Improved bounds on Fourier entropy and Min-entropy

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Abstract

Given a Boolean function $f : \{-1,1\}^n \to \{-1,1\}$, define the *Fourier distribution* to be the distribution on subsets of $[n]$, where each $S \subseteq [n]$ is sampled with probability $\widehat{f}(S)^2$. The Fourier Entropy-Influence (FEI) conjecture of Friedgut and Kalai [24] seeks to relate two fundamental measures associated with the Fourier distribution: does there exist a universal constant $C > 0$ such that $\mathbb{H}(\hat{f}^2) \leq C \cdot \mathsf{Inf}(f)$, where $\mathbb{H}(\hat{f}^2)$ is the Shannon entropy of the Fourier distribution of f and $\mathsf{Inf}(f)$ is the total influence of f?

In this paper we present three new contributions towards the FEI conjecture:

(i) Our first contribution shows that $\mathbb{H}(\hat{f}^2) \leq 2 \cdot \mathsf{aUC}^{\oplus}(f)$, where $\mathsf{aUC}^{\oplus}(f)$ is the average unambiguous parity-certificate complexity of f. This improves upon several bounds shown by Chakraborty et al. [16]. We further improve this bound for unambiguous DNFs.

(ii) We next consider the weaker *Fourier Min-entropy-Influence* (FMEI) conjecture posed by O'Donnell and others [43, 40] which asks if $\mathbb{H}_\infty(\hat{f}^2) \leq C \cdot \mathsf{Inf}(f)$, where $\mathbb{H}_\infty(\hat{f}^2)$ is the min-entropy of the Fourier distribution. We show $\mathbb{H}_\infty(\hat{f}^2) \leq 2 \cdot \mathsf{C}^{\oplus}_{\min}(f)$, where $\mathsf{C}^{\oplus}_{\min}(f)$ is the minimum parity certificate complexity of f. We also show that for all $\varepsilon \geq 0$, we have $\mathbb{H}_\infty(\hat{f}^2) \leq 2\log(\|\widehat{f}\|_{1,\varepsilon}/(1-\varepsilon))$, where $\|\widehat{f}\|_{1,\varepsilon}$ is the approximate spectral norm of f. As a corollary, we verify the FMEI conjecture for the class of read-k DNFs (for constant k).

(iii) Our third contribution is to better understand implications of the FEI conjecture for the structure of polynomials that 1/3-approximate a Boolean function on the Boolean cube. We pose a conjecture: no *flat polynomial* (whose non-zero Fourier coefficients have the same magnitude) of degree d and sparsity $2^{\omega(d)}$ can 1/3-approximate a Boolean function. This conjecture is known to be true assuming FEI and we prove the conjecture unconditionally (i.e., without assuming the FEI conjecture) for a class of polynomials. We discuss an intriguing connection between our conjecture and the constant for the Bohnenblust-Hille inequality, which has been extensively studied in functional analysis.

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1 Introduction

Boolean functions $f : \{-1,1\}^n \to \{-1,1\}$ naturally arise in many areas of theoretical computer science and mathematics such as learning theory, complexity theory, quantum computing, inapproximability, graph theory, extremal combinatorics, etc. Fourier analysis over the Boolean cube $\{-1,1\}^n$ is a powerful technique that has been used often to analyze problems in these areas. For a survey on the subject, see [40, 54]. One of the most important and longstanding open problems in this field is the *Fourier Entropy-Influence* (FEI) conjecture, first formulated by Ehud Friedgut and Gil Kalai in 1996 [24]. The FEI conjecture seeks to relate the following two fundamental properties of a Boolean function f: the *Fourier entropy* of f and the *total influence* of f, which we define now.

For a Boolean function $f : \{-1,1\}^n \to \{-1,1\}$, Parseval's identity relates the *Fourier coefficients* $\{\widehat{f}(S)\}_S$ and the values $\{f(x)\}_x$ by

$$\sum_{S\subseteq[n]} \widehat{f}(S)^2 = \mathbb{E}_x[f(x)^2] = 1,$$

where the expectation is taken uniformly over the Boolean cube $\{-1,1\}^n$. An immediate implication of this equality is that the squared Fourier coefficients $\{\widehat{f}(S)^2 : S \subseteq [n]\}$ can be viewed as a *probability distribution* over subsets $S \subseteq [n]$, which we often refer to as the *Fourier distribution*. The *Fourier entropy of* f (denoted $\mathbb{H}(\hat{f}^2)$) is then defined as the Shannon entropy of the Fourier distribution, i.e.,

$$\mathbb{H}(\hat{f}^2) := \sum_{S\subseteq[n]} \widehat{f}(S)^2 \log \frac{1}{\widehat{f}(S)^2}.$$

The *total influence of* f (denoted $\mathsf{Inf}(f)$) measures the *expected size* of a subset $S \subseteq [n]$, where the expectation is taken according to the Fourier distribution, i.e.,

$$\mathsf{Inf}(f) = \sum_{S\subseteq[n]} |S|\ \widehat{f}(S)^2.$$

Combinatorially $\mathsf{Inf}(f)$ is the same as the average sensitivity $\mathsf{as}(f)$ of f. In particular, for $i \in [n]$, define $\mathsf{Inf}_i(f)$ to be the probability that on a uniformly random input flipping the i-th bit changes the function value. Then, $\mathsf{Inf}(f)$ is defined to be $\sum_{i=1}^n \mathsf{Inf}_i(f)$.

Intuitively, the Fourier entropy measures how "spread out" the Fourier distribution is over the 2^n subsets of $[n]$ and the total influence measures the concentration of the Fourier distribution on the "high" level coefficients. Informally, the FEI conjecture states that Boolean functions whose Fourier distribution is well "spread out" (i.e., functions with large Fourier entropy) must have significant Fourier weight on the high-degree monomials (i.e., their total influence is large). Formally, the FEI conjecture can be stated as follows:

▷ Conjecture 1.1 (FEI Conjecture). There exists a universal constant $C > 0$ such that for every Boolean function $f : \{-1,1\}^n \to \{-1,1\}$,

$$\mathbb{H}(\hat{f}^2) \le C \cdot \mathsf{Inf}(f). \tag{1}$$

The original motivation of Friedgut and Kalai for the FEI conjecture came from studying threshold phenomena of monotone graph properties in random graphs [24]. For example, resolving the FEI conjecture would imply that every threshold interval of a monotone graph property on n vertices is of length at most $c(\log n)^{-2}$ (for some universal constant $c > 0$).

The current best upper bound, proven by Bourgain and Kalai [11], is $c_\varepsilon(\log n)^{-2+\varepsilon}$ for every $\varepsilon > 0$.

Besides this application, the FEI conjecture is known to imply the famous Kahn-Kalai-Linial theorem [30] (otherwise referred to as the KKL theorem). The KKL theorem was one of the first major applications of Fourier analysis to understanding properties of Boolean functions and has since found many application in various areas of theoretical computer science.

▶ **Theorem 1.2** (KKL theorem). *For every $f : \{-1,1\}^n \to \{-1,1\}$, there exists an $i \in [n]$ such that $\mathsf{Inf}_i(f) \geq \mathsf{Var}(f) \cdot \Omega\Big(\frac{\log n}{n}\Big)$.*

See Section 2 for the definitions of these quantities. Another motivation to study the FEI conjecture is that a positive answer to this conjecture would resolve the notoriously hard conjecture of Mansour [37] from 1995.

▷ Conjecture 1.3 (Mansour's conjecture). Suppose $f : \{-1,1\}^n \to \{-1,1\}$ is computed by a t-term DNF.[1] Then for every $\varepsilon > 0$, there exists a family $\mathcal{T}$ of subsets of $[n]$ such that $|\mathcal{T}| \leq t^{O(1/\varepsilon)}$ (i.e., size of $\mathcal{T}$ is polynomial in t) and $\sum_{T\in\mathcal{T}} \widehat{f}(T)^2 \geq 1 - \varepsilon$.

A positive answer to Mansour's conjecture, along with the query algorithm of Gopalan et al. [26], would resolve a long-standing open question in computational learning theory of agnostically learning DNFs under the uniform distribution in polynomial time (up to any constant accuracy).

More generally, the FEI conjecture implies that every Boolean function can be approximated (in ℓ_2-norm) by *sparse* polynomials over $\{-1,1\}$. In particular, for a Boolean function f and $\varepsilon > 0$, the FEI conjecture implies the existence of a polynomial p with $2^{O(\mathsf{Inf}(f)/\varepsilon)}$ monomials such that $\mathbb{E}_x[(f(x) - p(x))^2] \leq \varepsilon$. The current best known bound in this direction is $2^{O(\mathsf{Inf}(f)^2/\varepsilon^2)}$, proven by Friedgut [23].[2]

Given the inherent difficulty in answering the FEI conjecture for arbitrary Boolean functions, there have been many recent works studying the conjecture for specific classes of Boolean functions. We give a brief overview of these results in the next section. Alongside the pursuit of resolving the FEI conjecture, O'Donnell and others [43, 40] have asked if a weaker question than the FEI conjecture, the *Fourier Min-entropy-Influence* (FMEI) conjecture can be resolved. The FMEI conjecture asks if the entropy-influence inequality in Eq. (1) holds when the entropy of the Fourier distribution is replaced by the *min-entropy* of the Fourier distribution (denoted $\mathbb{H}_\infty(\hat{f}^2)$). The min-entropy of $\{\widehat{f}(S)^2\}_S$ is defined as

$$\mathbb{H}_\infty(\hat{f}^2) := \min_{\substack{S\subseteq[n]:\\ \widehat{f}(S)\neq 0}} \left\{ \log \frac{1}{\widehat{f}(S)^2} \right\}$$

and thus it is easily seen that $\mathbb{H}_\infty(\hat{f}^2) \leq \mathbb{H}(\hat{f}^2)$. In fact, $\mathbb{H}_\infty(\hat{f}^2)$ could be much smaller compared to $\mathbb{H}(\hat{f}^2)$. For instance, consider the function $f(x) := x_1 \vee \mathsf{IP}(x_1, \ldots, x_n)$; then $\mathbb{H}_\infty(\hat{f}^2) = O(1)$ whereas $\mathbb{H}(\hat{f}^2) = \Omega(n)$. (IP is the inner-product-mod-2 function.) So the FMEI conjecture could be strictly weaker than the FEI conjecture, making it a natural candidate to resolve first.

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[1] A t-term DNF is a disjunction of at most t conjunctions of variables and their negations.

[2] Friedgut's Junta theorem says that f is ε-close to a junta on $2^{O(\mathsf{Inf}(f)/\varepsilon)}$ variables. We refer to [40, Section 9.6, page 269, Friedgut's Junta Theorem] for details.

▷ Conjecture 1.4 (FMEI Conjecture). There exists a universal constant $C > 0$ such that for every Boolean function $f : \{-1,1\}^n \to \{-1,1\}$, we have $\mathbb{H}_\infty(\hat{f}^2) \leq C \cdot \mathsf{Inf}(f)$.

Another way to formulate the FMEI conjecture is, suppose $f : \{-1,1\}^n \to \{-1,1\}$, then does there exist a Fourier coefficient $\widehat{f}(S)$ such that $|\widehat{f}(S)| \geq 2^{-O(\mathsf{Inf}(f))}$? By the *granularity* of Fourier coefficients it is well-known that *every* Fourier coefficient of a Boolean function f is an integral multiple of $2^{-\mathsf{deg}(f)}$, see [40, Exercise 1.11] for a proof of this. (Here the $\mathsf{deg}(f)$ refers to the degree of the unique multilinear polynomial that represents f.) The FMEI conjecture asks if we can prove a lower bound of $2^{-O(\mathsf{Inf}(f))}$ on *any one* Fourier coefficient, and even this remains open. Proving the FMEI conjecture seems to require proving interesting structural properties of Boolean functions. In fact, as observed by [43], the FMEI conjecture suffices to imply the KKL theorem.

Understanding the min-entropy of a Fourier distribution is important in its own right too. It was observed by Akavia et al. [2] that for a circuit class $\mathcal{C}$, tighter relations between min-entropy of $f \in \mathcal{C}$ and f_A defined as $f_A(x) := f(Ax)$, for an arbitrary linear transformation A, could enable us to translate lower bounds against the class $\mathcal{C}$ to the class $\mathcal{C} \circ \mathsf{MOD}_2$. In particular, they conjectured that min-entropy of f_A is only polynomially larger than f when $f \in \mathsf{AC}^0[\mathsf{poly}(n), O(1)]$. ($\mathsf{AC}^0[s,d]$ is the class of unbounded fan-in circuits of size at most s and depth at most d.) It is well-known that when $f \in \mathsf{AC}^0[s,d]$, $\mathbb{H}_\infty(\hat{f}^2)$ is at most $O((\log s)^{d-1} \cdot \log\log s)$ [35, 10, 51]. Depending on the tightness of the relationship between $\mathbb{H}_\infty(\hat{f}^2)$ and $\mathbb{H}_\infty(\widehat{f_A}^2)$, one could obtain near-optimal lower bound on the size of $\mathsf{AC}^0[s,d] \circ \mathsf{MOD}_2$ circuits computing IP (inner-product-mod-2). This problem has garnered a lot of attention in recent times for a variety of reasons [48, 46, 2, 18, 17]. The current best known lower bound for IP against $\mathsf{AC}^0[s,d] \circ \mathsf{MOD}_2$ is quadratic when $d = 4$, and only super-linear for all $d = O(1)$ [17].

Organization We end this introduction with an overview of prior work on the FEI and FMEI conjecture in Section 1.1. We then describe our contributions and sketch the proofs in Section 3. We conclude in Section 4. Due to lack of space the proofs have been omitted. We refer to the full version [5] for any omission from this version.

1.1 Prior work

After Friedgut and Kalai [24] posed the FEI conjecture in 1996, there was not much work done towards resolving it, until the work of Klivans et al. [33] in 2010. They showed that the FEI conjecture holds true for random DNF formulas. Since then, there have been many significant steps taken in the direction of resolving the FEI conjecture. We review some recent works here, referring the interested reader to the blog post of Kalai [31] for additional discussions on the FEI conjecture.

The FEI conjecture is known to be true when we replace the universal constant C with $\log n$ in Eq. (1). In fact we know $\mathbb{H}(\hat{f}^2) \leq O(\mathsf{Inf}(f) \cdot \log n)$ for *real-valued* functions $f : \{-1,1\}^n \to \mathbb{R}$ (see [43, 32] for a proof and [16] for an improvement of this statement).[3] If we strictly require C to be a universal constant, then the FEI conjecture is known to be false for real-valued functions. Instead, for real-valued functions an analogous statement called the *logarithmic Sobolev Inequality* [28] is known to be true. The logarithmic Sobolev inequality states that for every $f : \{-1,1\}^n \to \mathbb{R}$, we have $\mathsf{Ent}(f^2) \leq 2 \cdot \mathsf{Inf}(f)$, where $\mathsf{Ent}(f)$

[3] For Boolean functions, the $\log n$-factor was improved by [27] to $\log(\mathsf{s}(f))$ (where $\mathsf{s}(f)$ is the sensitivity of the Boolean function f).

is defined as $\mathsf{Ent}(f) = \mathbb{E}[f \ln(f)] - \mathbb{E}[f] \ln(\mathbb{E}[f])$, where the expectation is taken over uniform $x \in \{-1,1\}^n$.

Restricting to Boolean functions, the FEI conjecture is known to be true for the "standard" functions that arise often in analysis, such as AND, OR, Majority, Parity, Bent functions and Tribes. There have been many works on proving the FEI conjecture for specific classes of Boolean functions. O'Donnell et al. [43] showed that the FEI conjecture holds for symmetric Boolean functions and read-once decision trees. Keller et al. [32] studied a generalization of the FEI conjecture when the Fourier coefficients are defined on biased product measures on the Boolean cube. Then, Chakraborty et al. [16] and O'Donnell and Tan [41], independently and simultaneously, proved the FEI conjecture for read-once formulas. In fact, O'Donnell and Tan proved an interesting composition theorem for the FEI conjecture (we omit the definition of composition theorem here, see [41] for more). For general Boolean functions, Chakraborty et al. [16] gave several upper bounds on the Fourier entropy in terms of combinatorial quantities larger than the total influence, e.g., average decision tree depth, etc., and sometimes even quantities that could be much smaller than influence, namely, average parity-decision tree depth.

Later Wan et al. [53] used Shannon's source coding theorem [49] (which characterizes entropy) to establish the FEI conjecture for read-k decision trees for constant k. Using their novel interpretation of the FEI conjecture they also reproved O'Donnell-Tan's composition theorem in an elegant way. Recently, Shalev [47] improved the constant in the FEI inequality for read-k decision trees, and further verified the conjecture when either the influence is *too low*, or the entropy is *too high*. The FEI conjecture is also verified for random Boolean functions by Das et al. [20] and for random linear threshold functions (LTFs) by Chakraborty et al. [15].

There has also been some work in giving lower bounds on the constant C in the FEI conjecture. Hod [29] gave a lower bound of $C > 6.45$ (the lower bound holds even when considering the class of monotone functions), improving upon the lower bound of O'Donnell and Tan [41].

However, there has not been much work on the FMEI conjecture. It was observed in [43, 15] that the KKL theorem implies the FMEI conjecture for monotone functions and linear threshold functions. Finally, the FMEI conjecture for "regular" read-k DNFs was recently established by Shalev [47].

2 Preliminaries

Notation. We denote the set $\{1, 2, \ldots, n\}$ by $[n]$. A *partial assignment* of $[n]$ is a map $\tau : [n] \to \{-1, 1, *\}$. Define $|\tau| = |\tau^{-1}(1) \cup \tau^{-1}(-1)|$. A subcube of the Boolean cube $\{-1,1\}^n$ is a set of $x \in \{-1,1\}^n$ that agrees with some partial assignment τ, i.e., $\{x \in \{-1,1\}^n : x_i = \tau(i)$ for every i with $\tau(i) \neq *\}$.

Fourier Analysis. We recall some definitions and basic facts from analysis of Boolean functions, referring to [40, 54] for more. Consider the space of all functions from $\{-1,1\}^n$ to $\mathbb{R}$ equipped with the inner product defined as

$$\langle f, g \rangle := \mathbb{E}_x[f(x)g(x)] = \frac{1}{2^n} \sum_{x \in \{-1,1\}^n} f(x)g(x).$$

For $S \subseteq [n]$, the character function $\chi_S : \{-1,1\}^n \to \{-1,1\}$ is defined as $\chi_S(x) := \prod_{i \in S} x_i$. Then the set of character functions $\{\chi_S\}_{S \subseteq [n]}$ forms an orthonormal basis for the space of

all real-valued functions on $\{-1,1\}^n$. Hence, every real-valued function $f:\{-1,1\}^n \to \mathbb{R}$ has a unique Fourier expansion

$$f(x) = \sum_{S\subseteq[n]} \widehat{f}(S)\chi_S(x).$$

The *degree* of f, denoted $\mathsf{deg}(f)$, is defined as $\max\{|S| : \widehat{f}(S) \neq 0\}$. The *spectral norm* of f is defined to be $\sum_S |\widehat{f}(S)|$. The *Fourier weight* of a function f on a set of coefficients $\mathcal{S} \subseteq 2^{[n]}$ is defined as $\sum_{S\in\mathcal{S}} \widehat{f}(S)^2$. The *approximate spectral norm* of a Boolean function f is defined as

$$\|\widehat{f}\|_{1,\varepsilon} = \min\Big\{ \sum_S |\widehat{p}(S)| : |p(x) - f(x)| \leq \varepsilon \text{ for every } x \in \{-1,1\}^n \Big\}.$$

We note a well-known fact that follows from the orthonormality of the character functions.

▷ Fact 2.1 (Plancherel's Theorem). For any $f, g\colon \{-1,1\}^n \to \mathbb{R}$,

$$\mathbb{E}_x[f(x)g(x)] = \sum_S \widehat{f}(S)\widehat{g}(S).$$

In particular, if $f\colon \{-1,1\}^n \to \{-1,1\}$ is Boolean-valued and $g = f$, we have Parseval's Identity $\sum_S \widehat{f}(S)^2 = \mathbb{E}[f(x)^2]$, which in turn equals 1. Hence $\sum_S \widehat{f}(S)^2 = 1$ and we can view $\{\widehat{f}(S)^2\}_S$ as a probability distribution, which allows us to discuss the Fourier entropy and min-entropy of the distribution $\{\widehat{f}(S)^2\}_S$, defined as

▶ **Definition 2.2.** *For a Boolean function $f : \{-1,1\}^n \to \{-1,1\}$, its Fourier entropy (denoted $\mathbb{H}(\hat{f}^2)$) and min-entropy (denoted $\mathbb{H}_\infty(\hat{f}^2)$) are*

$$\mathbb{H}(\hat{f}^2) := \sum_{S\subseteq[n]} \widehat{f}(S)^2 \log \frac{1}{\widehat{f}(S)^2}, \quad \textit{and} \quad \mathbb{H}_\infty(\hat{f}^2) := \min_{\substack{S\subseteq[n]:\\ \widehat{f}(S)\neq 0}} \Big\{ \log \frac{1}{\widehat{f}(S)^2} \Big\}.$$

Similarly, we can also define the Rényi Fourier entropy.

▶ **Definition 2.3** (Rényi Fourier entropy). *For $f : \{-1,1\}^n \to \{-1,1\}$, $\alpha \geq 0$ and $\alpha \neq 1$, the Rényi Fourier entropy of f of order α is defined as*

$$\mathbb{H}_\alpha(\hat{f}^2) := \frac{1}{1-\alpha} \log \left(\sum_{S\subseteq[n]} |\widehat{f}(S)|^{2\alpha} \right).$$

It is known that in the limit as $\alpha \to 1$, $\mathbb{H}_\alpha(\hat{f}^2)$ is the (Shannon) Fourier entropy $\mathbb{H}(\hat{f}^2)$ (see [19, Chapter 17, Section 8]) and when $\alpha \to \infty$, observe that $\mathbb{H}_\alpha(\hat{f}^2)$ converges to $\mathbb{H}_\infty(\hat{f}^2)$. It is easily seen that $\mathbb{H}_\infty(\hat{f}^2) \leq \mathbb{H}(\hat{f}^2) \leq \mathbb{H}_{\frac{1}{2}}(\hat{f}^2) \leq \mathbb{H}_0(\hat{f}^2)$.

For $f : \{-1,1\}^n \to \{-1,1\}$, the *influence* of a coordinate $i \in [n]$, denoted $\mathsf{Inf}_i(f)$, is defined as

$$\mathsf{Inf}_i(f) = \Pr_{x\in\{-1,1\}^n}[f(x) \neq f(x^{(i)})] = \mathbb{E}_x\Big[\Big(\frac{f(x) - f(x^{(i)})}{2}\Big)^2\Big],$$

where the probability and expectation is taken according to the uniform distribution on $\{-1,1\}^n$ and $x^{(i)}$ is x with the i-th bit flipped. The *total influence* of f, denoted $\mathsf{Inf}(f)$, is

$$\mathsf{Inf}(f) = \sum_{i\in[n]} \mathsf{Inf}_i(f).$$

In terms of the Fourier coefficients of f, it can be shown, e.g., [30], that $\mathsf{Inf}_i(f) = \sum_{S \ni i} \widehat{f}(S)^2$, and therefore

$$\mathsf{Inf}(f) = \sum_{S \subseteq [n]} |S| \widehat{f}(S)^2.$$

The *variance* of a real-valued function f is given by $\mathsf{Var}(f) = \sum_{S \neq \emptyset} \widehat{f}(S)^2$. It easily follows that $\mathsf{Var}(f) \leq \mathsf{Inf}(f)$. We will also need the following version of the well-known KKL theorem.

▶ **Theorem 2.4** (KKL Theorem, [30]). *There exists a universal constant $c > 0$ such that for every $f\colon \{-1,1\}^n \to \{-1,1\}$, we have*

$$\mathsf{Inf}(f) \geq c \cdot \mathsf{Var}(f) \cdot \log \frac{1}{\max_i \mathsf{Inf}_i(f)}.$$

We now introduce some basic complexity measures of Boolean functions which we use often, referring to [13] for more.

Sensitivity. For $x \in \{-1,1\}^n$, the *sensitivity* of f at x, denoted $\mathsf{s}_f(x)$, is defined to be the number of neighbors y of x in the Boolean hypercube (i.e., y is obtained by flipping *exactly* one bit of x) such that $f(y) \neq f(x)$. The sensitivity $\mathsf{s}(f)$ of f is $\max_x\{\mathsf{s}_f(x)\}$. The *average sensitivity* $\mathsf{as}(f)$ of f is defined to be $\mathbb{E}_x[\mathsf{s}_f(x)]$. By the linearity of expectation observe that

$$\mathbb{E}_x[\mathsf{s}_f(x)] = \sum_{i=1}^{n} \Pr_x[f(x) \neq f(x^{(i)})] = \sum_{i=1}^{n} \mathsf{Inf}_i(f) = \mathsf{Inf}(f),$$

so the average sensitivity of f equals the total influence of f. As a result, the FEI conjecture asks if $\mathbb{H}(\hat{f}^2) \leq C \cdot \mathsf{as}(f)$ for every Boolean function f.

Certificate complexity. For $x \in \{-1,1\}^n$, the *certificate complexity* of f at x, denoted $\mathsf{C}(f,x)$, is the minimum number of bits in x that needs to be fixed to ensure that the value of f is constant. The certificate complexity $\mathsf{C}(f)$ of f is $\max_x\{\mathsf{C}(f,x)\}$. The minimum certificate complexity of f is $\mathsf{C}_{\min}(f) = \min_x\{\mathsf{C}(f,x)\}$. The 0-certificate complexity $\mathsf{C}^0(f)$ of f is $\max_{x:f(x)=1}\{\mathsf{C}(f,x)\}$. Similarly, the 1-certificate complexity $\mathsf{C}^1(f)$ of f is $\max_{x:f(x)=-1}\{\mathsf{C}^1(f,x)\}$. Observe that for every $x \in \{-1,1\}^n$, $\mathsf{s}(f,x) \leq \mathsf{C}(f,x)$. This gives $\mathsf{s}(f) \leq \mathsf{C}(f)$ and $\mathsf{as}(f) \leq \mathsf{aC}(f)$ where $\mathsf{aC}(f)$ denotes the *average* certificate complexity of f. As before, the average is taken with respect to the uniform distribution on $\{-1,1\}^n$.

Parity certificate complexity. Analogously, we define the *parity certificate complexity* $\mathsf{C}^{\oplus}(f,x)$ of f at x as the minimum number of parities on the input variables one has to fix in order to fix the value of f at x, i.e.,

$$\mathsf{C}^{\oplus}(f,x) \coloneqq \min\{\mathsf{co\text{-}dim}(H) \mid H \text{ is an affine subspace on which } f \text{ is constant and } x \in H\},$$

where $\mathsf{co\text{-}dim}(H)$ is the *co-dimension* of the affine subspace H. It is easily seen that $\mathsf{C}^{\oplus}(f,x) \leq \mathsf{C}(f,x)$. We also define $\mathsf{C}^{\oplus}(f) \coloneqq \max_x\{\mathsf{C}^{\oplus}(f,x)\}$, and $\mathsf{C}^{\oplus}_{\min}(f) \coloneqq \min_x \mathsf{C}^{\oplus}(f,x)$.

Unambiguous certificate complexity. We now define the *unambiguous certificate complexity* of f. Let $\tau : [n] \to \{-1, 1, *\}$ be a partial assignment. We refer to $S_\tau = \{x \in \{-1,1\}^n : x_i = \tau(i) \text{ for every } i \in [n] \backslash \tau^{-1}(*)\}$ as the subcube generated by τ. We call $C \subseteq \{-1,1\}^n$ a *subcube* of $\{-1,1\}^n$ if there exists a partial assignment τ such that $C = S_\tau$ and the co-dimension of C is the number of bits fixed by τ, i.e., $\mathsf{co\text{-}dim}(C) = |\{i \in [n] : \tau(i) \neq *\}|$. A set of subcubes $\mathcal{C} = \{C_1, \ldots, C_m\}$ *partitions* $\{-1,1\}^n$ if the subcubes are disjoint and they cover $\{-1,1\}^n$, i.e., $C_i \cap C_j = \emptyset$ for $i \neq j$ and $\cup_i C_i = \{-1,1\}^n$.

An *unambiguous certificate* $\mathcal{U} = \{C_1, \ldots, C_m\}$ (also referred to as a *subcube partition*) is a set of subcubes partitioning $\{-1,1\}^n$. We say $\mathcal{U}$ computes a Boolean function $f : \{-1,1\}^n \to \{-1,1\}$ if f is constant on each C_i (i.e., $f(x)$ is the same for all $x \in C_i$). For an unambiguous certificate $\mathcal{U}$, the *unambiguous certificate complexity* on input x (denoted $\mathsf{UC}(\mathcal{U}, x)$), equals $\mathsf{co\text{-}dim}(C_i)$ for the C_i satisfying $x \in C_i$. Define the *average unambiguous certificate complexity* of f with respect to $\mathcal{U}$ as $\mathsf{aUC}(f, \mathcal{U}) \coloneqq \mathbb{E}_x[\mathsf{UC}(\mathcal{U}, x)]$. Then, the *average unambiguous certificate complexity* of f is defined as

$$\mathsf{aUC}(f) \coloneqq \min_{\mathcal{U}} \mathsf{aUC}(f, \mathcal{U}),$$

where the minimization is over all unambiguous certificates for f. Finally, the *unambiguous certificate complexity of* f is

$$\mathsf{UC}(f) \coloneqq \min_{\mathcal{U}} \max_{x} \mathsf{UC}(\mathcal{U}, x).$$

Note that since unambiguous certificates are more restricted than general certificates, we have $\mathsf{C}(f) \leq \mathsf{UC}(f)$.

An unambiguous $\oplus$-certificate $\mathcal{U} = \{C_1, \ldots, C_m\}$ for f is defined to be a collection of monochromatic *affine subspaces* that together partition the space $\{-1,1\}^n$. It is easily seen that a subcube is also an affine subspace. Analogously, for an unambiguous $\oplus$-certificate $\mathcal{U}$, on an input x, $\mathsf{UC}^{\oplus}(\mathcal{U}, x) \coloneqq \mathsf{co\text{-}dim}(C_i)$ for the C_i satisfying $x \in C_i$, and $\mathsf{aUC}^{\oplus}(f, \mathcal{U}) \coloneqq \mathbb{E}_x[\mathsf{UC}^{\oplus}(\mathcal{U}, x)]$. Similarly, we define $\mathsf{aUC}^{\oplus}(f)$ and $\mathsf{UC}^{\oplus}(f)$.

DNFs. A DNF (disjunctive normal form) is a disjunction (OR) of conjunctions (ANDs) of variables and their negations. An *unambiguous* DNF is a DNF that satisfies the additional property that: on every (-1)-input, exactly one of the conjunctions outputs -1.

Approximate degree. The ε-*approximate degree* of $f : \{-1,1\}^n \to \mathbb{R}$, denoted $\mathsf{deg}_\varepsilon(f)$, is defined to be the minimum degree among all multilinear real polynomials p such that $|f(x) - p(x)| \leq \varepsilon$ for all $x \in \{-1,1\}^n$. Usually ε is chosen to be $1/3$, but it can be chosen to be any constant in $(0, 1)$, without significantly changing the model.

Deterministic decision tree. A deterministic decision tree for $f : \{-1,1\}^n \to \{-1,1\}$ is a rooted binary tree where each node is labelled by $i \in [n]$ and the leaves are labelled with an output bit $\{-1,1\}$. On input $x \in \{-1,1\}^n$, the tree proceeds at the i-th node by evaluating the bit x_i and continuing with the subtree corresponding to the value of x_i. Once a leaf is reached, the tree outputs a bit. We say that a deterministic decision tree computes f if for all $x \in \{-1,1\}^n$ its output equals $f(x)$.

A parity-decision tree for f is similar to a deterministic decision tree, except that each node in the tree is labelled by a subset $S \subseteq [n]$. On input $x \in \{-1,1\}^n$, the tree proceeds at the i-th node by evaluating the parity of the bits x_i for $i \in S$ and continues with the subtree corresponding to the value of $\oplus_{i \in S} x_i$. Note that if the subsets at each node have size $|S| = 1$, then we get the standard deterministic decision tree model.

Randomized decision tree. A randomized decision tree for f is a probability distribution R_μ over deterministic decision trees for f. On input x, a decision tree is chosen according to R_μ, which is then evaluated on x. The complexity of the randomized tree is the largest depth among all deterministic trees with non-zero probability of being sampled according to R_μ. One can similarly define a randomized parity-decision tree as a probability distribution $R_\mu^\oplus$ over deterministic parity-decision trees for f.

We say that a randomized decision tree computes f with bounded-error if for all $x \in \{-1,1\}^n$ its output equals $f(x)$ with probability at least $2/3$. $R_2(f)$ (resp. $R_2^\oplus(f)$) denotes the complexity of the optimal randomized (resp. parity) decision tree that computes f with bounded-error, i.e., errs with probability at most $1/3$.

Information Theory. We now recall the following consequence of the law of large numbers, called the *Asymptotic Equipartition Property (AEP)* or *the Shannon-McMillan-Breiman theorem*. See Chapter 3 in the book [19] for more details.

▶ **Theorem 2.5** (Asymptotic Equipartition Property (AEP) Theorem)**.** *Let $\mathbf{X}$ be a random variable drawn from a distribution P and suppose $\mathbf{X_1}, \mathbf{X_2}, \ldots, \mathbf{X_M}$ are independently and identically distributed copies of $\mathbf{X}$, then*

$$-\frac{1}{M}\log P(\mathbf{X}_1, \mathbf{X}_2, \ldots, \mathbf{X}_M) \longrightarrow \mathbb{H}(\mathbf{X})$$

in probability as $M \to \infty$.

▶ **Definition 2.6.** *Fix $\varepsilon \geq 0$. The* typical set $T_\varepsilon^{(M)}(\mathbf{X})$ *with respect to a distribution P is defined to be the set of sequences $(x_1, x_2, \ldots, x_M) \in \mathbf{X_1} \times \mathbf{X_2} \times \cdots \times \mathbf{X_M}$ such that*

$$2^{-M(\mathbb{H}(\mathbf{X})+\varepsilon)} \leq P(x_1, x_2, \ldots, x_M) \leq 2^{-M(\mathbb{H}(\mathbf{X})-\varepsilon)}.$$

The following properties of the typical set follows from the AEP.

▶ **Theorem 2.7** ([19, Theorem 3.1.2])**.** *Let $\varepsilon \geq 0$ and $T_\varepsilon^{(M)}(\mathbf{X})$ be a typical set with respect to P, then*

(i) $|T_\varepsilon^{(M)}(\mathbf{X})| \leq 2^{M(\mathbb{H}(\mathbf{X})+\varepsilon)}$.

(ii) *Suppose $x_1, \ldots, x_M$ are drawn i.i.d. according to $\mathbf{X}$, then* $\Pr[(x_1, \ldots, x_M) \in T_\varepsilon^{(M)}(\mathbf{X})] \geq 1-\varepsilon$ *for M sufficiently large.*

(iii) $|T_\varepsilon^{(M)}(\mathbf{X})| \geq (1-\varepsilon)2^{M(\mathbb{H}(\mathbf{X})-\varepsilon)}$ *for M sufficiently large.*

We also require the following stronger version of typical sequences and asymptotic equipartition property.

▶ **Definition 2.8** ([19, Chapter 11, Section 2])**.** *Let $\mathbf{X}$ be a random variable drawn according to a distribution P. Fix $\varepsilon > 0$. The* strongly typical set $T_\varepsilon^{*(M)}(\mathbf{X})$ *is defined to be the set of sequences $\rho = (x_1, x_2, \ldots, x_M) \in \mathbf{X_1} \times \mathbf{X_2} \times \cdots \times \mathbf{X_M}$ such that $N(x;\rho) = 0$ if $P(x) = 0$, and otherwise*

$$\left|\frac{N(x;\rho)}{M} - P(x)\right| \leq \frac{\varepsilon}{|\mathbf{X}|},$$

where $N(x;\rho)$ is defined as the number of occurrences of x in ρ.

The strongly typical set shares similar properties with its (weak) typical counterpart which we state now. See [19, Chapter 11, Section 2] for a proof of this theorem.

▶ **Theorem 2.9** (Strong AEP Theorem). *Following the notation in Definition 2.8, let* $T_\varepsilon^{*(M)}(\mathbf{X})$ *be a strongly typical set. Then, there exists* $\delta > 0$ *such that* $\delta \to 0$ *as* $\varepsilon \to 0$*, and the following hold:*

(i) *Suppose* $x_1, \ldots, x_M$ *are drawn i.i.d. according to* $\mathbf{X}$*, then* $\Pr[(x_1, \ldots, x_M) \in T_\varepsilon^{*(M)}(\mathbf{X})] \geq 1 - \varepsilon$ *for* M *sufficiently large.*

(ii) *If* $(x_1, \ldots, x_M) \in T_\varepsilon^{*(M)}(\mathbf{X})$*, then*

$$2^{-M(\mathbb{H}(\mathbf{X})+\delta)} \leq P(x_1, \ldots, x_M) \leq 2^{-M(\mathbb{H}(\mathbf{X})-\delta)}.$$

(iii) *For* M *sufficiently large,*

$$(1-\varepsilon)2^{M(\mathbb{H}(\mathbf{X})-\delta)} \leq |T_\varepsilon^{*(M)}(\mathbf{X})| \leq 2^{M(\mathbb{H}(\mathbf{X})+\delta)}.$$

3 Our Contributions

Our contributions in this paper are threefold, which we elaborate on below:

3.1 Better upper bounds for the FEI conjecture

Our first and main contribution of this paper is to give a better upper bound on the Fourier entropy $\mathbb{H}(\hat{f}^2)$ in terms of $\mathsf{aUC}(f)$, the *average unambiguous certificate complexity* of f. Informally, the unambiguous certificate complexity $\mathsf{UC}(f)$ of f is similar to the standard certificate complexity measure, except that the collection of certificates is now required to be *unambiguous*, i.e., every input should be consistent with a *unique* certificate. In other words, an unambiguous certificate is a monochromatic subcube partition of the Boolean cube. By the average unambiguous certificate complexity, $\mathsf{aUC}(f)$, we mean the expected number of bits set by an unambiguous certificate on a uniformly random input.

There have been many recent works on query complexity, giving upper and lower bounds on $\mathsf{UC}(f)$ in terms of other combinatorial measures such as decision-tree complexity, sensitivity, quantum query complexity, etc., see [25, 4, 8] for more. It follows from definitions that $\mathsf{UC}(f)$ lower bounds decision tree complexity. However, it is known that $\mathsf{UC}(f)$ can be quadratically smaller than decision tree complexity [4]. Our main contribution here is an improved upper bound of *average unambiguous certificate complexity* $\mathsf{aUC}(f)$ on $\mathbb{H}(\hat{f}^2)$. This improves upon the previously known bound of average decision tree depth on $\mathbb{H}(\hat{f}^2)$ [16].

▶ **Theorem 3.1.** *Let* $f : \{-1,1\}^n \to \{-1,1\}$ *be a Boolean function. Then,*

$$\mathbb{H}(\hat{f}^2) \leq 2 \cdot \mathsf{aUC}(f).$$

A new and crucial ingredient employed in the proof of the theorem is an analog of the law of large numbers in information theory, usually referred to as the *Asymptotic Equipartition Property (AEP)* theorem (Theorem 2.5). Employing information-theoretic techniques for the FEI conjecture seems very natural given that the conjecture seeks to bound the entropy of a distribution. Indeed, Keller et al. [32, Section 3.1] envisioned a proof of the FEI conjecture itself using large deviation estimates and the tensor structure (explained below) in a stronger way, and Wan et al. [53] used Shannon's source coding theorem [49] to verify the conjecture for bounded-read decision trees.

In order to prove Theorem 3.1, we study the *tensorized* version of f, $f^M : \{-1,1\}^{Mn} \to \{-1,1\}$, which is defined as follows,

$$f^M(x^1, \ldots, x^M) := f(x_1^1, \ldots, x_n^1) \cdot f(x_1^2, \ldots, x_n^2) \cdots f(x_1^M, \ldots, x_n^M).$$

Similarly we define a *tensorized* version $\mathcal{C}^M$ of an unambiguous certificate $\mathcal{C}$ of f,[4] i.e., a direct product of M independent copies of $\mathcal{C}$. It is not hard to see that $\mathcal{C}^M$ is also an unambiguous certificate of f^M. To understand the properties of $\mathcal{C}^M$ we study $\mathcal{C}$ in a probabilistic manner. We observe that $\mathcal{C}$ naturally inherits a distribution $\mathbf{C}$ on its certificates when the underlying inputs $x \in \{-1,1\}^n$ are distributed uniformly. Using the asymptotic equipartition property with respect to $\mathbf{C}$, we infer that for every $\delta > 0$, there exists $M_0 > 0$ such that for all $M \geq M_0$, there are at most $2^{M(\mathsf{aUC}(f,\mathcal{C})+\delta)}$ certificates in $\mathcal{C}^M$ that together cover at least $1-\delta$ fraction of the inputs in $\{-1,1\}^{Mn}$. Furthermore, each of these certificates fixes at most $M(\mathsf{aUC}(f,\mathcal{C})+\delta)$ bits. Hence, a particular certificate can contribute to at most $2^{M(\mathsf{aUC}(f,\mathcal{C})+\delta)}$ Fourier coefficients of f^M. Combining both these bounds, all these certificates can overall contribute to at most $2^{2M(\mathsf{aUC}(f,\mathcal{C})+\delta)}$ Fourier coefficients of f^M. Let's denote this set of Fourier coefficients by $\mathcal{B}$. We then argue that the Fourier coefficients of f^M that are *not* in $\mathcal{B}$ have Fourier weight at most δ. This now allows us to bound the Fourier entropy of f^M as follows,

$$\mathbb{H}(\widehat{f^M}^2) \leq \log|\mathcal{B}| + \delta nM + \mathsf{H}(\delta),$$

where $\mathsf{H}(\delta)$ is the binary entropy function. Since $\mathbb{H}(\widehat{f^M}^2) = M \cdot \mathbb{H}(\hat{f}^2)$, we have

$$\mathbb{H}(\hat{f}^2) \leq 2(\mathsf{aUC}(f,\mathcal{C}) + \delta) + \delta n + \frac{\mathsf{H}(\delta)}{M}.$$

By the AEP theorem, note that $\delta \to 0$ as $M \to \infty$. Thus, taking the limit as $M \to \infty$ we obtain our theorem.

Looking finely into how certificates contribute to Fourier coefficients in the proof above, we further strengthen Theorem 3.1 by showing that we can replace $\mathsf{aUC}(f)$ by the *average unambiguous parity-certificate complexity* $\mathsf{aUC}^{\oplus}(f)$ of f. Here $\mathsf{aUC}^{\oplus}(f)$ is defined similar to $\mathsf{aUC}(f)$ except that instead of being defined in terms of monochromatic subcube partitions of f, we now partition the Boolean cube with monochromatic *affine subspaces*. (Observe that subcubes are also affine subspaces.) This strengthening also improves upon the previously known bound of average parity-decision tree depth on $\mathbb{H}(\hat{f}^2)$ [16]. It is easily seen that $\mathsf{aUC}^{\oplus}(f)$ lower bounds the average parity-decision tree depth.

▶ **Theorem 3.2.** *Let $f : \{-1,1\}^n \to \{-1,1\}$ be any Boolean function. Then,*

$$\mathbb{H}(\hat{f}^2) \leq 2 \cdot \mathsf{aUC}^{\oplus}(f).$$

The proof outline remains the same as in Theorem 3.1. However, a particular certificate in $\mathcal{C}^M$ no longer fixes just variables. Instead these parity certificates now fix parities over variables, and so potentially could involve all variables. Hence we cannot directly argue that all the certificates contribute to at most $2^{M(\mathsf{aUC}^{\oplus}(f,\mathcal{C})+\delta)}$ Fourier coefficients of f^M. Nevertheless, by the AEP theorem we still obtain that a typical parity-certificate fixes at most $M(\mathsf{aUC}^{\oplus}(f,\mathcal{C}) + \delta)$ parities. Looking closely at the Fourier coefficients that a parity-certificate can contribute to, we now argue that such coefficients must lie in the linear span of the parities fixed by the parity-certificate. Therefore, a typical parity-certificate can overall contribute to at most $2^{M(\mathsf{aUC}^{\oplus}(f,\mathcal{C})+\delta)}$ Fourier coefficients of f^M. The rest of the proof now follows analogously.

[4] Recall an unambiguous certificate is a collection of certificates that partitions the Boolean cube $\{-1,1\}^n$.

▶ Remark 3.3. As a corollary to the theorem we obtain that the FEI conjecture holds for the class of functions f with constant $\mathsf{aUC}^{\oplus}(f)$, and $\mathsf{Inf}(f) \geq 1$. That is, for a Boolean function f with $\mathsf{Inf}(f) \geq 1$, we have

$$\mathbb{H}(\hat{f}^2) \leq 2 \cdot \mathsf{aUC}^{\oplus}(f) \cdot \mathsf{Inf}(f).$$

We note that the reduction in [53, Proposition E.2] shows that removing the requirement $\mathsf{Inf}(f) \geq 1$ from the above inequality will prove the FEI conjecture for all Boolean functions with $\mathsf{Inf}(f) \geq \log n$. Furthermore, if we could show the FEI conjecture for Boolean functions f where $\mathsf{aUC}^{\oplus}(f) = \omega(1)$ is a slow-growing function of n, again the padding argument in [53] shows that we would be able to establish the FEI conjecture for all Boolean functions.

Further extension to unambiguous DNFs

Consider an unambiguous certificate $\mathcal{C} = \{C_1, \ldots, C_t\}$ of f. It covers both 1 and -1 inputs of f. Suppose $\{C_1, \ldots, C_{t_1}\}$ for some $t_1 < t$ is a partition of $f^{-1}(-1)$ and $\{C_{t_1+1}, \ldots, C_t\}$ is a partition of $f^{-1}(1)$. To represent f, it suffices to consider $\bigvee_{i=1}^{t_1} C_i$. This is a DNF representation of f with an additional property that $\{C_1, \ldots, C_{t_1}\}$ forms a partition of $f^{-1}(-1)$. We call such a representation an *unambiguous* DNF. In general, a DNF representation need not satisfy this additional property.

Using the equivalence of total influence and average sensitivity, one can easily observe that

$$\mathsf{Inf}(f) \leq 2 \cdot \min \left\{ \sum_{i=1}^{t_1} \mathsf{co\text{-}dim}(C_i) \cdot 2^{-\mathsf{co\text{-}dim}(C_i)}, \sum_{i=t_1+1}^{t} \mathsf{co\text{-}dim}(C_i) \cdot 2^{-\mathsf{co\text{-}dim}(C_i)} \right\} \leq \mathsf{aUC}(f, \mathcal{C}),$$

where $\mathsf{co\text{-}dim}(\cdot)$ denotes the co-dimension of an affine space. Note that the quantity $\sum_{i=1}^{t_1} \mathsf{co\text{-}dim}(C_i) \cdot 2^{-\mathsf{co\text{-}dim}(C_i)}$, in a certain sense, is "average unambiguous 1-certificate complexity" and, similarly, $\sum_{i=t_1+1}^{t} \mathsf{co\text{-}dim}(C_i) \cdot 2^{-\mathsf{co\text{-}dim}(C_i)}$ captures "average unambiguous 0-certificate complexity".

Building on our ideas from the main theorem in the previous section and using a *stronger* version of the AEP theorem (Theorem 2.9) we essentially establish the aforementioned improved bound of the smaller quantity between "average unambiguous 1-certificate complexity" and "average unambiguous 0-certificate complexity" on the Fourier entropy. Formally, we prove the following.

▶ **Theorem 3.4.** *Let $f : \{-1,1\}^n \to \{-1,1\}$ be a Boolean function and $\mathcal{C} = \{C_1, \ldots, C_t\}$ be a monochromatic affine subspace partition of $\{-1,1\}^n$ with respect to f such that $\{C_1, \ldots, C_{t_1}\}$ for some $t_1 < t$ is an affine subspace partition of $f^{-1}(-1)$ and $\{C_{t_1+1}, \ldots, C_t\}$ is an affine subspace partition of $f^{-1}(1)$. Further, $p := \Pr_x[f(x) = 1]$. Then,*

$$\mathbb{H}(\hat{f}^2) \leq \begin{cases} 2\left(\sum_{i=1}^{t_1} \mathsf{co\text{-}dim}(C_i) \cdot 2^{-\mathsf{co\text{-}dim}(C_i)} + p \cdot \max_{i \in \{1,\ldots,t_1\}} \mathsf{co\text{-}dim}(C_i) \right), \\ 2\left(\sum_{i=t_1+1}^{t} \mathsf{co\text{-}dim}(C_i) \cdot 2^{-\mathsf{co\text{-}dim}(C_i)} + (1-p) \cdot \max_{i \in \{t_1+1,\ldots,t\}} \mathsf{co\text{-}dim}(C_i) \right). \end{cases}$$

We remark that to truly claim the bound of "average unambiguous 1-certificate complexity" one would like to remove the additive term $p \cdot \max_{i \in \{1,\ldots,t_1\}} \mathsf{co\text{-}dim}(C_i)$ from the stated bound in the above theorem. This is because when the $\max_i \mathsf{co\text{-}dim}(C_i)$ term is *not* weighted by

p, it becomes a trivial bound on entropy. Ideally, one would like to get rid of this term altogether, possibly at the expense of increasing the constant factor in the first summand.

We also note that a similar bound for the general DNF representation, i.e., when $\{C_1, \ldots, C_{t_1}\}$ is an arbitrary DNF representation of f where the C_is need not be disjoint, suffices to establish Mansour's conjecture (Conjecture 1.3). In fact, following the analogy, Theorem 3.4 implies a bound of "average 1-certificate complexity" in the general case. In this direction, we observe that a weaker bound of 1-certificate complexity, i.e., showing $\mathbb{H}(\widehat{f^2}) \leq O(\mathsf{C}_1(f))$, would already suffice to answer Mansour's conjecture positively. We refer to the full version [5] for a detailed discussion on this.

The outline for the proof of Theorem 3.4 remains the same as before, but it differs in implementation details. We sketch them now. Analogous to the proof of the main theorem we consider a partition of inputs with respect to f and its tensorized version. Motivated by the DNF representation, we study the following partition $\{C_1, \ldots, C_{t_1}, f^{-1}(1)\}$ which naturally inherits a distribution $\mathbf{C}$ given by the uniform distribution on the underlying inputs. Again we build a "small" set $\mathcal{B}$ of Fourier coefficients of f^M based on the Fourier expansions of strongly typical sequences. However, unlike before, the probability of observing a strongly typical sequence doesn't capture the number of coefficients it could contribute to $\mathcal{B}$. Here, we use stronger properties guaranteed by the strong AEP. In particular, it guarantees that the *empirical* distribution of a typical sequence is close to the distribution of $\mathbf{C}$. In contrast, the (weak) AEP only guarantees that the *empirical* entropy of a typical sequence is close to the entropy of $\mathbf{C}$. Using the stronger property we can now lower bound the magnitude of any non-zero Fourier coefficient in the Fourier expansion of the indicator function of a strongly typical sequence. We then use Parseval's Identity (Fact 2.1) to deduce an upper bound on its Fourier sparsity, which in turn is used to bound the size of $\mathcal{B}$. We also need to argue that coefficients *not* in $\mathcal{B}$ have negligible Fourier weight, which can be done as before. Using the two properties, we can now complete the proof.

3.2 New upper bounds for the FMEI conjecture

Given the hardness of obtaining better upper bounds on the Fourier entropy of a Boolean function, we make progress on a weaker conjecture, the FMEI conjecture. The FMEI conjecture is much less studied than the FEI conjecture. In fact, we are aware of only one recent paper [47] which studies the FMEI conjecture for a particular class of functions. Our second contribution is to give upper bounds on the min-entropy of general Boolean functions in terms of the minimum parity-certificate complexity (denoted $\mathsf{C}^{\oplus}_{\min}(f)$) and the approximate spectral norm of Boolean functions (denoted $\|\widehat{f}\|_{1,\varepsilon}$). The minimum parity-certificate complexity $\mathsf{C}^{\oplus}_{\min}(f)$ is also referred to as the parity kill number by O'Donnell et al. [42] and is closely related to the communication complexity of XOR functions [56, 39, 52]. The approximate spectral norm $\|\widehat{f}\|_{1,\varepsilon}$ is related to the *quantum* communication complexity of XOR functions [34, 55]. In particular, it characterizes the bounded-error quantum communication complexity of XOR functions with constant $\mathbb{F}_2$-degree [55]. (By $\mathbb{F}_2$-degree, we mean the degree of a function when viewed as a polynomial over $\mathbb{F}_2$.)

▶ **Theorem 3.5.** *Let $f : \{-1,1\}^n \to \{-1,1\}$ be a Boolean function. Then,*

(1) *For every $\varepsilon \geq 0$, $\mathbb{H}_\infty(\hat{f}^2) \leq 2 \cdot \log\left(\|\widehat{f}\|_{1,\varepsilon}/(1-\varepsilon)\right)$.*

(2) $\mathbb{H}_\infty(\hat{f}^2) \leq 2 \cdot \mathsf{C}^{\oplus}_{\min}(f)$.

(3) $\mathbb{H}_\infty(\hat{f}^2) \leq 2(1+\log_2 3)\cdot R_2^{\oplus}(f)$.[5]

The proof of Theorem 3.5 (1) expresses the quantity $\|\widehat{f}\|_{1,\varepsilon}$ as a (minimization) linear program. We consider the dual linear program and exhibit a feasible solution that achieves an optimum of $(1-\varepsilon)/\max_S |\widehat{f}(S)|$. This proves the desired inequality. In order to prove part (2) and (3) of the theorem, the idea is to consider a "simple" function g that has "good" correlation with f, and then upper bound the correlation between f and g using Plancherel's theorem (Fact 2.1) and the fact that g has a "simple" Fourier structure. For part (2), g is chosen to be the indicator function of an (affine) subspace where f is constant, whereas for part (3) the randomized parity-decision tree computing f itself plays the role of g.[6]

As a corollary of this theorem we also obtain upper bounds on the Rényi Fourier entropy $\mathbb{H}_{1+\delta}(\hat{f}^2)$ of order $1+\delta$ for all $\delta > 0$. Recall that $\mathbb{H}_{1+\delta}(\hat{f}^2) \geq \mathbb{H}_\infty(\hat{f}^2)$ for every $\delta \geq 0$ and as $\delta \to \infty$, $\mathbb{H}_{1+\delta}(\hat{f}^2)$ converges to $\mathbb{H}_\infty(\hat{f}^2)$. Also $\mathbb{H}_1(\hat{f}^2)$ is the standard Shannon entropy of the Fourier distribution. We refer to the full version [5] for a detailed treatment of it.

We believe that these improved bounds on min-entropy of the Fourier distribution give a better understanding of Fourier coefficients of Boolean functions, and could be of independent interest. As a somewhat non-trivial application of Theorem 3.5 (in particular, part (2)) we verify the FMEI conjecture for read-k DNFs, for constant k. (A read-k DNF is a formula where each variable appears in at most k terms.)

▶ **Theorem 3.6.** *For every Boolean function $f\colon \{-1,1\}^n \to \{-1,1\}$ that can be expressed as a read-k DNF, we have*

$$\mathbb{H}_\infty(\hat{f}^2) \;\leq\; O(\log k)\cdot \mathsf{Inf}(f).$$

This theorem improves upon a recent (and independent) result of Shalev [47] that establishes the FMEI conjecture for "regular" read-k DNFs (where regular means each term in the DNF has more or less the same number of variables, see [47] for a precise definition). In order to prove Theorem 3.6, we essentially show that $\mathsf{Inf}(f)$ is at least as large as the minimum certificate complexity $\mathsf{C}_{\min}(f)$ of f.

▶ **Lemma 3.7.** *There exists a universal constant $c > 0$ such that for all $f\colon \{-1,1\}^n \to \{-1,1\}$ that can be expressed as a read-k DNF, we have*

$$\mathsf{Inf}(f) \geq c\cdot \mathsf{Var}(f)\cdot (\mathsf{C}_{\min}(f) - 1 - \log k)\,.$$

The proof of this lemma is an application of the KKL theorem (Theorem 2.4). Now the proof of Theorem 3.6 follows with an application of the lemma in conjunction with Theorem 3.5 (2).

3.3 Implications of the FEI conjecture and connections to the Bohnenblust-Hille inequality

Our final contribution is to understand better the structure of polynomials that ε-approximate Boolean functions on the Boolean cube. To be more specific, for simplicity we fix $\varepsilon = 1/3$ and we consider polynomials p such that $|p(x) - f(x)| \leq 1/3$ for all $x \in \{-1,1\}^n$, where

[5] $R_2^{\oplus}(f)$ is the randomized parity-decision tree complexity of f (we define this formally in Section 2).

[6] We remark here that there exists simpler proof of part (1), along the lines of parts (2) and (3). However, we believe that the linear-programming formulation of $\mathbb{H}_\infty(\hat{f}^2)$ might help obtain better bounds, such as fractional block sensitivity.

f is a Boolean function. Such polynomials have proved to be powerful and found diverse applications in theoretical computer science. The single most important measure associated with such polynomials is its *degree*. The *least* degree of a polynomial that 1/3-approximates f is referred to as the *approximate degree* of f. Tight bounds on approximate degree have both algorithmic and complexity-theoretic implications, see for instance Sherstov's recent paper [50] and references therein.

In this work we ask, suppose the FEI conjecture were true, what can be said about approximating polynomials? For instance, are these approximating polynomials p sparse in their Fourier domain, i.e., is the number of monomials in p, $|\{S\colon \widehat{p}(S) \neq 0\}|$, small? Do approximating polynomials have small spectral norm (i.e., small $\sum_S |\widehat{p}(S)|$)? In order to understand these questions better, we restrict ourselves to a class of polynomials called *flat* polynomials over $\{-1, 1\}$, i.e., polynomials whose non-zero coefficients have the same magnitude.

We first observe that if a flat polynomial p 1/3-approximates a Boolean function f, then the entropy of the Fourier distribution of f must be "large". In particular, we show that $\mathbb{H}(\hat{f}^2)$ must be at least as large as the logarithm of the Fourier sparsity of p.

▷ Claim 3.8. If p is a flat polynomial with sparsity T that 1/3-approximates a Boolean function f, then

$$\mathbb{H}(\hat{f}^2) = \Omega(\log T).$$

It then follows that assuming the FEI conjecture, a flat polynomial of degree d and sparsity $2^{\omega(d)}$ cannot 1/3-approximate a Boolean function. However, it is not clear to us how to obtain the same conclusion *unconditionally* (i.e., without assuming that the FEI conjecture is true) and, so we pose the following conjecture.

▷ Conjecture 3.9. No flat polynomial of degree d and sparsity $2^{\omega(d)}$ can 1/3-approximate a Boolean function.

▶ Remark 3.10. We remark that there exists degree-d flat *Boolean* functions of sparsity 2^d. One simple example on 4 bits is the function $x_1(x_2 + x_3)/2 + x_4(x_2 - x_3)/2$. By taking a $(d/2)$-fold product of this Boolean function on disjoint variables, we obtain our remark.

Since we could not solve the problem as posed above, we make progress in understanding this conjecture by further restricting ourselves to the class of *block-multilinear* polynomials. An n-variate polynomial is said to be *block-multilinear* if the input variables can be *partitioned* into disjoint blocks such that every monomial in the polynomial has *at most* one variable from each block. Such polynomials have been well-studied in functional analysis since the work of Bohnenblust and Hille [9], but more recently have found applications in quantum computing [1, 38], classical and quantum XOR games [12], and polynomial decoupling [44]. In the functional analysis literature block-multilinear polynomials are known as *multilinear forms*. In an ingenious work [9], Bohnenblust and Hille showed that for every degree-d multilinear form $p : (\mathbb{R}^n)^d \to \mathbb{R}$, we have

$$\Big(\sum_{i_1,\ldots,i_d=1}^{n} |\widehat{p}_{i_1,\ldots,i_d}|^{\frac{2d}{d+1}} \Big)^{\frac{d+1}{2d}} \leq C_d \cdot \max_{x^1,\ldots,x^d \in [-1,1]^n} |p(x^1,\ldots,x^d)|, \tag{2}$$

where C_d is a constant that depends on d. In [9], they showed that it suffices to pick C_d to be exponential in d to satisfy the equation above. For $d = 2$, Eq. (2) generalizes Littlewood's famous 4/3-inequality [36]. Eq. (2) is commonly referred to as the Bohnenblust-Hille (BH)

inequality and is known to have deep applications in various fields of analysis such as operator theory, complex analysis, etc. There has been a long line of work on improving the constant C_d in the BH inequality (to mention a few [22, 21, 3, 6, 45]). The best known upper bound on C_d (we are aware of) is polynomial in d. It is also conjectured that it suffices to let C_d be a *universal* constant (independent of d) in order to satisfy Eq. (2).

In our context, using the best known bound on C_d in the BH-inequality implies that a flat block-multilinear polynomial of degree d and sparsity $2^{\omega(d \log d)}$ cannot 1/3-approximate a Boolean function. However, from the discussion before Conjecture 3.9, we know that the FEI conjecture implies the following theorem.

▶ **Theorem 3.11.** *If p is a flat block-multilinear polynomial of degree d and sparsity $2^{\omega(d)}$, then p cannot $1/8$-approximate a Boolean function.*

Moreover, the above theorem is also implied when the BH-constant C_d is assumed to be a universal constant. Our main contribution is to establish the above theorem *unconditionally*, i.e., neither assuming C_d is a universal constant nor assuming the FEI conjecture. In order to show the theorem, we show an inherent weakness of block-multilinear polynomials in approximating Boolean functions. More formally, we show the following.

▶ **Lemma 3.12.** *Let p be a block-multilinear polynomial of degree-d that $1/8$-approximates a Boolean function f. Then, $\mathsf{deg}(f) \leq d$.*

Now using the fact that Fourier entropy of f is at least as large as the logarithm of the sparsity of p (Claim 3.8), we obtain Theorem 3.11.

4 Conclusion

We gave improved upper bounds on Fourier entropy of Boolean functions in terms of average unambiguous (parity)-certificate complexity, and as a corollary verified the FEI conjecture for functions with bounded average unambiguous (parity)-certificate complexity. We established many bounds on Fourier min-entropy in terms of analytic and combinatorial measures, namely minimum certificate complexity, logarithm of the approximate spectral norm and randomized (parity)-decision tree complexity. As a corollary to this, we verified the FMEI conjecture for read-k DNFs. We also studied structural implications of the FEI conjecture on approximating polynomials. In particular, we proved that flat block-multilinear polynomials of degree d and sparsity $2^{\omega(d)}$ can not approximate Boolean functions.

We now list few open problems which we believe are structurally interesting and could lead towards proving the FEI or FMEI conjecture. Let $f : \{-1,1\}^n \to \{-1,1\}$ be a Boolean function.

(1) Does there exist a Fourier coefficient $S \subseteq [n]$ such that $|\widehat{f}(S)| \geq 2^{-O(\mathsf{deg}_{1/3}(f))}$? This would show $\mathbb{H}_\infty(\hat{f}^2) \leq O(\mathsf{deg}_{1/3}(f))$.

(2) Can we show $\mathbb{H}(\hat{f}^2) \leq O(Q(f))$? Or, $\mathbb{H}_\infty(\hat{f}^2) \leq O(Q(f))$? (where $Q(f)$ is the 1/3-error quantum query complexity of f, which Beals et al. [7] showed to be at least $\mathsf{deg}_{1/3}(f)/2$).

(3) Does there exist a universal constant $\lambda > 0$ such that $\mathbb{H}(\hat{f}^2) \leq \lambda \cdot \min\{\mathsf{C}^1(f), \mathsf{C}^0(f)\}$? This would resolve Mansour's conjecture.

In an earlier version of this manuscript we suggested that bounding the logarithm of the approximate spectral norm by $O(\mathsf{deg}_{1/3}(f))$ or $O(Q(f))$ might be an approach to answer Question (1) or (2) above. However, in a very recent work [14] it is shown that $\log(\|\widehat{f}\|_{1,\varepsilon})$ could be as large as $\Omega(Q(f) \cdot \log n)$, thus nullifying the suggested approach.

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