

Resolution of T. Ward’s Question and the Israel–Finch Conjecture. Precise Analysis of an Integer Sequence Arising in Dynamics

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Abstract

We analyze the first-order asymptotic growth of $a_n = \int_0^1 \prod_{j=1}^n 4 \sin^2(\pi j x) dx$. The integer a_n appears as the main term in a weighted average of the number of orbits in a particular quasi-hyperbolic automorphism of a $2n$ -torus, which has applications to ergodic and analytic number theory. The combinatorial structure of a_n is also of interest, as the “signed” number of ways in which 0 can be represented as the sum of $\epsilon_j j$ for $-n \leq j \leq n$ (with $j \neq 0$), with $\epsilon_j \in \{0, 1\}$. Our result answers a question of Thomas Ward (no relation to the fourth author) and confirms a conjecture of Robert Israel and Steven Finch.

Dedicated to the memory of Philippe Flajolet.

1 Introduction and Motivation

We analyze the precise first-order asymptotics of integer sequence **A133871** from the On-Line Encyclopedia of Integer Sequences [13]. The sequence (a_n) is defined by the definite integral

$$a_n := \int_0^1 \prod_{j=1}^n 4 \sin^2(\pi j x) dx, \quad n = 1, 2, 3, \dots \quad (1)$$

The first few values of a_n are

$$(a_n)_{n \geq 1} = (2, 4, 6, 10, 12, 20, 24, 34, 44, \dots).$$

Thomas Ward (no relation to the fourth author) introduced this sequence on OEIS in 2008, stating,

This quantity arises in some examples associated to the dynamical Mertens' theorem for quasihyperbolic toral automorphisms. The function being integrated to compute a_n vanishes on the set of points in the Farey sequence of level n . I am particularly interested in knowing how large the sequence is asymptotically. [13]

In this paper, we answer Thomas Ward's question about the asymptotics of a_n . Our main result is an exact first-order asymptotic analysis of a_n . We heartily thank Thomas Ward for explaining the motivation of the problem to us [21]. We explain this motivation further in this section. (The origins of this problem can be traced back to at least 1969, as explained in the motivation.)

Israel conjectured that $\frac{\log(a_n 2^{-n})}{n} \rightarrow -0.3\dots$, or equivalently, $\log a_n \sim (\log(2) - 0.3\dots)n$ (see [6]). Finch has a short manuscript [4], in which he gives the equivalent conjecture, without proof (see the top of Finch's page 3), that $a_n^{1/n} \sim 1.48\dots \sim 2e^{-0.29\dots}$. Our main result rigorously verifies the Israel–Finch conjecture and sharpens it, to give an exact first-order asymptotic characterization. Moreover, instead of a numerical approximation, we provide the exact values of the constants in the asymptotics.

In the OEIS entry, Steven Finch also points out that “ $a_n =$ coefficient of $x^{n(n+1)/2}$ in the polynomial $(-1)^n \prod_{k=1}^n (1 - x^k)^2$, and is the maximal such coefficient as well” [13]. Finch's observation about this equivalent representation can be seen, for instance, as follows: Since $4 \sin^2(\pi j x) = (1 - e^{2\pi i j x})(1 - e^{-2\pi i j x})$, then the integrand of a_n is $\prod_{j=1}^n (1 - e^{2\pi i j x})(1 - e^{-2\pi i j x})$. Note that $\int_0^1 e^{2\pi i \ell x} dx = 0$ for all nonzero integers ℓ , and $\int_0^1 e^{2\pi i 0 x} dx = 1$. So it follows that—if we compute a_n by expanding $\prod_{j=1}^n (1 - e^{2\pi i j x})(1 - e^{-2\pi i j x})$ and then integrating—only the terms *in which the j 's sum to 0* will contribute. Moreover, if the integral of a term is nonzero, it is either 1 or -1 , depending on whether an even or odd number of j 's were involved in the product.

This observation leads to the combinatorial representation

$$a_n = [x^0] \prod_{j=1}^n (1 - x^j)(1 - x^{-j}),$$

where $[x^0]$ denotes the constant coefficient (see Finch [4]). We can therefore think of a_n combinatorially as the *signed* total number of $(2n)$ -tuples $(\epsilon_{-n}, \dots, \epsilon_{-1}, \epsilon_1, \dots, \epsilon_n) \in \{0, 1\}^{2n}$ such that

$$\sum_{\substack{-n \leq j \leq n \\ j \neq 0}} \epsilon_j j = 0.$$

By “signed” we are referring to a weighting scheme in which a $(2n)$ -tuple $(\epsilon_{-n}, \dots, \epsilon_{-1}, \epsilon_1, \dots, \epsilon_n) \in \{0, 1\}^{2n}$ provides a contribution of -1 to the *signed* total number if an odd number of ϵ_j are nonzero (i.e., equal 1), or provides a contribution of $+1$ to the *signed* total number otherwise.

Example 1.1 *When $n = 4$, exactly 18 of the 8-tuples have an even number of nonzero terms (i.e., of 1's):*

(1, 0, 0, 0, 0, 0, 0, 0)	(1, 1, 1, 1, 1, 1, 1, 1)		
(0, 0, 0, 1, 1, 0, 0, 0)	(0, 0, 1, 0, 0, 1, 0, 0)	(0, 1, 0, 0, 0, 0, 1, 0)	(1, 0, 0, 0, 0, 0, 0, 1)
(0, 0, 1, 1, 1, 1, 0, 0)	(0, 1, 0, 1, 1, 0, 1, 0)	(0, 1, 1, 0, 0, 1, 1, 0)	(1, 0, 0, 1, 1, 0, 0, 1)
(1, 0, 1, 0, 0, 1, 0, 1)	(1, 1, 0, 0, 0, 0, 1, 1)	(0, 1, 1, 0, 1, 0, 0, 1)	(1, 0, 0, 1, 0, 1, 1, 0)
(0, 1, 1, 1, 1, 1, 1, 0)	(1, 0, 1, 1, 1, 1, 0, 1)	(1, 1, 0, 1, 1, 0, 1, 1)	(1, 1, 1, 0, 0, 1, 1, 1)

and exactly 8 of the 8-tuples have an odd number of nonzero terms (i.e., of 1's):

$$\begin{array}{cccc} (0, 0, 1, 1, 0, 0, 1, 0) & (0, 1, 0, 0, 1, 1, 0, 0) & (0, 1, 0, 1, 0, 0, 0, 1) & (1, 0, 0, 0, 1, 0, 1, 0) \\ (0, 1, 1, 1, 0, 1, 0, 1) & (1, 0, 1, 0, 1, 1, 1, 0) & (1, 0, 1, 1, 0, 0, 1, 1) & (1, 1, 0, 0, 1, 1, 0, 1) \end{array}$$

Thus $a_4 = 18(+1) + 8(-1) = 10$.

The number of ways in which 0 can be written in an unweighted fashion as $\sum_{j=-n}^n \epsilon_j j$ is a well-understood quantity (see Clark [2], Entringer [3], Louchard and Prodinger [9], van Lint [19], and others). To the best of our knowledge, our derivation is the first result in which the contributions are *signed* according to the parity of the number of nonzero terms.

Paul Hanna also has a note in the OEIS entry [13] that a_n equals the sum of the squares of the coefficients in the polynomial $\prod_{k=1}^n (1 - x^k)$.

From a topological/dynamical perspective, the quantity a_n is the asymptotic coefficient in the weighted sum of the orbital numbers of a certain toral automorphism. The study of this automorphism is motivated by the search for a topological analogue to Mertens' prime number theorem. There is a strong structural similarity between the distribution of the prime integers and that of the orbits of an automorphism acting on an n -torus $\mathbb{T}^n = S^1 \times \cdots \times S^1$. Specifically, the classical Mertens' Theorem gives

$$\prod_{p \leq N} \left(\frac{1}{1 - 1/p} \right) \sim \log(N),$$

and one has the analogous hyperbolic toral diffeomorphism result

$$M_T(N) := \sum_{|\tau| \leq N} \frac{1}{e^{h|\tau|}} \sim \log(N), \quad (2)$$

where each $\tau = \{x, T(x), \dots, T^k(x) = x\}$ denotes a closed orbit of length k (here k and $|\tau|$ are both used interchangeably to represent the length), and h represents the topological entropy. Noorani [12] showed that when T is merely an ergodic toral automorphism (such an automorphism is said to *quasihyperbolic*), one has

$$M_T(N) = m \log(N) + C_1 + o(1) \quad (3)$$

for some positive integer m , where a_n is precisely the m in (3) for a specific automorphism, which we will introduce in the next paragraph. Jaidee, Stevens, and Ward [7] improved Noorani's estimate and also showed that the constant m is given by

$$m = \int_X \prod_{j=1}^n 4 \sin^2(\pi x_j) d_{x_1} \cdots d_{x_j}, \quad (4)$$

where X is found as follows: one first finds all eigenvalues of modulus 1 of the matrix A defining the automorphism T , and then, if these eigenvalues are $e^{\pm 2\pi i \theta_1}, \dots, e^{\pm 2\pi i \theta_t}$, one lets $X \subset \mathbb{T}^d$ denote the closure of the set $\{(k\theta_1, \dots, k\theta_t) : k \in \mathbb{Z}\}$ in \mathbb{T}^d .

The particular toral automorphism that gives rise to our a_n has been of interest since at least 1969; see Walters' analysis [20]. Walters introduced the automorphism given by the matrix

$$A = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 8 \\ 0 & 1 & 0 & -6 \\ 0 & 0 & 1 & 8 \end{pmatrix}$$

on the 4-torus $\mathbb{T}^4 = S^1 \times S^1 \times S^1 \times S^1$ for an example of an affine mapping between compact connected metric abelian groups, for which the mapping commutes only with continuous maps that are also affine. For this matrix A , the eigenvalues are:

$$2 + \sqrt{3} \pm \sqrt{6 + 4\sqrt{3}} \quad \text{and} \quad 2 - \sqrt{3} \pm i\sqrt{4\sqrt{3} - 6}.$$

The latter two eigenvalues, $2 - \sqrt{3} \pm i\sqrt{4\sqrt{3} - 6}$, each have modulus 1. Thus, the θ_1 from the previous paragraph is $\theta_1 = \frac{1}{2\pi} \arctan\left(\frac{2-\sqrt{3}}{\sqrt{-6+4\sqrt{3}}}\right)$. Noorani [12] further cited A as an example of a strictly quasi-hyperbolic automorphism on the torus. Jaidee et al. later considered A as their example of a toral automorphism whose asymptotic coefficient $m = 6$ exceeded $2^t = 2$ (where $t = 1$ since A has $2 = 2t$ eigenvalues on the unit circle), and in the same work used A to define the automorphism $A^1 \oplus A^2 \oplus \dots \oplus A^n$ on the $4n$ -torus \mathbb{T}^{4n} . This is the defining context of our a_n : it is precisely the coefficient m of $\log(N)$ in (3), in the asymptotic growth of $M_T(n)$, when M_T is defined as in (2) with \mathbb{T}^{4n} the torus under consideration and $A^1 \oplus \dots \oplus A^n$ the quasihyperbolic automorphism. This choice of automorphisms and tori gives a particularly nice form of (4), in that all the x_j are the same variable and the region of integration X is just $[0, 1]$.

2 Main Result

Our goal is to determine the asymptotic growth of the quantity

$$a_n = \int_0^1 \prod_{j=1}^n 4 \sin^2(\pi j x) dx.$$

Our main result is a precise first-order characterization of the asymptotic growth of a_n :

Theorem 2.1 *Let a_n be defined as above, and let $G(x)$ be the function defined as*

$$G(x) := \int_0^1 \log(\sin(\pi x t)) dt.$$

Then there is a unique point $x_0 = 0.7912265710\dots$ on $(0, 1)$ at which G attains its maximum $\max_{x \in (0, 1)} G(x) = -.4945295654\dots$ on the unit interval $(0, 1)$. Furthermore, if r and C denote the constants

$$r := e^{2G(x_0)} = 0.3719264606\dots, \quad \text{and} \quad C := \frac{4 \sin(\pi x_0)}{x_0} \sqrt{\frac{\pi}{-G''(x_0)}} = 2.405745839\dots,$$

then the first-order asymptotic growth of a_n is $C(4r)^n n^{-1/2}$, i.e.,

$$\lim_{n \rightarrow \infty} \frac{a_n}{C(4r)^n n^{-1/2}} = 1.$$

We also prove a pair of twin theorems, stated below. Theorem 2.1 follows directly from these two theorems.

Theorem 2.2 *Let C, r be defined as in Theorem 2.1. Then*

$$\lim_{n \rightarrow \infty} \frac{\int_{[0, \frac{1}{n}] \cup [\frac{n-1}{n}, 1]} \prod_{j=1}^n \sin^2(\pi j x) dx}{C r^n n^{-1/2}} = 1.$$

Theorem 2.3 *Let r be defined as in Theorem 2.1. Then*

$$\int_{1/n}^{(n-1)/n} \prod_{j=1}^n \sin^2(\pi j x) dx = O(\rho^n),$$

for some $\rho < r$.

Recall from equation (1) that a_n is defined as:

$$a_n := \int_0^1 \prod_{j=1}^n 4 \sin^2(\pi j x) dx, \quad n = 1, 2, 3, \dots$$

Theorem 2.2 precisely characterizes the dominant contribution to the integral that defines a_n ; this dominant contribution comes from integrating over the region $[0, \frac{1}{n}] \cup [\frac{n-1}{n}, 1]$. Theorem 2.3 says that the integral over the middle interval $[\frac{1}{n}, \frac{n-1}{n}]$ is (comparatively) negligible. The proofs of Theorems 2.2 and 2.3 will occupy the remainder of the paper. The fact that the majority of the contribution to the integral comes from $x \in [0, \frac{1}{n}] \cup [\frac{n-1}{n}, 1]$ is illustrated in Figure 1.

3 Derivation of Asymptotics: Proof of Theorem 2.2

We first note that because $\sin^2(\pi j x)$ is symmetric about $x = \frac{1}{2}$, then by a change of variables, we can express $\int_{[0, \frac{1}{n}] \cup [\frac{n-1}{n}, 1]} \prod_{j=1}^n \sin^2(\pi j x) dx$ as $\frac{2}{n} \int_0^1 \prod_{j=1}^n \sin^2(\frac{\pi j}{n} x) dx$. We can write this new integrand $\prod_{j=1}^n \sin^2(\frac{\pi j}{n} x)$ as an exponential function, which will allow us to use Laplace's method.

Lemma 3.1 *Let $G(x) := \int_0^1 \log(\sin(\pi x t)) dt$, and let*

$$h_n(x) := \frac{\prod_{j=1}^n \sin^2(\frac{\pi j}{n} x)}{2^n e^{2nG(x)}} \quad \text{for } 0 < x \leq 1.$$

We can (continuously) extend the domain of $h_n(x)$ to $[0, 1]$ by defining $h_n(0) := \lim_{x \rightarrow 0^+} h_n(x)$. Then we have

$$h_n(x) = \frac{\sin(\pi x)}{x} + O\left(\frac{1}{n}\right),$$

and this holds uniformly for $x \in [0, 1]$.

We postpone the proof of Lemma 3.1 for the moment, in order to show the connection to Theorem 2.2. We first state Laplace's method.

Theorem 3.2 *(Laplace's method; an easy extension of the usual version, e.g., as given in [1] or in Appendix B.6 of [5]) Let $g : [a, b] \rightarrow \mathbb{R}$ be twice-differentiable and concave on $[a, b]$, and suppose there is a unique point $x_0 \in [a, b]$ such that $g(x_0) = \max_{x \in [a, b]} g(x)$. Let (f_n) be a sequence of functions on $[a, b]$ which are uniformly bounded over all n , continuous on some common interval $[x_0 - \epsilon, x_0 + \epsilon] \subset [a, b]$, and uniformly convergent on $[x_0 - \epsilon, x_0 + \epsilon]$ to some $f : [x_0 - \epsilon, x_0 + \epsilon] \rightarrow \mathbb{R}$. Then*

$$\lim_{n \rightarrow \infty} \frac{\int_a^b f_n(x) e^{ng(x)} dx}{f(x_0) e^{ng(x_0)} \sqrt{\frac{2\pi}{n(-g''(x_0))}}} = 1.$$

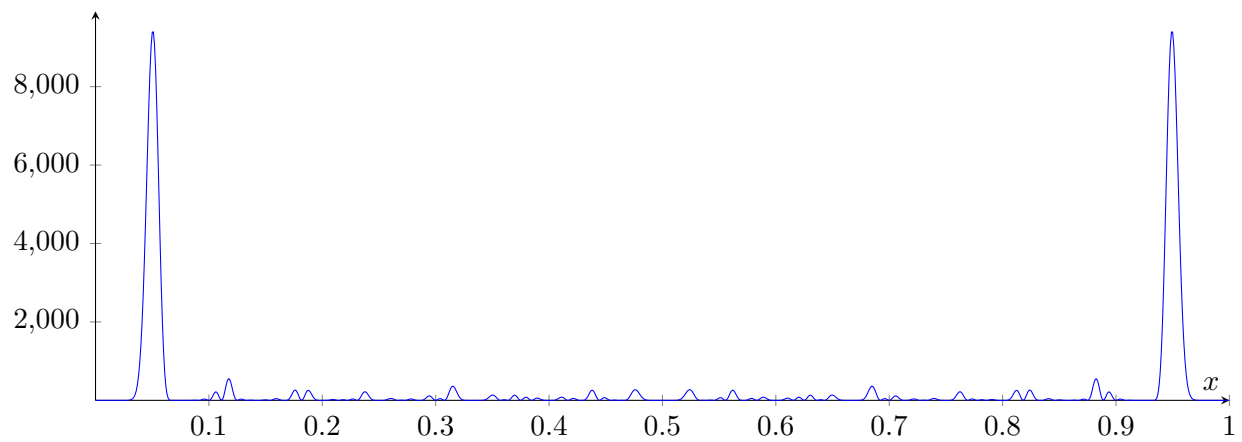
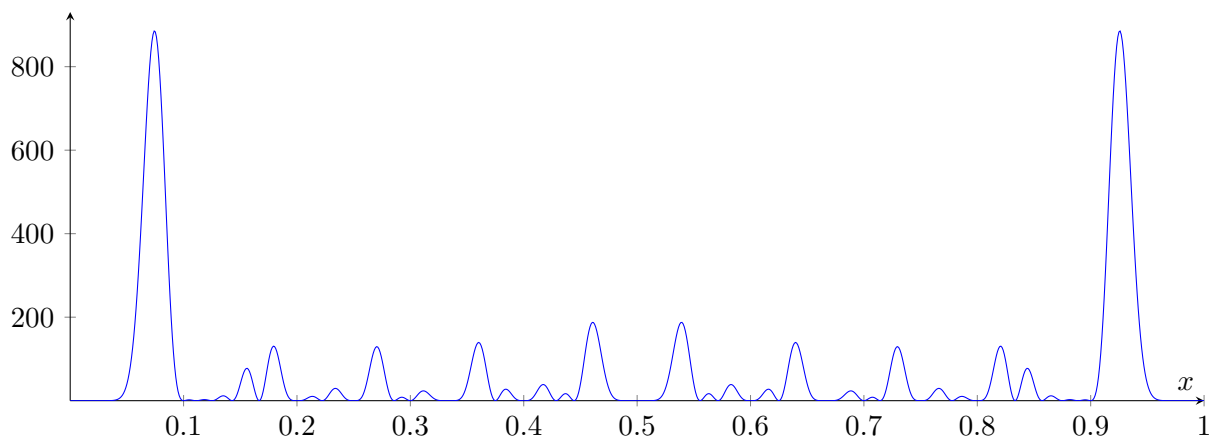
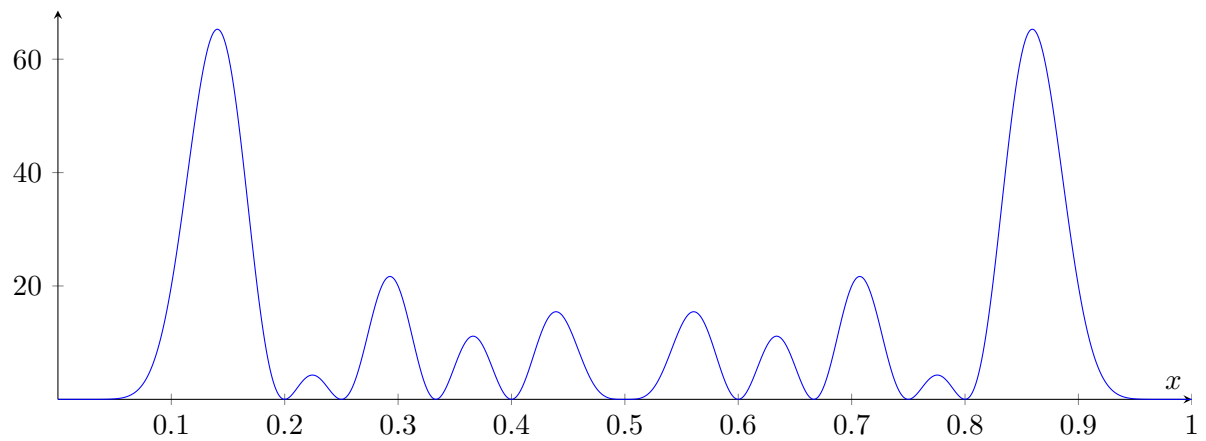


Figure 1: Plot of the integrand $\prod_{j=1}^n 4 \sin^2(\pi j x)$ of $a_n := \int_0^1 \prod_{j=1}^n 4 \sin^2(\pi j x) dx$ for $n = 5, 10, 15$.

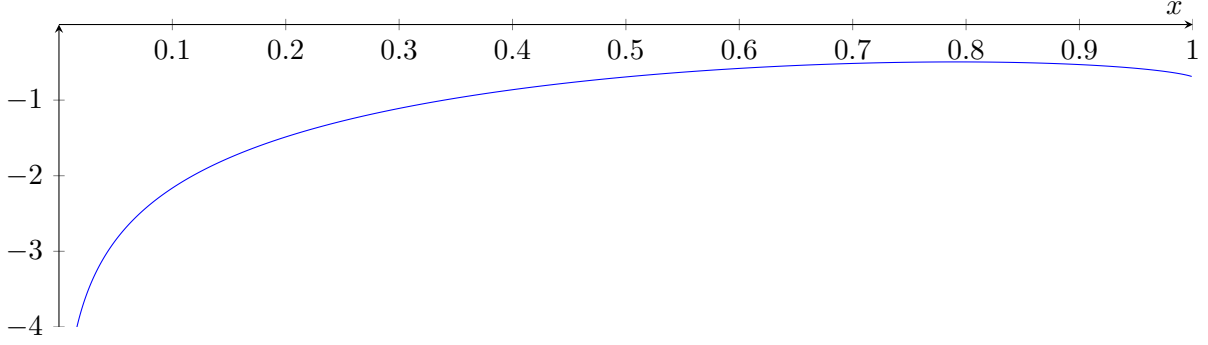


Figure 2: Plot of $G(x) := \int_0^1 \log(\sin(\pi xt)) dt$ for $x \in (0, 1)$.

We note that $G(x)$ is concave on $(0, 1)$ since

$$G''(x) = - \int_0^1 \frac{\pi^2 t^2}{\sin^2(\pi xt)} dt < 0,$$

and it has the unique critical point $x_0 = 0.7912265710\dots$, so that $G(x_0) > G(x)$ for all $x \in (0, 1)$ with $x \neq x_0$. The function $G(x)$ is depicted in Figure 2.

Now we apply Laplace's method with

$$f_n := h_n, \quad f(x_0) := \frac{\sin(\pi x_0)}{x_0}, \quad [a, b] := [0, 1], \quad g := 2G,$$

we obtain

$$\lim_{n \rightarrow \infty} \frac{\int_0^1 h_n(x) e^{2nG(x)} dx}{\frac{\sin(\pi x_0)}{x_0} e^{2nG(x_0)} \sqrt{\frac{\pi}{n(-G''(x_0))}}} = 1. \quad (5)$$

By definition, we have $r := e^{2G(x_0)}$ and $C := \frac{4 \sin(\pi x_0)}{x_0} \sqrt{\frac{\pi}{-G''(x_0)}}$. Also

$$\int_{[0, \frac{1}{n}] \cup [\frac{n-1}{n}, 1]} \prod_{j=1}^n \sin^2(\pi j x) dx = \frac{2}{n} \int_0^1 \prod_{j=1}^n \sin^2\left(\frac{\pi j}{n} x\right) dx = 4 \int_0^1 h_n(x) e^{2nG(x)} dx.$$

Thus equation (5) becomes

$$\lim_{n \rightarrow \infty} \frac{\int_{[0, \frac{1}{n}] \cup [\frac{n-1}{n}, 1]} \prod_{j=1}^n \sin^2(\pi j x) dx}{C r^n n^{-1/2}} = 1,$$

which is exactly the statement of Theorem 2.2.

So all that remains is to prove Lemma 3.1. Consider the function

$$u(t) = \log \frac{\sin(\pi t)}{\pi t(1-t)},$$

with $u(0) = u(1) = 0$. This function is continuous and infinitely differentiable on $[0, 1]$, so all its derivatives are also bounded on $[0, 1]$. The Euler-Maclaurin formula yields

$$\sum_{j=0}^n u\left(\frac{jx}{n}\right) = \int_0^n u\left(\frac{xt}{n}\right) dt + \frac{u(0) + u(x)}{2} + \frac{x(u'(x) - u'(0))}{12n} - \frac{x^2}{2n^2} \int_0^n B_2(\{t\})u''\left(\frac{xt}{n}\right) dt,$$

where $B_2(y) = y^2 - y + \frac{1}{6}$ is the second Bernoulli polynomial. Since the integrand in the last integral is bounded (uniformly in x), we get

$$\sum_{j=1}^n u\left(\frac{jx}{n}\right) = \int_0^n u\left(\frac{xt}{n}\right) dt + \frac{u(x)}{2} + O\left(\frac{1}{n}\right),$$

using also the fact that $u(0) = 0$. Now we have

$$\begin{aligned} \log h_n(x) &= 2 \sum_{j=1}^n u\left(\frac{jx}{n}\right) - \log(2n) - 2nG(x) + 2 \sum_{j=1}^n \log\left(\frac{\pi jx}{n} \left(1 - \frac{jx}{n}\right)\right) \\ &= 2n \int_0^1 u(xt) dt + u(x) - \log(2n) - 2nG(x) + 2 \sum_{j=1}^n \log\left(\frac{\pi jx}{n} \left(1 - \frac{jx}{n}\right)\right) + O\left(\frac{1}{n}\right) \\ &= -2n \int_0^1 \log(\pi xt(1 - xt)) dt + u(x) - \log(2n) + 2 \sum_{j=1}^n \log\left(\frac{\pi jx}{n} \left(1 - \frac{jx}{n}\right)\right) + O\left(\frac{1}{n}\right) \\ &= 4n + \frac{2n}{x}(1 - x) \log(1 - x) - 2n \log(\pi x) + u(x) - \log(2n) + 2n \log(\pi x/n) + 2 \log(n!) \\ &\quad + 2 \log \prod_{j=1}^n \left(1 - \frac{jx}{n}\right) + O\left(\frac{1}{n}\right). \end{aligned}$$

Now we use Stirling's approximation and simplify to get

$$\log h_n(x) = \log \frac{\sin(\pi x)}{x} + 2n + \left(\frac{2n}{x} - 2n - 1\right) \log(1 - x) + 2 \log \prod_{j=1}^n \left(1 - \frac{jx}{n}\right) + O\left(\frac{1}{n}\right). \quad (6)$$

Next, note that

$$\prod_{j=1}^n \left(1 - \frac{jx}{n}\right) = \left(\frac{x}{n}\right)^n \prod_{j=1}^n \left(\frac{n}{x} - j\right) = \left(\frac{x}{n}\right)^n \frac{\Gamma(n/x)}{\Gamma(n/x - n)}.$$

Since n/x goes to infinity regardless of the value of x (unlike $n/x - n$, which we will discuss later), we can apply Stirling's approximation again to find

$$\log \prod_{j=1}^n \left(1 - \frac{jx}{n}\right) = \left(\frac{n}{x} - n\right) \log(n/x) - \frac{n}{x} + \frac{1}{2} \log\left(\frac{2\pi x}{n}\right) - \log \Gamma\left(\frac{n}{x} - n\right) + O\left(\frac{1}{n}\right).$$

Plugging this into (6) and simplifying once again yields

$$\begin{aligned} \log h_n(x) &= \log \frac{\sin(\pi x)}{x} + \left(\frac{2n}{x} - 2n - 1\right) \log\left(\frac{n}{x} - n\right) - 2\left(\frac{n}{x} - n\right) + \log(2\pi) \\ &\quad - 2 \log \Gamma\left(\frac{n}{x} - n\right) + O\left(\frac{1}{n}\right), \end{aligned} \quad (7)$$

and this estimate is still uniform in x . Now define another function γ by $\gamma(t) = t^t e^{-t} \Gamma(t)^{-1} \sqrt{2\pi/t}$. This function is continuous on $[0, \infty)$ with $\gamma(0) = 0$ and $\gamma(t) = 1 + O(1/t)$ as $t \rightarrow \infty$ by Stirling's formula. Now we can write (7) in the more compact form

$$\log h_n(x) = \log \frac{\sin(\pi x)}{x} + 2 \log \gamma \left(\frac{n}{x} - n \right) + O \left(\frac{1}{n} \right)$$

or

$$h_n(x) = \frac{\sin(\pi x)}{x} \gamma \left(\frac{n}{x} - n \right)^2 \left(1 + O \left(\frac{1}{n} \right) \right) = \frac{\sin(\pi x)}{x} \gamma \left(\frac{n}{x} - n \right)^2 + O \left(\frac{1}{n} \right)$$

and thus

$$h_n(x) - \frac{\sin(\pi x)}{x} = \frac{\sin(\pi x)}{x} \left(\gamma \left(\frac{n}{x} - n \right)^2 - 1 \right) + O \left(\frac{1}{n} \right).$$

All this is still uniform in x . If x is very close to 1, say $x \geq n/(n+1)$ (so that $n/x - n \leq 1$), then $\sin(\pi x)/x = O(1/n)$, while the second factor on the right hand side is bounded. If, on the other hand, $x \leq n/(n+1)$, then $\gamma(n/x - n)^2 - 1 = O((n/x - n)^{-1})$ and thus

$$\frac{\sin(\pi x)}{x} \left(\gamma \left(\frac{n}{x} - n \right)^2 - 1 \right) = O \left(\frac{\sin(\pi x)}{(1-x)n} \right) = O \left(\frac{1}{n} \right).$$

In either case, we have the desired estimate, which completes our proof.

Remark 3.3 *If we include further terms in the Euler-Maclaurin formula and Stirling's approximation, we find that*

$$h_n(x) = \frac{\sin(\pi x)}{x} + \frac{\pi \cos(\pi x)}{6n} + O \left(\frac{1}{n^2} \right),$$

uniformly on compact subsets of $[0, 1]$, in particular on an interval around x_0 . This also makes it possible to obtain a more precise asymptotic formula for a_n :

$$a_n = \frac{(4r)^n}{\sqrt{n}} \left(C + \frac{C_1}{n} + O \left(\frac{1}{n^2} \right) \right),$$

where r and C are as in Theorem 2.1 and

$$C_1 = \frac{\sqrt{\pi} \sin(\pi x_0) (24G''(x_0)^2 - 12\pi^2 x_0^2 G'''(x_0)^2 + 12x_0 G''(x_0) G'''(x_0) + 5x_0^2 G'''(x_0)^2 - 3x_0^2 G''(x_0) G^{(4)}(x_0))}{12x_0^3 (-G''(x_0))^{7/2}} + \frac{\pi^{3/2} \cos(\pi x_0) (6G''(x_0) + 2x_0^2 G'''(x_0)^2 + 3x_0 G'''(x_0))}{3x_0^2 (-G''(x_0))^{5/2}} = 0.0262451044 \dots$$

In principle, once can extend the asymptotic formula further to include arbitrarily many terms.

4 Error Bounding: Proof of Theorem 2.3

We now begin the proof of Theorem 2.3, which says that $\int_{1/n}^{(n-1)/n} \prod_{j=1}^n \sin^2(\pi j x) dx = O(\rho^n)$ for some $\rho < r$. The following result will imply Theorem 2.3 immediately.

Theorem 4.1 *Let r be defined as in Theorem 2.1. Then there exist $C < \log r$ and $N \in \mathbb{N}$ such that for all $n \geq N$ we have*

$$\frac{1}{n} \sum_{j=1}^n \log(\sin^2(\pi j x)) \leq C \quad \text{for all } x \in \left[\frac{1}{n}, \frac{n-1}{n} \right].$$

To prove Theorem 4.1, we will approximate each $x \in [\frac{1}{n}, \frac{n-1}{n}]$ with a rational. Dirichlet's theorem provides exactly the sharp approximation that we require.

Theorem 4.2 (*Dirichlet; see [17]*) *Let $x \in \mathbb{R}$, $n \in \mathbb{N}$. Then there exist coprime $p_{n,x}, q_{n,x} \in \mathbb{Z}$, where $1 \leq q_{n,x} \leq n$, such that*

$$\left| x - \frac{p_{n,x}}{q_{n,x}} \right| \leq \frac{1}{q_{n,x}(n+1)}. \quad (8)$$

To begin, we fix $n \in \mathbb{N}$ and $x \in [\frac{1}{n}, \frac{n-1}{n}]$. Let coprime $p_{n,x}, q_{n,x} \in \mathbb{Z}$ be as described in Theorem 4.2. Without loss of generality, $x \geq \frac{p_{n,x}}{q_{n,x}}$, because otherwise we can use (instead) the values $1-x$ and $\frac{q_{n,x}-p_{n,x}}{q_{n,x}}$, since $\sin^2(\pi jt)$ is the same for both x and $1-x$, and since the bound in Theorem 4.2 will still hold. We then set $y := x - \frac{p_{n,x}}{q_{n,x}}$, so that we have

$$x = \frac{p_{n,x}}{q_{n,x}} + y, \quad \text{where} \quad 0 \leq y \leq \frac{1}{q_{n,x}(n+1)}. \quad (9)$$

Henceforth we suppress the (n, x) subscript, and simply write $p := p_{n,x}$ and $q := q_{n,x}$ (but we must keep in mind that these values actually depend on n and x).

Now, our overall goal is to bound the quantity $L := \frac{1}{n} \sum_{j=1}^n \log(\sin^2(\pi jx))$; and we are approximating x with the rational p/q . So it makes sense to partition the values of $j = 1 \dots n$ by their equivalence classes modulo q . If we define $k := \lceil n/q \rceil - 1$ and $s := n \bmod q$, then we have

$$\begin{aligned} L &= \frac{1}{n} \sum_{m=0}^{k-1} \sum_{\ell=1}^q \log \left(\sin^2 \left(\pi(mq + \ell) \left(\frac{p}{q} + y \right) \right) \right) + \frac{1}{n} \sum_{\ell=1}^s \log \left(\sin^2 \left(\pi(kq + \ell) \left(\frac{p}{q} + y \right) \right) \right) \\ &= \frac{1}{n} \sum_{m=0}^{k-1} \sum_{\ell=1}^q \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (mq + \ell)y \right) \right) \right) + \frac{1}{n} \sum_{\ell=1}^s \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (kq + \ell)y \right) \right) \right). \end{aligned} \quad (10)$$

This is the basic paradigm under which we will operate for the remainder of our proof. We now break the argument into two cases, depending on the relative size of q and n .

Case 1: $q \leq \sqrt{n}$.

The basic idea here will be to form Riemann sums at each $\frac{\ell p}{q}$. Dropping the remainder-term in (10) (which we can do since $\log(\sin^2(\cdot))$ is always non-positive), yields

$$L \leq \frac{1}{n} \sum_{\ell=1}^q \sum_{m=0}^{k-1} \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (mq + \ell)y \right) \right) \right) \quad (11)$$

$$= \frac{1}{nqy} \sum_{\ell=1}^q \left[qy \sum_{m=0}^{k-1} \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + \ell y + m q y \right) \right) \right) \right]. \quad (12)$$

We note that the inner bracketed terms (12) look like Riemann sums. And if we remove, for fixed ℓ , half the 0th term and half the $(k-1)$ st, what remains will be a trapezoidal sum for $\int_{\ell y}^{\ell y + (k-1)qy} \log(\sin^2(\pi(\frac{\ell p}{q} + t))) dt$. The trapezoidal sum does not exceed the value of the integral, since the integrand is concave. And since the integrand is non-positive, we can shorten the region of integrating without increasing the value. Thus,

$$L \leq \frac{1}{nqy} \sum_{\ell=1}^q \int_{\ell y}^{\ell y + (k-1)qy} \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + t \right) \right) \right) dt \leq \frac{1}{nqy} \sum_{\ell=1}^q \int_{qy}^{(k-1)qy} \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + t \right) \right) \right) dt. \quad (13)$$

Now, since p and q are relatively prime, the quantity $\frac{\ell p}{q} \bmod 1$ will range over all values $\{\frac{1}{q}, \frac{2}{q}, \dots, 1\}$ as ℓ ranges from 1 to q . Then by the identity

$$\prod_{j=1}^q \sin(\pi(\frac{j}{q} + t)) = -\frac{\sin(\pi qt)}{2^{q-1}}, \quad (14)$$

inequality (13) implies

$$\begin{aligned} L &\leq \frac{1}{nqy} \int_{qy}^{(k-1)qy} \log\left(\frac{\sin^2(\pi qt)}{4^{q-1}}\right) dt \\ &= \frac{(k-2)(q-1)}{n} \log\left(\frac{1}{4}\right) + \frac{1}{nq^2y} \int_{q^2y}^{(k-1)q^2y} \log(\sin^2(\pi t)) dt \\ &= \frac{k-2}{n} \left[(q-1) \log\left(\frac{1}{4}\right) + \frac{1}{(k-2)q^2y} \int_{q^2y}^{(k-1)q^2y} \log(\sin^2(\pi t)) dt \right]. \end{aligned} \quad (15)$$

And since $k = \lfloor \frac{n}{q} \rfloor - 1$ and $q \leq \sqrt{n}$, we have $\frac{k-2}{n} = \frac{1}{q} + O(n^{-1}) = \frac{1}{q}(1 + O(n^{-1/2}))$. Plugging that into (15), we obtain

$$L \leq \left(1 + O(n^{-1/2})\right) \left[\frac{q-1}{q} \log\left(\frac{1}{4}\right) + \frac{1}{q(k-2)q^2y} \int_{q^2y}^{(k-1)q^2y} \log(\sin^2(\pi t)) dt \right]. \quad (16)$$

From here our strategy will be to transform the integral on the right-hand side (16) into a value of the function $2G(x) = \int_0^1 \log(\sin^2(\pi xt)) dt$. We note that $\frac{1}{(k-2)q^2y} \int_{q^2y}^{(k-1)q^2y} \log(\sin^2(\pi t)) dt$ is an average-value integral, whose integrand $\log(\sin^2(\pi t))$ is concave with a unique maximum at $t = \frac{1}{2}$. So if $(k-1)q^2y < \frac{1}{8}$ (say) then since $\frac{1}{8} < \frac{1}{2}$ and $\log(\sin^2(\frac{\pi}{8})) < \log(\frac{1}{4})$, we have

$$L \leq \left(1 + O(n^{-1/2})\right) \left[\frac{q-1}{q} \log\left(\frac{1}{4}\right) + \frac{1}{q} \log\left(\sin^2\left(\frac{\pi}{8}\right)\right) \right] \leq \left(1 + O(n^{-1/2})\right) \log\left(\frac{1}{4}\right).$$

Since $1/4 < r = 0.3719264606\dots$, and thus $\log(\frac{1}{4}) = -1.386294361\dots < \log r = -.9890591305\dots$, we are in this case done. So we may assume that $(k-1)q^2y \geq \frac{1}{8}$. In this case we can extend the lower limit of the integral in (16) to $t = 0$ for the price of an $O(n^{-1/4})$ term. For we have

$$\begin{aligned} \frac{1}{(k-2)q^2y} \int_0^{q^2y} \log(\sin^2(\pi t)) dt &= \left[\frac{1}{(k-2)\sqrt{q^2y}} \right] \frac{1}{\sqrt{q^2y}} \int_0^{q^2y} \log(\sin^2(\pi t)) dt \\ &= \frac{1}{(k-2)\sqrt{q^2y}} O(1) \\ &= O\left(\frac{\sqrt{8(k-1)}}{(k-2)}\right) \\ &= O(n^{-1/4}) \end{aligned} \quad (17)$$

where the $O(1)$ bound in (17) is easily verified through L'Hopital's rule, and the $O(n^{-1/4})$ follows from the fact that $k = \lfloor \frac{n}{q} \rfloor$ where $q \leq \sqrt{n}$.

Then, operating on the integral in (16), we have

$$\begin{aligned}
\frac{1}{(k-2)q^2y} \int_{q^2y}^{(k-1)q^2y} \log(\sin^2(\pi t)) dt &= \frac{1}{(k-2)q^2y} \int_0^{(k-1)q^2y} \log(\sin^2(\pi t)) dt + O(n^{-1/4}) \\
&\leq \frac{1}{(k-1)q^2y} \int_0^{(k-1)q^2y} \log(\sin^2(\pi t)) dt + O(n^{-1/4}) \\
&= \int_0^1 \log(\sin^2(\pi(k-1)q^2yt)) dt + O(n^{-1/4}) \\
&= 2G((k-1)q^2y) + O(n^{-1/4}) \leq \log r + O(n^{-1/4}).
\end{aligned}$$

Plugging into (16), we obtain

$$L \leq \left(1 + O(n^{-1/2})\right) \left[\frac{q-1}{q} \log\left(\frac{1}{4}\right) + \frac{1}{q} (\log r + O(n^{-1/4})) \right] \leq \left(1 + O(n^{-1/4})\right) \left[\frac{\log(\frac{1}{4}) + \log r}{2} \right].$$

We note here that q cannot be 1, since for $x \in [\frac{1}{n}, \frac{n-1}{n}]$, the distance to the nearest integer is at least $1/n > 1/(n+1)$, contradicting (8). Thus $q \geq 2$. Since $\log(\frac{1}{4}) < \log r$, this completes our consideration of the case when $q \leq \sqrt{n}$.

Case 2: $q > \sqrt{n}$.

In Case 1 we took Riemann sums at each $\frac{i}{q}$. In this case we will let the values $0, \frac{1}{q}, \dots, \frac{q-1}{q}$ form a Riemann sum that ranges over all of $[0, 1]$. We begin by referring back to the canonical representation of (10),

$$L = \frac{1}{n} \sum_{m=0}^{k-1} \sum_{\ell=1}^q \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (mq + \ell)y \right) \right) \right) + \frac{1}{n} \sum_{\ell=1}^s \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (kq + \ell)y \right) \right) \right), \quad (18)$$

where $s = n \bmod q$ and in Case 1 we discarded the right-hand remainder sum at the very beginning. We will not be able to do so in this case.

We summarize our approach to Case 2 in the following proposition.

Proposition 4.3 *For fixed $m \leq k$ and fixed i , $1 \leq i \leq q$, there is at most one ℓ , $1 \leq \ell \leq q$, such that*

$$\left(\frac{\ell p}{q} + (mq + \ell)y \right) \bmod 1 \in \left[\frac{i-1}{q}, \frac{i}{q} \right).$$

Furthermore, if $m < k$, there is exactly one such ℓ .

Given $m < k$ and ℓ such that $(\frac{\ell p}{q} + (mq + \ell)y) \bmod 1 \in [\frac{i-1}{q}, \frac{i}{q})$, we define $z_{m,i} := (\frac{\ell p}{q} + (mq + \ell)y) \bmod 1$.

The content of this proposition follows immediately from the Dirichlet bound of (9) and the relative primality of p and q .

Now, for fixed m , the points $z_{m,1}, \dots, z_{m,q}$ will *not* be equidistant. However, by the concavity and symmetry of the function $\log(\sin^2(\pi(\cdot)))$, we will always have either $\log(\sin^2(\pi z_{m,i})) \leq \log(\sin^2(\frac{\pi i}{q}))$ or $\log(\sin^2(\pi z_{m,i})) \leq \log(\sin^2(\frac{\pi(i-1)}{q}))$, depending on whether $\frac{i}{q} < \frac{1}{2}$ or $\frac{i}{q} > \frac{1}{2}$. (We will not have such a bound in the case where $\frac{i-1}{q} < \frac{1}{2} < \frac{i}{2}$; but the midpoint takes care of itself, since $\log(\sin^2(\frac{\pi}{2})) = 0$.) So we have

$$\frac{1}{n} \sum_{m=0}^{k-1} \sum_{\ell=1}^q \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (mq + \ell)y \right) \right) \right) \leq \frac{1}{n} \sum_{m=0}^{k-1} \sum_{i=1}^{q-1} \log \left(\sin^2 \left(\frac{\pi i}{q} \right) \right) = \frac{k}{n} \log \left(\frac{q^2}{4^{q-1}} \right),$$

where the final equality follows from a variant on the sine-identity (14). Plugging this inequality into our base-expression (18), we obtain

$$L \leq \frac{k}{n} \log \left(\frac{q^2}{4^{q-1}} \right) + \frac{1}{n} \sum_{\ell=1}^s \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (kq + \ell)y \right) \right) \right). \quad (19)$$

We note that we still have a strange remainder-sum lurking at the end of (19). We will handle this remainder-sum in two separate cases.

Case 2a: $\frac{s}{q} \in [\frac{1}{2}, \frac{3}{5}]$.

This is the hard case; Case 2b will follow very easily from it. We begin by noting that by Proposition 4.3, each of the values $(\frac{\ell p}{q} + (kq + \ell)y) \bmod 1$ will lie in a different interval $[\frac{i-1}{q}, \frac{i}{q}]$. The difficulty here is that since ℓ will only range from 1 to s , not all of these intervals will contain such a point. To handle this problem, we rename and order the set $\{(\frac{\ell p}{q} + (kq + \ell)y) \bmod 1 : \ell = 1 \dots s\}$ as $\{\beta_1, \beta_2, \dots, \beta_s\}$, where the points are ordered by increasing distance from the point $x = \frac{1}{2}$. To avoid considering separate cases for odd and even q , we ignore the first point β_1 . But we must have

$$\log(\sin^2(\pi\beta_{2j})) \leq \log(\sin^2(\pi(\frac{1}{2} - \frac{j-1}{q}))), \quad \text{and identically for } \beta_{2j+1}, \quad \text{for } j = 1 \dots \lfloor \frac{s}{2} \rfloor. \quad (20)$$

The underlying logic here is that the second and third points can be no closer to $\frac{1}{2}$ than 0, the fourth and fifth can be no closer than $\frac{1}{q}$, and so on, since they all lie in separate intervals $[\frac{i-1}{q}, \frac{i}{q}]$ and are ordered by their distances from $\frac{1}{2}$.

So we have the global approximation $\sum_{j=1}^s \log(\sin^2(\pi\beta_{2j})) \leq 2 \sum_{j=1}^{\lfloor \frac{s}{2} \rfloor} \log(\sin^2(\pi(\frac{1}{2} - \frac{j-1}{q})))$. However, it will be necessary to consider how much error we accumulate in carrying it out. The following lemma will give us a means of bounding this error from below.

Lemma 4.4 *Under the hypotheses of Case 2a, there is some positive integer N such that whenever $n > N$, at least $\frac{q}{12}$ of the points $\{(\frac{\ell p}{q} + \ell y + kq y) \bmod 1\}_{\ell=1}^s$ lie in the region $A = [0, \frac{1}{10}] \cup [\frac{9}{10}, 1]$.*

Proof: Asymptotically, $\frac{q}{5}$ of the intervals $\{[\frac{\ell p \bmod q}{q}, \frac{(\ell p + 1) \bmod q}{q}]\}_{\ell=1}^q$ will lie strictly within A . So we can find N such that at least $\frac{q}{6}$ of these intervals lie in A whenever $n > N$. Now we know that for every i , $1 \leq i \leq q$ such that $[\frac{i-1}{q}, \frac{i}{q}] \subset A$, there is unique $\ell_i, 1 \leq \ell_i \leq q$ such that $\ell_i p \bmod q = i - 1$. If it happens that this $\ell_i > s$, then since $s \geq \frac{q}{2}$ by the hypotheses of Case 2a, we must have $q - \ell_i \leq s$. Then $(q - \ell_i)p \bmod q = q - i + 1$, and since $\frac{i}{q} \in A$ we must have $\frac{q-i}{q} \in A$ also, by the symmetry of A . It is possible that $\frac{q-i+1}{q}$ will not be in A despite $\frac{q-i}{q}$'s being in there, but this can happen for at most one i ; this contingency is therefore asymptotically negligible. So asymptotically at least half the $\ell \leq q$ such that $[\frac{\ell p \bmod q}{q}, \frac{(\ell p + 1) \bmod q}{q}] \subset A$ will also satisfy $\ell \leq s$; so there will be at least $(\frac{1}{2})(\frac{q}{6}) = \frac{q}{12}$ such ℓ .

This lemma says that when we make the $s - 1$ substitutions described in (20), at least $\frac{q}{12}$ of the β_j we substitute for will lie in A . And since in each case our substituted value will be $\frac{1}{2} - \frac{j-1}{q}$ for some $1 \leq j \leq \lfloor \frac{s}{2} \rfloor$, for at least $\frac{q}{12}$ points, we will have an error of at least $\log(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})})$.

We have, then,

$$\begin{aligned}
\frac{1}{n} \sum_{\ell=1}^s \log \left(\sin^2 \left(\pi \left(\frac{\ell p}{q} + (kq + \ell)y \right) \right) \right) &\leq \frac{2}{n} \sum_{\ell=1}^{\lfloor \frac{s}{2} \rfloor} \log \left(\sin^2 \left(\pi \left(\frac{1}{2} - \frac{\ell-1}{q} \right) \right) \right) + \frac{q}{12n} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) \\
&\leq \frac{2q}{n} \int_{\frac{1}{2} - \frac{s-1}{2q} + \frac{1}{q}}^{\frac{1}{2}} \log(\sin^2(\pi t)) dt + \frac{q}{12n} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) \\
&= \frac{2q}{n} \int_{\frac{1}{2} - \frac{s}{2q}}^{\frac{1}{2}} \log(\sin^2(\pi t)) dt + \frac{q}{12n} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) + O\left(\frac{\log n}{n}\right),
\end{aligned} \tag{21}$$

where we get the second inequality by removing half the first and last terms to make a trapezoid-sum. Plugging (21) into (19), we obtain

$$\begin{aligned}
L &\leq \frac{k}{n} \log \left(\frac{q^2}{4^{q-1}} \right) + \frac{2q}{n} \int_{\frac{1}{2} - \frac{s}{2q}}^{\frac{1}{2}} \log(\sin^2(\pi t)) dt + \frac{q}{12n} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) + O\left(\frac{\log n}{n}\right) \\
&= \frac{2k(q-1)}{n} \log \left(\frac{1}{2} \right) + \frac{2q}{n} \int_{\frac{1}{2} - \frac{s}{2q}}^{\frac{1}{2}} \log(\sin^2(\pi t)) dt + \frac{q}{12n} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) + O\left(\frac{\log n}{\sqrt{n}}\right).
\end{aligned} \tag{22}$$

Now, since $\log(\frac{1}{2}) = \int_0^{1/2} \log(\sin^2(\pi t)) dt$, we can, by symmetry of $\log(\sin^2(\pi t))$ about $t = \frac{1}{2}$, write

$$\begin{aligned}
\frac{2q}{n} \log \left(\frac{1}{2} \right) + \frac{2q}{n} \int_{\frac{1}{2} - \frac{s}{2q}}^{\frac{1}{2}} \log(\sin^2(\pi t)) dt &= \frac{2q}{n} \int_0^{\frac{1}{2} + \frac{s}{2q}} \log(\sin^2(\pi t)) dt = \frac{2q}{n} \frac{\frac{1}{2} + \frac{s}{2q}}{\frac{1}{2} + \frac{s}{2q}} \int_0^{\frac{1}{2} + \frac{s}{2q}} \log(\sin^2(\pi t)) dt \\
&= \frac{q+s}{n} \cdot 2G\left(\frac{1}{2} + \frac{s}{2q}\right) \leq \frac{q+s}{n} \log r.
\end{aligned}$$

Plugging into (22), we obtain

$$\begin{aligned}
L &\leq \frac{2k(q-1)}{n} \log \left(\frac{1}{2} \right) - \frac{2q}{n} \log \left(\frac{1}{2} \right) + \frac{q+s}{n} \log r + \frac{q}{12n} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) + O\left(\frac{\log n}{\sqrt{n}}\right) \\
&\leq \frac{2(k-1)q}{n} \log \left(\frac{1}{2} \right) + \frac{q+s}{n} \log r + \frac{q+s}{24n} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) + O\left(\frac{\log n}{\sqrt{n}}\right) \\
&= \frac{(k-1)q}{n} \log \left(\frac{1}{4} \right) + \frac{q+s}{n} \left(\log r + \frac{1}{24} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) \right) + O\left(\frac{\log n}{\sqrt{n}}\right) \\
&\leq \frac{(k-1)q + q + s}{n} \max \left(\log \left(\frac{1}{4} \right), \log r + \frac{1}{24} \log \left(\frac{\sin^2(\frac{\pi}{10})}{\sin^2(\frac{\pi}{5})} \right) \right) + O\left(\frac{\log n}{\sqrt{n}}\right).
\end{aligned}$$

Since $(k-1)q + q + s = kq + s = n$ and both constants inside the maximum are strictly less than $\log r$, this concludes our consideration of Case 2a.

Case 2b: $\frac{s}{q} \notin [\frac{1}{2}, \frac{3}{5}]$.

In this case we follow the same procedure as in Case 2a, but do not have to trouble ourselves about the error accumulated when we shift our β_i . We pick up at (22) with the $\frac{q}{12n}$ bit removed:

$$\begin{aligned}
L &\leq \frac{2k(q-1)}{n} \log\left(\frac{1}{2}\right) + \frac{2q}{n} \int_{\frac{1}{2}-\frac{s}{2q}}^{\frac{1}{2}} \log(\sin^2(\pi t)) dt + O\left(\frac{\log n}{\sqrt{n}}\right) \\
&= \frac{(k-1)q}{n} \log\left(\frac{1}{4}\right) + \frac{q+s}{n} \cdot 2G\left(\frac{1}{2} + \frac{s}{2q}\right) + O\left(\frac{\log n}{\sqrt{n}}\right) \\
&\leq \frac{(k-1)q}{n} \log\left(\frac{1}{4}\right) + \frac{q+s}{n} \cdot \left[\sup_{t \notin [\frac{3}{4}, \frac{4}{5}]} 2G(t) \right] + O\left(\frac{\log n}{\sqrt{n}}\right) \\
&\leq \frac{(k-1)q + q + s}{n} \max\left(\log\left(\frac{1}{4}\right), \sup_{t \notin [\frac{3}{4}, \frac{4}{5}]} 2G(t)\right) + O\left(\frac{\log n}{\sqrt{n}}\right).
\end{aligned}$$

Again, we are done since both $\log(\frac{1}{4})$ and the sup are fixed constants $< \log r$, as in the previous case. This concludes our consideration of Case 2b, proving Theorem 4.1. Theorem 2.3 immediately follows, and we are done.

5 Final remarks

Shaun Stevens (Shaun.Stevens@uea.ac.uk) recently asked [18] how fast or slow the asymptotic growth of $\int_0^1 \prod_{j=1}^n 4 \sin^2(\pi b_j x) dx$ can be, for general b_j (we have analyzed the $b_j = j$ case). He conjectured that the fastest growth is for $b_j = 1$ (which, as he notes, gives growth rate $\frac{2^{2n}}{\sqrt{2n}}$, using Stirling's approximation). This is indeed true: to prove it, we require a version of the rearrangement inequality for integrals. For a measurable function $f : \mathbb{R} \rightarrow [0, \infty)$, the *symmetric decreasing rearrangement* f^* is the symmetric decreasing function whose level sets have the exact same size: for $A \subseteq \mathbb{R}$, let A^* be the interval $(-\lambda(A)/2, \lambda(A)/2)$, where λ denotes the Lebesgue measure. Moreover, set $L_f(t) = \{y : f(y) > t\}$, and let $I_{L_f^*(t)}$ be the indicator function of $L_f^*(t)$. Then f^* is given by

$$f^*(x) = \int_0^\infty I_{L_f^*(t)}(x) dt = \sup\{t : x \in L_f^*(t)\}.$$

Note that $L_{f^*}(t) = L_f^*(t)$ and thus $\lambda(L_{f^*}(t)) = \lambda(L_f(t))$ for all $t \geq 0$. The following theorem is a special case of [8, Theorem 3.8]: if f_1, f_2, \dots are L^∞ -functions from \mathbb{R} to $[0, \infty)$ with compact support, then

$$\int_{-\infty}^\infty f_1(x) f_2(x) \cdots f_n(x) dx \leq \int_{-\infty}^\infty f_1^*(x) f_2^*(x) \cdots f_n^*(x) dx.$$

It is not difficult to see that the symmetric decreasing rearrangement of $f(x) = \sin(\pi b x)^2$ on $[0, 1]$ is $f^*(x) = \cos(\pi x)^2$ with support $(-1/2, 1/2)$ for every positive integer b . So we obtain

$$\int_0^1 \prod_{j=1}^n 4 \sin^2(\pi b_j x) dx \leq 4^n \int_{-1/2}^{1/2} \cos^{2n}(\pi x) dx = \binom{2n}{n},$$

with equality whenever the sequence b_1, b_2, \dots, b_n is constant.

We are also eager to better understand the asymptotic growth of

$$a_{n,k} = [x^k] \prod_{j=1}^n (1-x^j)(1-x^{-j}) = \int_0^1 e^{-2\pi i k x} \prod_{j=1}^n 4 \sin^2(\pi j x) dx.$$

As discussed in the introduction, the a_n 's throughout this paper correspond to the case $k = 0$. If $k/n \rightarrow a$ as $n \rightarrow \infty$, then the proof of Theorem 2.1 can be modified easily to prove that

$$\frac{a_{n,k}}{a_n} = \frac{a_{n,k}}{a_{n,0}} \rightarrow \cos(2\pi ax_0).$$

Things get more complicated when k is even larger, though, so that one probably needs to distinguish different cases.

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References

- [1] N. Bleistein and R. Handelsman. *Asymptotic Expansions of Integrals*. Dover Publications, 2010.
- [2] Lane Clark. On the representation of m as $\sum_{k=-n}^n \varepsilon_k k$. *International Journal of Mathematics and Mathematical Sciences*, 23:77–80, 2000.
- [3] R. C. Entringer. Representation of m as $\sum_{k=-n}^n \varepsilon_k k$. *Canadian Mathematical Bulletin*, 11:289–293, 1968.
- [4] Steven R. Finch. Signum equations and extremal coefficients, 2009. <http://www.people.fas.harvard.edu/~sfinch/csolve/signm.pdf>.
- [5] Philippe Flajolet and Robert Sedgewick. *Analytic Combinatorics*. Cambridge University Press, 2009.
- [6] Robert Israel. Post on the newsgroup `sci.math.research`, 17 January 2008.
- [7] Sawian Jaidee, Shaun Stevens, and Thomas Ward. Mertens' theorem for toral automorphisms. *Proceedings of the American Mathematical Society*, 139:1819–1824, 2011.

- [8] Elliott H. Lieb and Michael Loss. *Analysis*, volume 14 of *Graduate Studies in Mathematics*. American Mathematical Society, Providence, RI, second edition, 2001.
- [9] Guy Louchard and Helmut Prodinger. Representations of numbers as $\sum_{k=-n}^n \varepsilon_k k$: A saddle point approach. In Margaret Archibald, Vasco Brattka, Valentin Goranko, and Benedikt Löwe, editors, *Infinity in Logic and Computation*, volume 5489 of *Lecture Notes in Computer Science*, pages 87–96. Springer, 2009.
- [10] Guy Louchard and Helmut Prodinger. Representations of numbers as $\sum_{k=-n}^n \varepsilon_k k$: A saddle point approach. In *Infinity in Logic and Computation*, volume 5489 of *Lecture Notes in Computer Science*, pages 87–96. Springer, 2010.
- [11] Kent E. Morrison. Cosine products, fourier transforms, and random sums. *American Mathematics Monthly*, 102:716–724, 1995.
- [12] M. Noorani and M. Salmi. Mertens theorem and closed orbits of ergodic toral automorphisms. *Bulletin of the Malaysian Mathematical Society, Second Series*, 22:127–133, 1999.
- [13] On-line Encyclopedia of Integer Sequences. Sequence #A133871; <http://oeis.org/A133871>.
- [14] Helmut Prodinger. On a generalization of the Dyck-language over a two letter alphabet. *Discrete Mathematics*, 28:269–276, 1979.
- [15] Helmut Prodinger. On the number of partitions of $\{1, \dots, N\}$ into two sets of equal cardinalities and equal sums. *Canadian Mathematical Bulletin*, 25:238–241, 1982.
- [16] Helmut Prodinger. On the number of partitions of $\{1, \dots, n\}$ into r sets of equal cardinalities and sums. *Tamkang Journal of Mathematics*, 15:161–164, 1984.
- [17] W. Schmidt. *Diophantine Approximation: Lecture Notes in Mathematics*, volume 785. Springer, 1980.
- [18] Shaun Stevens, 2012. Personal communication with the authors.
- [19] J. H. van Lint. Representation of 0 as $\sum_{k=-N}^n \varepsilon_k k$. *Proceedings of the American Mathematical Society*, 18:182–184, 1967.
- [20] Peter Walters. Topological conjugacy of affine transformations of compact abelian groups. *Transactions of the American Mathematical Society*, 140:95–107, 1969.
- [21] Thomas Ward, 2012. Personal communication with the authors.