally compute a certain multilinear function. Note, however, that for many multilinear functions, circuits that are not multilinear are very counter-intuitive, as they require a "magical" cancellation of all high powers of variables. For many multilinear functions, it seems "obvious" that the smallest circuits and formulas should be multilinear. Moreover, for most multilinear functions, no gain is known to come from permitting higher powers.

For example, the (first entry of the) product of n matrices of size $n \times n$ is a multilinear function, and the smallest known circuits for this function are multilinear. It seems intuitively clear that the smallest

[1] Moreover, if s, d are both polynomial in the number of input variables n, then the circuit can be translated into a polynomial-size circuit of depth $O(\log^2 n)$, that is, an NC_2 circuit [8].

circuits for this function should be multilinear. On the other hand, for some multilinear functions the smallest known circuits are not multilinear. For example, the determinant of an $n \times n$ matrix is a multilinear function (of the n^2 entries) that has polynomial size arithmetic circuits but doesn't have known subexponential size multilinear circuits.

Super-polynomial lower bounds for the size of multilinear formulas were recently proved [7]. In particular, it was proved that over any field, any multilinear formula for the permanent or the determinant of an $n \times n$ matrix is of size $n^{\Omega(\log n)}$. Note, however, that all known multilinear circuits for the permanent or the determinant are of exponential size, and hence these bounds don't give any separation between multilinear circuit and formula size.

For more background and motivation for the study of multilinear circuits and formulas see [5, 7, 1]. For general background on algebraic complexity theory see [9, 2].

1.3 Our results

We construct an explicit polynomial with the properties specified in the following theorem.

Theorem 1.1. *There exists an explicit multilinear polynomial $f(x_1,\dots,x_n)$, with coefficients in $\{0,1\}$, such that over any field:*

(a) f can be computed by a polynomial-size multilinear circuit of depth $O(\log^2 n)$;

(b) any multilinear formula for f is of size $n^{\Omega(\log n)}$.

Item (a) means that f has a multilinear NC_2 circuit. Item (b) implies that f cannot be computed by a polynomial-size multilinear circuit of depth $O(\log n)$, that is, by a multilinear NC_1 circuit.[2] This gives a super-polynomial gap between multilinear circuit and formula size, and separates multilinear NC_1 circuits from multilinear NC_2 circuits.

For the proof of our lower bound on the multilinear formula size of f, we use methods from [7]. The main contribution of this paper is the construction of a polynomial f that can be computed by small multilinear circuits, and to which these methods can be applied.

2 Syntactic multilinear formulas

Let Φ be an arithmetic circuit over the set of variables $\{x_1,\dots,x_n\}$. For every node v in the circuit, denote by Φ_v the sub-circuit with root v, and denote by X_v the set of variables that occur in the circuit Φ_v. We say that an arithmetic circuit Φ is *syntactic multilinear* if for every product gate v of Φ, with children v_1, v_2, the sets of variables X_{v_1} and X_{v_2} are disjoint.

Note that any syntactic multilinear circuit is clearly multilinear. At the other hand, a multilinear circuit is not necessarily syntactic multilinear. Nevertheless, the following proposition shows that without loss of generality we can assume that a multilinear formula is syntactic multilinear.

[2] Note that any (multilinear) circuit of depth $O(\log n)$ can trivially be translated into a polynomial size (multilinear) formula (of depth $O(\log n)$).

Proposition 2.1 ([7]). *For any multilinear formula, there exists a syntactic multilinear formula of the same size that computes the same polynomial.*

Proof. Let Φ be a multilinear formula. Let v be a product gate in Φ, with children v_1, v_2, and assume that X_{v_1} and X_{v_2} both contain the same variable x_i. Since Φ is multilinear, $\hat{\Phi}_v$ is a multilinear polynomial and hence in at least one of the polynomials $\hat{\Phi}_{v_1}, \hat{\Phi}_{v_2}$ the variable x_i doesn't occur. W.l.o.g. assume that in the polynomial $\hat{\Phi}_{v_1}$ the variable x_i doesn't occur. Then every occurrence of x_i in Φ_{v_1} can be replaced by the constant 0. By repeating this for every product gate in the formula, as many times as needed, we obtain a syntactic multilinear formula that computes the same polynomial. □

3 Lower bounds for multilinear formulas

In this section, we prove general lower bounds for the size of multiliear formulas. To prove these bounds we follow very closely the techniques from [7]. As in [7], our starting point is the partial derivatives method of Nisan and Wigderson [4, 5]. As in [7], to handle sets of partial derivatives, we make use of the *partial derivatives matrix* (first used in [4]).

3.1 The partial-derivatives matrix

Let f be a multilinear polynomial over the set of variables $\{y_1, \ldots, y_m\} \dot\cup \{z_1, \ldots, z_m\}$. For a multilinear monomial p in the set of variables $\{y_1, \ldots, y_m\}$ and a multilinear monomial q in the set of variables $\{z_1, \ldots, z_m\}$, denote by $M_f(p,q)$ the coefficient of the monomial pq in the polynomial f. Since the number of multilinear monomials in a set of m variables[3] is 2^m, we can think of M_f as a $2^m \times 2^m$ matrix, with entries in the field F. We call M_f the *partial derivatives matrix* of f. We will be interested in the rank of the matrix M_f over the field F.

The following two propositions give some basic facts about the partial derivatives matrix.

Proposition 3.1. *Let f, f_1, f_2 be three multilinear polynomials over the set of variables $\{y_1, \ldots, y_m\} \dot\cup \{z_1, \ldots, z_m\}$, such that $f = f_1 + f_2$. Then $M_f = M_{f_1} + M_{f_2}$.*

Proof. Immediate from the definition of the partial derivatives matrix. □

Proposition 3.2. *Let f, f_1, f_2 be three multilinear polynomials over the set of variables $\{y_1, \ldots, y_m\} \dot\cup \{z_1, \ldots, z_m\}$, such that $f = f_1 \cdot f_2$, and such that the set of variables that f_1 depends on and the set of variables that f_2 depends on are disjoint. Then,* $\mathrm{Rank}(M_f) = \mathrm{Rank}(M_{f_1}) \cdot \mathrm{Rank}(M_{f_2})$.

Proof. Note that the matrix M_f is the tensor product of M_{f_1} and M_{f_2} (where all matrices are restricted to rows and columns that are non-zero). Hence, the rank of M_f is the product of the rank of M_{f_1} and the rank of M_{f_2}. □

Let Φ be a multilinear formula over the set of variables $\{y_1, \ldots, y_m\} \dot\cup \{z_1, \ldots, z_m\}$. Recall that the output $\hat{\Phi}$ of the formula Φ is a multilinear polynomial over $\{y_1, \ldots, y_m\} \dot\cup \{z_1, \ldots, z_m\}$. For simplicity, we denote the matrix $M_{\hat{\Phi}}$ also by M_Φ. We will be interested in bounding the rank of the matrix M_Φ

[3] We only consider monomials with coefficient 1 (such as $x_1x_3x_4$, as opposed to, say, $3x_1x_3x_4$).

over the field F. (Note, however, that the rank of M_Φ may be as large as 2^m (i. e., full rank), even if the formula Φ is of linear size.)

3.2 Unbalanced nodes

Let Φ be a syntactic multilinear formula over the set of variables $\{y_1,\dots,y_m\} \dot\cup \{z_1,\dots,z_m\}$. For every node v in the formula, denote by Y_v the set of variables in $\{y_1,\dots,y_m\}$ that occur in the formula Φ_v, and denote by Z_v the set of variables in $\{z_1,\dots,z_m\}$ that occur in the formula Φ_v.

Denote by $b(v)$ the average of $|Y_v|$ and $|Z_v|$ and denote by $a(v)$ their minimum. Let $d(v) = b(v) - a(v)$. We say that a node v is k-*unbalanced* if $d(v) \geq k$.

Let γ be a simple path from a leaf w to a node v of the formula Φ. We say that γ is k-*unbalanced* if it contains at least one k-unbalanced node. We say that γ is *central* if for every u, u_1 on the path γ such that u_1 is a child of u, we have $b(u) \leq 2b(u_1)$. Note that for every node u in the formula, with children u_1, u_2, we have $b(u) \leq b(u_1) + b(u_2)$. Hence, by induction, for every node u in the formula, there exists at least one central path that reaches u. In particular, at least one central path reaches the root.

We say that the formula Φ is k-*weak* if every central path that reaches the root of the formula contains at least one k-unbalanced node. The following lemma from [7] shows that if the formula Φ is k-weak then the rank of the matrix M_Φ can be bounded.

Lemma 3.3 ([7]). *Let Φ be a syntactic multilinear formula over the set of variables $\{y_1,\dots,y_m\} \dot\cup \{z_1,\dots,z_m\}$, and assume that Φ is k-weak. Then,*

$$\mathrm{Rank}(M_\Phi) \leq |\Phi| \cdot 2^{m-k/2} \quad .$$

3.3 Random partition

Let $n = 2m$. Let Φ be a syntactic multilinear formula over the set of variables $X = \{x_1,\dots,x_n\}$. Let A be a random partition of the variables in X into $\{y_1,\dots,y_m\} \dot\cup \{z_1,\dots,z_m\}$. Formally, A is a (randomly chosen) one-to-one function from the set of variables X to the set of variables $\{y_1,\dots,y_m\} \dot\cup \{z_1,\dots,z_m\}$.

Denote by Φ_A the formula Φ after replacing every variable of X by the variable assigned to it by A. Obviously, Φ_A is a syntactic multilinear formula over the set of variables $\{y_1,\dots,y_m\} \dot\cup \{z_1,\dots,z_m\}$.

The following lemma shows that if $|\Phi|$ is small then with high probability Φ_A is k-weak for $k = n^{1/8}$. We will give the proof of the lemma in the next section.

Lemma 3.4. *Let $n = 2m$. Let Φ be a syntactic multilinear formula over the set of variables $X = \{x_1,\dots,x_n\}$, such that every variable in X occurs in Φ, and such that $|\Phi| \leq n^{\varepsilon \log n}$, where ε is a sufficiently small universal constant (e.g., $\varepsilon = 10^{-6}$). Let A be a random partition of the variables in X into $\{y_1,\dots,y_m\} \dot\cup \{z_1,\dots,z_m\}$. Then, with probability of at least $1 - n^{-\Omega(\log n)}$ the formula Φ_A is k-weak, for $k = n^{1/8}$.*

3.4 The lower bounds

Lower bounds for the size of multilinear formulas can be proved as a corollary to Lemma 3.3 and Lemma 3.4. We will prove lower bounds for functions that satisfy the following *high rank* property.[4]

Definition 3.5 (High rank). Let $n = 2m$. Let f be a multilinear polynomial (over a field F) over the set of variables $X = \{x_1, \ldots, x_n\}$. We say that f is of **high rank** over F if the following is satisfied: Let A be a random partition of the variables in X into $\{y_1, \ldots, y_m\} \dot\cup \{z_1, \ldots, z_m\}$. Then, with probability of at least $n^{-o(\log n)}$,

$$\mathrm{Rank}(M_{f_A}) \geq 2^{m - m^{1/8}/2} \quad ,$$

where the rank is over F, and f_A denotes the polynomial f after replacing every variable in X by the variable assigned to it by A.

The following corollary is our basic lower bound.

Corllary 3.6. *Let $n = 2m$. Let f be a multilinear polynomial (over a field* F*) over the set of variables $X = \{x_1, \ldots, x_n\}$. If f is of high rank over* F *(see Definition 3.5) then for any multilinear formula Φ for f,*

$$|\Phi| \geq n^{\Omega(\log n)} \quad .$$

Proof. By Proposition 2.1, we can assume w.l.o.g. that Φ is syntactic multilinear. Note also that we can assume w.l.o.g. that all the variables in X occur in Φ, as we can always add variables multiplied by 0. Assume for a contradiction that $|\Phi| \leq n^{\varepsilon \log n}$, where ε is the universal constant from Lemma 3.4. Let A be a random partition of the variables in X into $\{y_1, \ldots, y_m\} \dot\cup \{z_1, \ldots, z_m\}$. Then, by Lemma 3.4, with probability of at least $1 - n^{-\Omega(\log n)}$ the formula Φ_A is k-weak, for $k = n^{1/8}$.

Hence, by Lemma 3.3, with probability of at least $1 - n^{-\Omega(\log n)}$,

$$\mathrm{Rank}(M_{\Phi_A}) < 2^{m - m^{1/8}/2} \quad .$$

Thus Φ cannot be a formula for the high rank function f. □

We will now consider multilinear polynomials f (over a field F) over two sets of variables: $X = \{x_1, \ldots, x_n\}$ and $X' = \{x'_1, \ldots, x'_l\}$. We think of the variables in X' as auxiliary variables. Let $A' : X' \to$ F be an assignment of values in F to all the variables in X'. We denote by $f_{A'}$ the polynomial f, after substituting in every variable in X' the value assigned to it by A'. Note that $f_{A'}$ is a multilinear polynomial over the set of variables X.

Corllary 3.7. *Let $n = 2m$. Let f be a multilinear polynomial (over a field* F*) over the sets of variables $X = \{x_1, \ldots, x_n\}$ and $X' = \{x'_1, \ldots, x'_l\}$. If for some assignment $A' : X' \to$ F the polynomial $f_{A'}$ is of high rank over* F *(see Definition 3.5) then for any multilinear formula Φ for f,*

$$|\Phi| \geq n^{\Omega(\log n)} \quad .$$

[4]Note that the functions f used in this paper will actually satisfy a much stronger property. Namely, for any partition A, we will have $\mathrm{Rank}(M_{f_A}) = 2^m$ (where all notation is as in Definition 3.5).

Proof. Denote by $\Phi_{A'}$ the formula Φ after replacing every variable of X' by the value assigned to it by A'. Then, $\Phi_{A'}$ is a formula for $f_{A'}$, and $|\Phi_{A'}| = |\Phi|$. Hence, by Corollary 3.6, $|\Phi| = |\Phi_{A'}| \geq n^{\Omega(\log n)}$. □

In some cases, in order to find an assignment A' such that the polynomial $f_{A'}$ is of high rank, we will need to consider extensions G of the field F. Note that any polynomial f over F is also a polynomial over any field extending F.

Corllary 3.8. *Let $n = 2m$. Let f be a multilinear polynomial (over a field* F*) over the sets of variables $X = \{x_1, \dots, x_n\}$ and $X' = \{x'_1, \dots, x'_l\}$. If for some field* G $\supset$ F *there exists an assignment $A' : X' \to$ G, such that the polynomial $f_{A'}$ is of high rank over* G *(see Definition 3.5) then for any multilinear formula Φ for f (over the field* F*),*

$$|\Phi| \geq n^{\Omega(\log n)} \ .$$

Proof. Any multilinear formula for f over the field F is also a multilinear formula for f over the field G. The proof hence follows by Corollary 3.7. □

4 Proof of Lemma 3.4

Let us first give a brief sketch of the proof. Note that the intuition and the basic structure of the proof are the same as in [7], but the details here are much simpler.

Intuitively, since A is random, every node v with large enough X_v will be k-unbalanced with high probability. The probability that such v is not k-unbalanced is smaller than $O(n^{-\delta})$, for some constant δ. This may not be enough since the number of central paths is possibly as large as $n^{\varepsilon \log n}$. Nevertheless, each central path contains $\Omega(\log n)$ nodes so we can hope to prove that the probability that none of them is k-unbalanced is as small as $n^{-\Omega(\log n)}$.

This, however, is not trivial since there are dependencies between the different nodes. We will identify $\Omega(\log n)$ nodes, $v_1, \dots, v_l$, on the path (that will be "far enough" from each other). We will show that for every v_i, the probability that v_i is not k-unbalanced is smaller than $O(n^{-\delta})$, even when conditioning on the event that $v_1, \dots, v_{i-1}$ are not k-unbalanced.

4.1 Notation

For any integer n, denote $[n] = \{1, \dots, n\}$.

To simplify notation, we denote in this section the formula Φ_A by Ψ. There is a one-to-one correspondence between the nodes of Φ and the nodes of Ψ. For every node v in Φ, there is a corresponding node in Ψ and vice versa. For simplicity, we denote both these nodes by v, and we think of them as the same node. Hence, X_v denotes the set of variables in X that occur in the formula Φ_v, while Y_v denotes the set of variables in $\{y_1, \dots, y_m\}$ that occur in the formula Ψ_v, and Z_v denotes the set of variables in $\{z_1, \dots, z_m\}$ that occur in Ψ_v. Let

$$\alpha(v) = |X_v|/n \ .$$

For three integers $M_1, M_2 \leq N$, denote by $\mathcal{H}(N, M_1, M_2)$ the hypergeometric distribution with parameters N, M_1, M_2, that is, the distribution of the size of the intersection of a random set of size M_2 and a set of size M_1 in a universe of size N.

Proposition 4.1. *Let χ be a random variable that has the hypergeometric distribution $\mathcal{H}(N, M_1, M_2)$, where $N/4 \leq M_2 \leq 3N/4$, and $N^{1/2} \leq M_1 \leq N/2$. Then, χ takes any specific value with probability of at most $O(N^{-1/4})$. That is, for any number a,*

$$\Pr[\chi = a] \leq O(N^{-1/4}) \quad .$$

Proof. Follows by the definition of the hypergeometric distribution and standard bounds on binomial coefficients. □

4.2 Central paths are unbalanced

Let γ be a simple path from a leaf to a node in Φ. Note that γ is central in Ψ iff for every u, u_1 on the path γ, such that u_1 is a child of u, we have $\alpha(u) \leq 2\alpha(u_1)$. Since this property doesn't depend on the partition A, we say in this case that γ is central in Φ. We will show that if γ is central then with high probability γ is unbalanced in the formula Ψ.

Claim 4.2. *Let γ be a central path from a leaf to the root of Φ. Then,*

$$\Pr[\gamma \textit{ is not } k\textit{-unbalanced in } \Psi\,] \leq n^{-\Omega(\log n)} \quad .$$

Proof. Recall that the first node of γ is a leaf and hence $\alpha(v)$ for that node is at most $1/n$, and the last node of γ is the root and hence $\alpha(v)$ for that node is 1. Note that $\alpha(v)$ is monotonously increasing along γ. Let $v_1, \ldots, v_l$ be nodes on γ, chosen by the following process: Let v_1 be the first node on γ, such that $\alpha(v_1) \geq n^{-1/2}$. For every i, let v_{i+1} be the first node on γ, such that $\alpha(v_{i+1}) \geq 2 \cdot \alpha(v_i)$. Stop when $\alpha(v_{i+1}) > 1/4$. Denote by l the index i of the last v_i in this process.

Since γ is central, for every u, u' on γ, such that u' is a child of u, we have $\alpha(u) \leq 2\alpha(u')$. Hence, for every $i \in [l-1]$, we have $\alpha(v_{i+1}) < 4 \cdot \alpha(v_i)$. Hence, the process above continues for $\Omega(\log n)$ steps. To summarize, we have $l = \Omega(\log n)$ and nodes $v_1, \ldots, v_l$ on γ, such that for every $i \in \{2, \ldots, l\}$,

$$1/4 \geq \alpha(v_i) \geq 2 \cdot \alpha(v_{i-1}) \geq n^{-1/2} \quad .$$

Denote by $\mathcal{E}$ the event that γ is not k-unbalanced in the formula Ψ. For every $i \in [l]$, denote by $\mathcal{E}_i$ the event that the node v_i is not k-unbalanced in the formula Ψ. Since $\mathcal{E} \subset \cap_{i \in [l]} \mathcal{E}_i$,

$$\Pr[\mathcal{E}] \leq \Pr\left[\bigcap_{i \in [l]} \mathcal{E}_i\right] = \prod_{i \in [l]} \Pr\left[\mathcal{E}_i \,\middle|\, \bigcap_{i' \in [i-1]} \mathcal{E}_{i'}\right] \quad .$$

We will bound for every $i > 1$ the conditional probability $\Pr[\mathcal{E}_i \mid \cap_{i' \in [i-1]} \mathcal{E}_{i'}]$.

Fix $i \in \{2, \ldots, l\}$. Note that $X_{v_{i-1}} \subset X_{v_i}$. Given the set $Y_{v_{i-1}}$, we can write,

$$|Y_{v_i}| = |Y_{v_{i-1}}| + \chi \quad ,$$

where χ has the distribution $\mathcal{H}(N, M_1, M_2)$, with $N = n - |X_{v_{i-1}}|$, $M_1 = |X_{v_i}| - |X_{v_{i-1}}|$, $M_2 = m - |Y_{v_{i-1}}|$.

Hence, by Proposition 4.1, $|Y_{v_i}|$ does not take any specific value with probability larger than $O(n^{-1/4})$, even when conditioning on (the content of) the set $Y_{v_{i-1}}$.

Note that the event $\bigcap_{i'\in[i-1]} \mathcal{E}_{i'}$ depends only on the content of the set $Y_{v_{i-1}}$. Therefore, $|Y_{v_i}|$, and hence also $d(v_i)$, do not take any specific value with probability larger than $O(n^{-1/4})$, even when conditioning on the event $\bigcap_{i'\in[i-1]} \mathcal{E}_{i'}$. Recall that v_i is not k-unbalanced iff $d(v_i) < k$. Since $d(v_i)$ is integer, the probability for that is at most $O(k \cdot n^{-1/4}) = O(n^{-1/8})$, even when conditioning on the event $\bigcap_{i'\in[i-1]} \mathcal{E}_{i'}$. That is,

$$\Pr\left[\mathcal{E}_i \,\middle|\, \bigcap_{i'\in[i-1]} \mathcal{E}_{i'}\right] \leq O(n^{-1/8}) \quad .$$

We can now bound

$$\Pr[\mathcal{E}] \leq \prod_{i\in[l]} \Pr\left[\mathcal{E}_i \,\middle|\, \bigcap_{i'\in[i-1]} \mathcal{E}_{i'}\right] = n^{-\Omega(\log n)} \quad .$$

□

We can now complete the proof of Lemma 3.4. By Claim 4.2, if γ is a central path from a leaf to the root of Φ, then γ is not k-unbalanced (in Ψ) with probability of at most $n^{-\Omega(\log n)}$. The number of paths from a leaf to the root of Φ is the same as the number of leaves in Φ, which is smaller than $n^{\varepsilon \log n}$ (and we assumed that ε is small enough). Hence, by the union bound, with probability of at least $1 - n^{-\Omega(\log n)}$ all central paths from a leaf to the root of Ψ are k-unbalanced, that is, the formula Ψ is k-weak.

5 Multilinear-$NC_1 \neq$ Multilinear-NC_2

In this section, we present our construction for a multilinear polynomial f that has polynomial-size multilinear circuits and doesn't have polynomial-size multilinear formulas. Let us start with some notation and concepts needed to define f.

Let $[n] = \{1, \ldots, n\}$. For every $i, j \in [n]$ such that $i \leq j$, denote by $[i, j]$ the interval of $[n]$ starting at i and ending at j, that is, $[i, j] = \{i, i+1, \ldots, j\}$. Denote by $\mathcal{S}$ the set of all such intervals, including the empty interval (which is denoted by $\emptyset$). For $s_1, s_2 \in \mathcal{S}$, such that s_1, s_2 are disjoint and s_2 is consecutive[5] to s_1, denote by $s_1 \circ s_2$ their concatenation, that is, if $s_1 = [i, j]$, and $s_2 = [j+1, j']$ then $s_1 \circ s_2 = [i, j']$.

Denote by $\mathcal{T}$ the set of (ordered) pairs of disjoint intervals in $\mathcal{S}$, that is,

$$\mathcal{T} = \{(s_1, s_2) \in \mathcal{S} \times \mathcal{S} \ : \ s_1 \cap s_2 = \emptyset\} \quad .$$

For $t_1, t_2 \in \mathcal{T}$, such that, $t_1 = (s_{1,1}, s_{1,2}), t_2 = (s_{2,1}, s_{2,2})$, and such that $s_{1,1}, s_{1,2}, s_{2,1}, s_{2,2}$ are all disjoint and $s_{2,1}$ is consecutive to $s_{1,1}$ and $s_{2,2}$ is consecutive to $s_{1,2}$, denote by $t_1 \circ t_2$ their pairwise concatenation, that is, $t_1 \circ t_2 = (s_{1,1} \circ s_{2,1}, s_{1,2} \circ s_{2,2}) \in \mathcal{T}$.

For every $s \in \mathcal{S}$, denote by $l(s)$ its length (i. e., the number of elements in it). For $t = (s_1, s_2) \in \mathcal{T}$, denote $l(t) = l(s_1) + l(s_2)$. For $t = (s_1, s_2) \in \mathcal{T}$, define $L(t) = l(t)$ if both s_1, s_2 are non-empty, and $L(t) = 0.75 \cdot l(t)$ if either s_1 or s_2 is empty. (We will use $L(t)$ as a measure for the "size" of t. For technical reasons we want t to be considered smaller if either s_1 or s_2 is empty).

[5]We think of the empty interval as consecutive to every interval, and every interval is consecutive to it.

For $t_1,t_2,t_3,t \in \mathcal{T}$, such that, $t_1 = (s_{1,1},s_{1,2}), t_2 = (s_{2,1},s_{2,2}), t_3 = (s_{3,1},s_{3,2}), t = (s_1,s_2)$, we say that $\{t_1,t_2\}$ is a *partition* of t if $\{s_{1,1},s_{1,2},s_{2,1},s_{2,2}\}$ is a partition of $s_1 \cup s_2$ as sets. We say that the partition is *proper* if $t = t_1 \circ t_2$, and $l(t_1), l(t_2) > 0$. In the same way, $\{t_1,t_2,t_3\}$ is a partition of t if $\{s_{1,1},s_{1,2},s_{2,1},s_{2,2},s_{3,1},s_{3,2}\}$ is a partition of $s_1 \cup s_2$ as sets. The partition is proper if $t = t_1 \circ t_2 \circ t_3$, and $l(t_1), l(t_2), l(t_3) > 0$.

For a function $A : [n] \to \{1,-1\}$ and for $s \in \mathcal{S}$, denote by $A(s)$ the sum of A on the elements in s. In the same way, for $t \in \mathcal{T}$, denote by $A(t)$ the sum of A on the elements in the union of the two intervals in t. We say that A is balanced on $s \in \mathcal{S}$ if $A(s) = 0$, and in the same way, A is balanced on $t \in \mathcal{T}$ if $A(t) = 0$. Denote by $\mathcal{B}_A$ the set of all $t \in \mathcal{T}$ on which A is balanced, that is,

$$\mathcal{B}_A = \{t \in \mathcal{T} \,:\, A(t) = 0\} \ .$$

Obviously, the length $l(t)$ of every $t \in \mathcal{B}_A$ is even.

For our proof, we will need the following technical lemma. Roughly speaking, the lemma states that any $t \in \mathcal{B}_A$ can be partitioned into three significantly smaller $t_1,t_2,t_3 \in \mathcal{B}_A$. We defer the proof of the lemma to Section 5.5.

Lemma 5.1. *Let A be a function $A : [n] \to \{1,-1\}$. Let $t \in \mathcal{B}_A$ be such that $l(t) > 2$. Then, there exist $t_1,t_2,t_3 \in \mathcal{B}_A$, such that $\{t_1,t_2,t_3\}$ is a partition of t, and $L(t_1), L(t_2), L(t_3) \le 0.75 \cdot L(t)$.*

For any $t \in \mathcal{T}$, such that $l(t)$ is even, denote by $\mathcal{P}(t)$ the set of all $\{t_1,t_2,t_3\}$, such that: $t_1,t_2,t_3 \in \mathcal{T}$, and $\{t_1,t_2,t_3\}$ is a partition of t, and $l(t_1), l(t_2), l(t_3)$ are even, and $L(t_1), L(t_2), L(t_3) \le 0.75 \cdot L(t)$.

5.1 The construction

We will now define our multilinear polynomial f (with coefficients in $\{0,1\}$), such that over any field, f can be computed by a polynomial-size multilinear circuit and cannot be computed by a polynomial-size multilinear formula. f will be defined over the set of variables $X = \{x_1,\ldots,x_n\}$ (where n is even) and a set of (auxiliary) variables

$$X' = \left\{x'_{t,t_1,t_2,t_3}\right\}_{t,t_1,t_2,t_3 \in \mathcal{T}} \ .$$

That is, for every $t,t_1,t_2,t_3 \in \mathcal{T}$ we have an (auxiliary) variable x'_{t,t_1,t_2,t_3}. Note that the total number of auxiliary variables is polynomial in n.

f will be defined in the following way. For every $t \in \mathcal{T}$, such that $l(t)$ is even, we will define a multilinear polynomial f_t. We then define

$$f = f_{([n],\emptyset)} \ .$$

We define the polynomials f_t by induction on $L(t)$:

Case 1 $L(t) = l(t) = 0$. We define in this case, $f_t = 1$.

Case 2 $0 < L(t) \le 2$. Since $l(t)$ is even, $l(t) = 2$. Hence, the union of the two intervals in t contains two indices. Denote these indices by i_t, j_t. We define in this case,

$$f_t = x_{i_t} \cdot x_{j_t} + 1 \ .$$

Note that for the two possible partitions of $\{x_{i_t}, x_{j_t}\}$ into $\{y_1\} \dot\cup \{z_1\}$, the partial derivatives matrix of f_t is the identity matrix of size 2×2 and is hence of rank 2 (i. e., full rank).

Case 3 $L(t) > 2$. Since $l(t)$ is even, $l(t)$ is at least 4. We define in this case,

$$f_t = \sum_{\{t_1,t_2,t_3\} \in \mathcal{P}(t)} x'_{t,t_1,t_2,t_3} \cdot f_{t_1} \cdot f_{t_2} \cdot f_{t_3} \quad .$$

Observe that (by the inductive definition) for any $\{t_1,t_2,t_3\}$ that give a partition of t, the polynomials $f_{t_1}, f_{t_2}, f_{t_3}$ depend on disjoint sets of variables. Hence, since we only sum over $\{t_1,t_2,t_3\}$ that give partitions of t, it follows by induction that the polynomial f_t is multilinear.

5.2 Upper bound

The inductive definition of f gives a syntactic multilinear circuit for f. Note that since we defined an arithmetic circuit to be of fan-in (i. e., in-degree) 2 (see Section 1.1), we need to replace the sum in the definition of each f_t by a tree of depth $O(\log n)$ of sum gates (of in-degree 2).

The final circuit is of size polynomial in n, since the size of $\mathcal{T}$ (and hence also the size of X' and the size of $\mathcal{P}(t)$ for every $t \in \mathcal{T}$) is polynomial in n.

The circuit is of depth $O(\log^2 n)$, since in the definition of f_t we only sum over $\{t_1,t_2,t_3\}$ with $L(t_1), L(t_2), L(t_3) \leq 0.75 \cdot L(t)$ and since $L(([n], \emptyset)) < n$. (Note that this gives a depth of $O(\log n)$, but since we replace every sum by a tree of depth $O(\log n)$ of sum gates we get another factor of $O(\log n)$).

Corllary 5.2. *Over any field* $\mathbb{F}$, *the polynomial* f *(as defined above) can be computed by a polynomial-size syntactic multilinear circuit of depth* $O(\log^2 n)$.

5.3 Lower bound

We will now show that any multilinear formula for f, over any field $\mathbb{F}$, is of size $n^{\Omega(\log n)}$. For the proof, we use Corollary 3.8.

Let $n = 2m$. Let $\mathbb{G}$ be a field extending $\mathbb{F}$, such that the transcendental dimension of $\mathbb{G}$ over $\mathbb{F}$ is infinite, that is, $\mathbb{G}$ contains an infinite number of elements that are algebraically independent over $\mathbb{F}$. Define $A' : X' \to \mathbb{G}$ to be such that the variables in X' are mapped to elements that are algebraically independent over $\mathbb{F}$.

Let A be any partition of the variables in X into $\{y_1,\ldots,y_m\} \dot\cup \{z_1,\ldots,z_m\}$. Denote by $f_{A',A}$ the polynomial f after substituting in every variable in X' the value assigned to it by A' and after replacing every variable in X by the variable assigned to it by A.

Claim 5.3. *Over the field* $\mathbb{G}$,

$$\mathrm{Rank}(M_{f_{A',A}}) = 2^m \quad .$$

Proof. In this proof, the Rank function is always taken over the field $\mathbb{G}$. For simplicity, we denote in this proof by g the polynomial $f_{A',A}$, and for every t we denote by g_t the polynomial $f_{t,A',A}$ (i. e., the polynomial f_t after substituting in every variable in X' the value assigned to it by A' and after replacing every variable in X by the variable assigned to it by A).

Define the function $\tilde{A} : [n] \to \{1,-1\}$ by $\tilde{A}(i) = 1$ if $A(x_i) \in \{y_1,\ldots,y_m\}$ and $\tilde{A}(i) = -1$ if $A(x_i) \in \{z_1,\ldots,z_m\}$. For simplicity, we denote the set $\mathcal{B}_{\tilde{A}}$ also by $\mathcal{B}_A$. We will prove by induction on $L(t)$ that for every $t \in \mathcal{B}_A$,

$$\mathrm{Rank}(M_{g_t}) \geq 2^{l(t)/2} \quad .$$

For $L(t) = l(t) = 0$, we defined $f_t = 1$. Hence, M_{g_t} is the 1×1 identity matrix and its rank is 1. For $0 < L(t) \leq 2$, we know that $l(t) = 2$, and we defined $f_t = x_{i_t} \cdot x_{j_t} + 1$. Since $t \in \mathcal{B}_A$, the matrix M_{g_t} is the 2×2 identity matrix and its rank is 2.

For $L(t) > 2$,

$$f_t = \sum_{\{t_1,t_2,t_3\} \in \mathcal{P}(t)} x'_{t,t_1,t_2,t_3} \cdot f_{t_1} \cdot f_{t_2} \cdot f_{t_3} \quad .$$

Hence,

$$g_t = \sum_{\{t_1,t_2,t_3\} \in \mathcal{P}(t)} A'(x'_{t,t_1,t_2,t_3}) \cdot g_{t_1} \cdot g_{t_2} \cdot g_{t_3} \quad ,$$

and by Proposition 3.1,

$$M_{g_t} = \sum_{\{t_1,t_2,t_3\} \in \mathcal{P}(t)} A'(x'_{t,t_1,t_2,t_3}) \cdot M_{g_{t_1} \cdot g_{t_2} \cdot g_{t_3}} \quad .$$

Therefore, since every $A'(x'_{t,t_1,t_2,t_3})$ is algebraically independent (over F) of all the other elements in the domain of A' and all the coefficients that occur in any of the matrices in the sum[6],

$$\text{Rank}(M_{g_t}) \geq \max_{\{t_1,t_2,t_3\} \in \mathcal{P}(t)} \text{Rank}(M_{g_{t_1} \cdot g_{t_2} \cdot g_{t_3}}) \quad .$$

By Lemma 5.1, there exist $\hat{t}_1, \hat{t}_2, \hat{t}_3 \in \mathcal{B}_A$, such that $\{\hat{t}_1, \hat{t}_2, \hat{t}_3\} \in \mathcal{P}(t)$. Thus, by Proposition 3.2 and by the inductive hypothesis for $\hat{t}_1, \hat{t}_2, \hat{t}_3$,

$$\begin{aligned} \text{Rank}(M_{g_t}) \geq \text{Rank}(M_{g_{\hat{t}_1} \cdot g_{\hat{t}_2} \cdot g_{\hat{t}_3}}) &= \text{Rank}(M_{g_{\hat{t}_1}}) \cdot \text{Rank}(M_{g_{\hat{t}_2}}) \cdot \text{Rank}(M_{g_{\hat{t}_3}}) \\ &\geq 2^{l(\hat{t}_1)/2} \cdot 2^{l(\hat{t}_2)/2} \cdot 2^{l(\hat{t}_3)/2} = 2^{l(t)/2} \quad . \end{aligned}$$

Since this is true for every $t \in \mathcal{B}_A$, we can apply it to $t = ([n], \emptyset) \in \mathcal{B}_A$ and get

$$\text{Rank}(M_g) \geq 2^m \quad .$$

Since M_g is a matrix of size $2^m \times 2^m$, we actually have an equality in the last formula. □

Corllary 5.4. *Over any field* F, *any multilinear formula for the polynomial* f *(as defined above) is of size* $n^{\Omega(\log n)}$.

Proof. Follows immediately from Corollary 3.8 and Claim 5.3. □

5.4 Proof of Theorem 1.1

Theorem 1.1 follows immediately from Corollary 5.2 and Corollary 5.4.

[6]More precisely, $A'(x'_{t,t_1,t_2,t_3})$ is transcendental over the field F extended by every other element in the domain of A'. That field obviously contains any coefficient that occurs in any of the matrices in the sum.

5.5 Proof of Lemma 5.1

Before giving the proof of Lemma 5.1, we will need to prove two other lemmas.

Lemma 5.5. *Let A be a function $A : [n] \to \{1, -1\}$. Let $t = (s_1, s_2) \in \mathcal{B}_A$ be such that $l(t) > 2$ and $l(s_1), l(s_2) > 0$. Then, there exist $t_1, t_2 \in \mathcal{B}_A$, such that $\{t_1, t_2\}$ is a proper partition of t.*

Proof. Let $s_1 = [i_1, j_1]$, $s_2 = [i_2, j_2]$. Since $t \in \mathcal{B}_A$, we have $A(s_1) + A(s_2) = 0$. If $A(s_1) = A(s_2) = 0$ then we can define $t_1 = (s_1, \emptyset)$, $t_2 = (\emptyset, s_2)$. Otherwise, we can assume w.l.o.g. that $A(s_1)$ is negative and $A(s_2)$ is positive.

If $A(i_1) \neq A(i_2)$, we can define $t_1 = ([i_1, i_1], [i_2, i_2])$, $t_2 = ([i_1 + 1, j_1], [i_2 + 1, j_2])$. Otherwise, we can assume w.l.o.g. that $A(i_1) = A(i_2) = 1$.

Since $A(s_1)$ is negative and $A(i_1) = 1$, there must exist $j' \in s_1$, such that $A([i_1, j']) = 0$. We can then define $t_1 = ([i_1, j'], \emptyset)$, $t_2 = ([j' + 1, j_1], s_2)$. Since we required $l(t) > 2$ and $l(s_1), l(s_2) > 0$, we have in all cases $l(t_1), l(t_2) > 0$, and hence $\{t_1, t_2\}$ is a proper partition of t. □

Lemma 5.6. *Let A be a function $A : [n] \to \{1, -1\}$. Let $t = (s_1, s_2) \in \mathcal{B}_A$ be such that $l(t) > 2$ and $l(s_1), l(s_2) > 0$. Then, there exist $t_1, t_2, t_3 \in \mathcal{B}_A$, such that $\{t_1, t_2, t_3\}$ is a partition of t, and*

1. *$L(t_1), L(t_3) \leq 0.5 \cdot L(t)$.*
2. *$L(t_2) \leq 0.75 \cdot L(t)$.*
3. *$l(t_2) \leq \max(l(s_1), l(s_2))$.*

Proof. First note that since $l(s_1), l(s_2) > 0$, we have $L(t) = l(t)$, and since $l(t) > 2$ and is even, $L(t) = l(t) \geq 4$. We will describe a procedure for finding t_1, t_2, t_3 with the required properties.

We start with $\hat{t}_1 = (\emptyset, \emptyset)$, $\hat{t}_2 = (s_1, s_2)$ and $\hat{t}_3 = (\emptyset, \emptyset)$. Note that $t = \hat{t}_1 \circ \hat{t}_2 \circ \hat{t}_3$.

Claim 5.7. *Let $t'_1, t'_2, t'_3 \in \mathcal{B}_A$ be such that $t = t'_1 \circ t'_2 \circ t'_3$. Assume that $l(t'_1), l(t'_3) \leq 0.5 \cdot l(t)$ and that both intervals in t'_2 are non-empty, and $l(t'_2) > 2$. Then, there exist $t''_1, t''_2, t''_3 \in \mathcal{B}_A$, such that $t = t''_1 \circ t''_2 \circ t''_3$, and $l(t''_1), l(t''_3) \leq 0.5 \cdot l(t)$, and $l(t''_2) < l(t'_2)$.*

Proof. By Lemma 5.5 (applied to t'_2), there exist $\tilde{t}_1, \tilde{t}_3 \in \mathcal{B}_A$, such that $\{\tilde{t}_1, \tilde{t}_3\}$ is a proper partition of t'_2. Since $t = t'_1 \circ t'_2 \circ t'_3$ and since $t'_2 = \tilde{t}_1 \circ \tilde{t}_3$, we have $t = t'_1 \circ \tilde{t}_1 \circ \tilde{t}_3 \circ t'_3$.

If $l(t'_1) + l(\tilde{t}_1) \leq 0.5 \cdot l(t)$ then we can define $t''_1 = t'_1 \circ \tilde{t}_1$, $t''_2 = \tilde{t}_3$, $t''_3 = t'_3$. Otherwise, $l(\tilde{t}_3) + l(t'_3) \leq 0.5 \cdot l(t)$, and we can define $t''_1 = t'_1$, $t''_2 = \tilde{t}_1$, $t''_3 = \tilde{t}_3 \circ t'_3$.

Since $\{\tilde{t}_1, \tilde{t}_3\}$ is a proper partition of t'_2, in both cases $l(t''_2) < l(t'_2)$. □

We now continue with the proof of Lemma 5.6. We apply Lemma 5.7 on $t'_1 = \hat{t}_1$, $t'_2 = \hat{t}_2$, $t'_3 = \hat{t}_3$, and we substitute (i. e., redefine) $\hat{t}_1 \doteq t''_1$, $\hat{t}_2 \doteq t''_2$, $\hat{t}_3 \doteq t''_3$. We keep applying Claim 5.7 and substituting in $\hat{t}_1, \hat{t}_2, \hat{t}_3$, until the conditions of Claim 5.7 are not satisfied by $\hat{t}_1, \hat{t}_2, \hat{t}_3$, namely, either $l(\hat{t}_2) \leq 2$ or one of the intervals in $\hat{t}_2$ is empty. (Note that the process must stop because $l(\hat{t}_2)$ keeps decreasing.) At this point we can define $t_1 = \hat{t}_1$, $t_2 = \hat{t}_2$, $t_3 = \hat{t}_3$.

Since t_1, t_2, t_3 are the output of Claim 5.7, $t_1, t_2, t_3 \in \mathcal{B}_A$, and $\{t_1, t_2, t_3\}$ is a partition of t, and $L(t_1), L(t_3) \leq 0.5 \cdot l(t) = 0.5 \cdot L(t)$. It remains to prove that $L(t_2) \leq 0.75 \cdot L(t)$, and $l(t_2) \leq \max(l(s_1), l(s_2))$. Recall that there were two possibilities: either $l(t_2) \leq 2$ or one of the intervals in t_2 is empty.

In the first case, $L(t_2) \leq l(t_2) \leq 2$. Since $L(t) = l(t) \geq 4$, we have in the first case, $L(t_2) \leq 0.5 \cdot L(t)$, and $l(t_2) \leq 0.5 \cdot l(t) \leq \max(l(s_1), l(s_2))$.

In the second case, $L(t_2) = 0.75 \cdot l(t_2) \leq 0.75 \cdot l(t) = 0.75 \cdot L(t)$. Since the non-empty interval of t_2 is a sub-interval of either s_1 or s_2, we have $l(t_2) \leq \max(l(s_1), l(s_2))$. □

Proof of Lemma 5.1. Let $t = (s_1, s_2)$. If $l(s_1), l(s_2) > 0$, then the proof follows by Lemma 5.6. Otherwise, one of the intervals s_1, s_2 is empty. W. l. o. g. assume that s_1 is empty. Then, since $t \in \mathcal{B}_A$, we know that $l(s_2) = l(t)$ is even. Partition s_2 into two intervals $\{s'_1, s'_2\}$ with $l(s'_1) = l(s'_2) = 0.5 \cdot l(s_2)$. The proof now follows by applying Lemma 5.6 on $t' = (s'_1, s'_2)$ as follows.

Note that $L(t) = 0.75 \cdot l(t) = 0.75 \cdot l(t') = 0.75 \cdot L(t')$. By Lemma 5.6 there exist $t_1, t_2, t_3 \in \mathcal{B}_A$, such that $\{t_1, t_2, t_3\}$ is a partition of t' (and hence also of t), and $L(t_1), L(t_3) \leq 0.5 \cdot L(t') < 0.75 \cdot L(t)$, and $L(t_2) \leq l(t_2) \leq \max(l(s'_1), l(s'_2)) = 0.5 \cdot l(t) < 0.75 \cdot L(t)$. □

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