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Michael Drmota, Georg Gutenbrunner

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The joint distribution of Q -additive functions on polynomials over finite fields

par MICHAEL DRMOTA et GEORG GUTENBRUNNER

RÉSUMÉ. Soient K un corps fini et $Q \in K[T]$ un polynôme de degré au moins égal à 1. Une fonction f sur $K[T]$ est dite (complètement) Q -additive si $f(A + BQ) = f(A) + f(B)$ pour tous $A, B \in K[T]$ tels que $\deg(A) < \deg(Q)$. Nous montrons que les vecteurs $(f_1(A), \dots, f_d(A))$ sont asymptotiquement équirépartis dans l'ensemble image $\{(f_1(A), \dots, f_d(A)) : A \in K[T]\}$ si les Q_j sont premiers entre eux deux à deux et si les $f_j : K[T] \rightarrow K[T]$ sont Q_j -additives. En outre, nous établissons que les vecteurs $(g_1(A), g_2(A))$ sont asymptotiquement indépendants et gaussiens si $g_1, g_2 : K[T] \rightarrow \mathbb{R}$ sont Q_1 - resp. Q_2 -additives.

ABSTRACT. Let K be a finite field and $Q \in K[T]$ a polynomial of positive degree. A function f on $K[T]$ is called (completely) Q -additive if $f(A + BQ) = f(A) + f(B)$, where $A, B \in K[T]$ and $\deg(A) < \deg(Q)$. We prove that the values $(f_1(A), \dots, f_d(A))$ are asymptotically equidistributed on the (finite) image set $\{(f_1(A), \dots, f_d(A)) : A \in K[T]\}$ if Q_j are pairwise coprime and $f_j : K[T] \rightarrow K[T]$ are Q_j -additive. Furthermore, it is shown that $(g_1(A), g_2(A))$ are asymptotically independent and Gaussian if $g_1, g_2 : K[T] \rightarrow \mathbb{R}$ are Q_1 - resp. Q_2 -additive.

1. Introduction

Let $g > 1$ be a given integer. A function $f : \mathbb{N} \rightarrow \mathbb{R}$ is called (completely) g -additive if

$$f(a + bg) = f(a) + f(b)$$

for $a, b \in \mathbb{N}$ and $0 \leq a < g$. In particular, if $n \in \mathbb{N}$ is given in its g -ary expansion

$$n = \sum_{j \geq 0} \varepsilon_{g,j}(n) g^j$$

then

$$f(n) = \sum_{j \geq 0} f(\varepsilon_{g,j}(n)).$$

g -additive functions have been extensively discussed in the literature, in particular their asymptotic distribution, see [1, 3, 4, 5, 6, 7, 8, 9, 11, 12, 14, 15]. We cite three of these results (in a slightly modified form). We want to emphasise that Theorems A and C also say that different g -ary expansions are (asymptotically) independent if the bases are coprime.

Theorem A. (Kim [13]) *Suppose that $g_1, \dots, g_d \geq 2$ are pairwise coprime integers, m_1, \dots, m_d positive integers, and let $f_j, 1 \leq j \leq d$, be completely g_j -additive functions. Set*

$$H := \{(f_1(n) \bmod m_1, \dots, f_d(n) \bmod m_d) : n \geq 0\}.$$

Then H is a subgroup of $\mathbb{Z}_{m_1} \times \dots \times \mathbb{Z}_{m_d}$ and for every $(a_1, \dots, a_d) \in H$ we have

$$\frac{1}{N} \# \left\{ n < N : \begin{array}{ccc} f_1(n) \bmod m_1 = a_1, & & \\ \vdots & & \vdots \\ f_d(n) \bmod m_d = a_d & & \end{array} \right\} = \frac{1}{|H|} + O(N^{-\delta}),$$

where $\delta = 1/(120d^2\bar{g}^3\bar{m}^2)$ with

$$\bar{g} = \max_{1 \leq j \leq d} g_j \quad \text{and} \quad \bar{m} = \max_{1 \leq j \leq d} m_j$$

and the O -constant depends only on d and g_1, \dots, g_d .

Remark. In [13] the set H is explicitly determined. Set $F_j = f_j(1)$ and $d_j = \gcd\{m_j, (q_j - 1)F_j, f_j(r) - rF_j \ (2 \leq j \leq q_j - 1)\}$. Then $(a_1, \dots, a_d) \in H$ if and only if the system of congruences $F_j n \equiv a_j \pmod{d_j}, 1 \leq j \leq d$, has a solution.

Theorem B. (Bassily-Katai [1]) *Let f be a completely g -additive function and let $P(x)$ be a polynomial of degree r with non-negative integer coefficients. Then, as $N \rightarrow \infty$,*

$$\frac{1}{N} \# \left\{ n < N : \frac{f(P(n)) - r\mu_f \log_g N}{\sqrt{r\sigma_f^2 \log_g N}} < x \right\} \rightarrow \Phi(x)$$

and

$$\frac{1}{\pi(N)} \# \left\{ p < N : p \text{ prime}, \frac{f(P(p)) - r\mu_f \log_g N}{\sqrt{r\sigma_f^2 \log_g N}} < x \right\} \rightarrow \Phi(x),$$

where

$$\mu_f = \frac{1}{g} \sum_{r=0}^{g-1} f(r) \quad \text{and} \quad \sigma_f^2 = \frac{1}{g} \sum_{r=0}^{g-1} f(r)^2 - \mu_f^2,$$

and

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-t^2/2} dt.$$

Remark. The result of [1] is more general. It also provides asymptotic normality if f is not strictly g -additive but the variance grows sufficiently fast.

Theorem C. (Drmotá [6]) *Suppose that $g_1 \geq 2$ and $g_2 \geq 2$ are coprime integers and that f_1 and f_2 are completely g_1 - resp. g_2 -additive functions. Then, as $N \rightarrow \infty$,*

$$\frac{1}{N} \# \left\{ n < N : \frac{f_1(n) - \mu_{f_1} \log_{g_1} N}{\sqrt{\sigma_{f_1}^2 \log_{g_1} N}} \leq x_1, \frac{f_2(n) - \mu_{f_2} \log_{g_2} N}{\sqrt{\sigma_{f_2}^2 \log_{g_2} N}} \leq x_2 \right\} \\ \rightarrow \Phi(x_1)\Phi(x_2).$$

Remark. Here it is also possible to provide general versions (see Steiner [17]) but – up to now – it was not possible to prove a similar property for three or more bases g_j .

The purpose of this paper is to generalize these kinds of result to polynomials over finite fields.

Let \mathbb{F}_q be a finite field of characteristic p (that is, $q = |\mathbb{F}_q|$ is a power of p) and let $\mathbb{F}_q[T]$ denotes the ring of polynomials over \mathbb{F}_q . The set of polynomials in \mathbb{F}_q of degree $< k$ will be denoted by $P_k = \{A \in \mathbb{F}_q[T] : \deg A < k\}$. Fix some polynomial $Q \in \mathbb{F}_q[T]$ of positive degree. A function $f : \mathbb{F}_q[T] \rightarrow G$ (where G is any abelian group) is called (completely) Q -additive if $f(A + BQ) = f(A) + f(B)$, where $A, B \in \mathbb{F}_q[T]$ and $\deg(A) < \deg(Q)$. More precisely, if a polynomial $A \in \mathbb{F}_q[T]$ is represented in its Q -ary digital expansion

$$A = \sum_{j \geq 0} D_{Q,j}(A) Q^j,$$

where $D_{Q,j}(A) \in P_k$ are the *digits*, that is, polynomials of degree smaller than $k = \deg Q$, then

$$f(A) = \sum_{j \geq 0} f(D_{Q,j}(A)).$$

For example, the *sum-of-digits function* $s_Q : \mathbb{F}_q[T] \rightarrow \mathbb{F}_q[T]$ is defined by

$$s_Q(A) = \sum_{j \geq 0} D_{Q,j}(A).$$

Note that the image set of a Q -additive function is always finite and that (in contrast to the integer case) the sum-of-digits function satisfies $s_Q(A+B) = s_Q(A) + s_Q(B)$.

2. Results

The first theorem is a direct generalization of Theorem A.

Theorem 2.1. *Let Q_1, Q_2, \dots, Q_d and M_1, M_2, \dots, M_d be non-zero polynomials in $\mathbb{F}_q[T]$ with $\deg Q_i = k_i$, $\deg M_i = m_i$ and $(Q_i, Q_j) = 1$ for $i \neq j$. Furthermore let $f_i : \mathbb{F}_q[T] \rightarrow \mathbb{F}_q[T]$ be Q_i -additive functions ($1 \leq i \leq d$). Set*

$$H := \{(f_1(A) \bmod M_1, \dots, f_d(A) \bmod M_d) : A \in \mathbb{F}_q[T]\}.$$

Then H is a subgroup of $P_{m_1} \times \dots \times P_{m_d}$ and for every $(R_1, \dots, R_d) \in H$ we have

$$\lim_{l \rightarrow \infty} \frac{1}{q^l} \# \{A \in P_l : f_1(A) \bmod M_1 = R_1, \dots, f_d(A) \bmod M_d = R_d\} = \frac{1}{|H|}.$$

Since the image sets of f_i are finite we can choose the degrees m_i of M_i sufficiently large and obtain

$$\lim_{l \rightarrow \infty} \frac{1}{q^l} \# \{A \in P_l : f_1(A) = R_1, \dots, f_d(A) = R_d\} = \frac{1}{|H'|},$$

where

$$H' := \{(f_1(A), \dots, f_d(A)) : A \in \mathbb{F}_q[T]\}.$$

In particular this theorem says that if there is $A \in \mathbb{F}_q[T]$ with $f_i(A) = R_i$ ($1 \leq i \leq d$) then there are infinitely many $A \in \mathbb{F}_q[T]$ with that property.

The next theorem is a generalization of Theorem B.

Theorem 2.2. *Let $Q \in \mathbb{F}_q[T]$, $k = \deg Q \geq 1$ be a given polynomial, $g : \mathbb{F}_q[T] \rightarrow \mathbb{R}$ be a Q -additive function, and set*

$$(2.1) \quad \mu_g := \frac{1}{q^k} \sum_{A \in P_k} g(A), \quad \sigma_g^2 := \frac{1}{q^k} \sum_{A \in P_k} g(A)^2 - \mu_g^2.$$

Let $P(T) \in \mathbb{F}_q[T]$ with $r = \deg P$ and suppose that $\sigma_g^2 > 0$. Then, as $n \rightarrow \infty$,

$$(2.2) \quad \frac{1}{q^n} \# \left\{ A \in P_n : \frac{g(P(A)) - \frac{nr}{k} \mu_g}{\sqrt{\frac{nr}{k} \sigma_g^2}} \leq x \right\} \rightarrow \Phi(x)$$

and

$$(2.3) \quad \frac{1}{|I_n|} \# \left\{ A \in I_n : \frac{g(P(A)) - \frac{nr}{k} \mu_g}{\sqrt{\frac{nr}{k} \sigma_g^2}} \leq x \right\} \rightarrow \Phi(x),$$

where I_n denotes the set of monic irreducible polynomials of degree $< n$.

Finally we present a generalization of Theorem C.

Theorem 2.3. *Suppose that $Q_1 \in \mathbb{F}_q[T]$ and $Q_2 \in \mathbb{F}_q[T]$ are coprime polynomials of degrees $k_1 \geq 1$ resp. $k_2 \geq 1$ such that at least one of the derivatives Q'_1, Q'_2 is non-zero. Further suppose that $g_1 : \mathbb{F}_q[T] \rightarrow \mathbb{R}$ and $g_2 : \mathbb{F}_q[T] \rightarrow \mathbb{R}$ are completely Q_1 - resp. Q_2 -additive functions.*

Then, as $n \rightarrow \infty$,

$$\begin{aligned} & \frac{1}{q^n} \# \left\{ A \in P_n : \frac{g_1(A) - \frac{n}{k_1} \mu_{g_1}}{\sqrt{\frac{n}{k_1} \sigma_{g_1}^2}} \leq x_1, \frac{g_2(A) - \frac{n}{k_2} \mu_{g_2}}{\sqrt{\frac{n}{k_2} \sigma_{g_2}^2}} \leq x_2 \right\} \\ & \rightarrow \Phi(x_1) \Phi(x_2). \end{aligned}$$

Furthermore, Theorems 2.1 and 2.3 say that Q -ary digital expansions are (asymptotically) independent if the base polynomials are pairwise coprime.

3. Proof of Theorem 2.1

Throughout the paper we will use the additive character E defined by

$$(3.1) \quad E(A) := e^{2\pi i \operatorname{tr}(\operatorname{Res}(A))/p},$$

that is defined for all formal Laurent series

$$A = \sum_{j \geq -k} a_j T^{-j}$$

with $k \in \mathbb{Z}$ and $a_j \in \mathbb{F}_q$. The residue $\operatorname{Res}(A)$ is given by $\operatorname{Res}(A) = a_1$ and tr is the usual trace $\operatorname{tr} : \mathbb{F}_q \rightarrow \mathbb{F}_p$.

Let Q_1, Q_2, \dots, Q_d and M_1, M_2, \dots, M_d be non-zero polynomials in $\mathbb{F}_q[T]$ with $\deg Q_i = k_i, \deg M_i = m_i$ and $(Q_i, Q_j) = 1$ for $i \neq j$. Furthermore let f_i be completely Q_i -additive functions. For every tuple $R = (R_1, \dots, R_d) \in P_{m_1} \times \dots \times P_{m_d}$ set

$$(3.2) \quad g_{R_i}(A) := E \left(\frac{R_i}{M_i} f_i(A) \right)$$

and

$$(3.3) \quad g_R(A) := \prod_{i=1}^d g_{R_i}(A) = E \left(\sum_{i=1}^d \frac{R_i}{M_i} f_i(A) \right).$$

Proposition 3.1. *Let $Q_1, Q_2, \dots, Q_d, M_1, M_2, \dots, M_d$, and $R = (R_1, \dots, R_d)$ be as above. Then we either have*

$$g_R(A) = 1 \quad \text{for all } A \in \mathbb{F}_q[T]$$

or

$$\lim_{l \rightarrow \infty} \frac{1}{q^l} \sum_{A \in P_l} g_R(A) = 0.$$

We will first prove Proposition 3.1 (following the lines of Kim [13]). Theorem 2.1 is then an easy corollary.

3.1. Preliminaries.

Lemma 3.1. *Let $H \neq 0, H, G \in \mathbb{F}_q[T]$, and let E be the character defined in (3.1), then:*

$$(3.4) \quad \sum_{\deg R < \deg H} E \left(\frac{G}{H} R \right) = \begin{cases} q^{\deg H} & \text{if } H \text{ divides } G \\ 0 & \text{otherwise.} \end{cases}$$

The next lemma is a version of the Weyl–van der Corput inequality.

Lemma 3.2. *For each $A \in \mathbb{F}_q[T]$ let u_A be a complex number, with $|u_A| = 1$, then*

$$(3.5) \quad \left| \frac{1}{q^l} \sum_{A \in P_l} u_A \right|^2 \leq \frac{1}{q^r} + \frac{1}{q^r} \sum_{D \in P_r \setminus \{0\}} \left| \frac{1}{q^l} \sum_{A \in P_l} \overline{u_A} u_{A+D} \right|.$$

Proof. Since $\langle P_l, + \rangle$ is a group we have

$$\begin{aligned} q^r \sum_{A \in P_l} u_A &= \sum_{B \in P_r} \sum_{A \in P_l} u_{A-B} \\ &= \sum_{A \in P_l} 1 \left(\sum_{B \in P_r} u_{A-B} \right). \end{aligned}$$

Hence, using the Cauchy-Schwarz-inequality

$$\begin{aligned}
 q^{2r} \left| \sum_{A \in P_l} u_A \right|^2 &\leq \sum_{A \in P_l} 1^2 \sum_{A \in P_l} \left| \sum_{B \in P_r} u_{A-B} \right|^2 \\
 &= q^l \sum_{A \in P_l} \sum_{B \in P_r} \sum_{C \in P_r} \bar{u}_{A-B} u_{A-C} \\
 &= q^l \sum_{D \in P_r} \sum_{A \in P_l} \sum_{B \in P_r} \bar{u}_{A-B} u_{A-B+D} \\
 &= q^l \sum_{D \in P_r} \sum_{B \in P_r} \sum_{A \in P_l} \bar{u}_{A-B} u_{A-B+D} \\
 &= q^{l+r} \sum_{D \in P_r} \sum_{A \in P_l} \bar{u}_A u_{A+D} \\
 &= q^{l+r} \sum_{A \in P_l} |u_A|^2 + q^{l+r} \sum_{D \in P_r \setminus \{0\}} \sum_{A \in P_l} \bar{u}_A u_{A+D}.
 \end{aligned}$$

The desired result follows from $|u_A| = 1$. □

Lemma 3.3. *Let f be a completely Q -additive function, and $t \in \mathbb{N}$, $K, R \in \mathbb{F}_q[T]$ with $\deg R, \deg K < \deg Q^t$. Then for all $N \in \mathbb{F}_q[T]$ satisfying $N \equiv R \pmod{Q^t}$ we have*

$$(3.6) \quad f(N + K) - f(N) = f(R + K) - f(R).$$

Proof. Due to the above conditions, $N = A \cdot Q^t + R$ for some $A \in \mathbb{F}_q[T]$. Since f is completely Q -additive, and $\deg(R + K) < \deg(Q^t)$, we have

$$\begin{aligned}
 f(N + K) - f(N) &= f(AQ^t + R + K) - f(AQ^t + R) \\
 &= f(A) + f(R + K) - (f(A) + f(R)) \\
 (3.7) \quad &= f(R + K) - f(R).
 \end{aligned}$$

□

3.2. Correlation Estimates. In this section we will first prove a correlation estimate (Lemma 3.4) which will be applied to prove a pre-version (Lemma 3.5) of Proposition 3.1.

Let $Q \in \mathbb{F}_q[T]$ of $\deg Q = k$, $M \in \mathbb{F}_q[T]$ of $\deg M = m$, and f be a (completely) Q -additive function. Furthermore for $R \in P_m$ set $g(A) := E\left(\frac{R}{M}f(A)\right)$.

Unless otherwise specified, n and l are arbitrary integers, and $D \in \mathbb{F}_q[T]$ arbitrary as well. We introduce the *correlation functions*

$$\Phi_n(D) = \frac{1}{q^n} \sum_{A \in P_n} \overline{g(A)} g(A + D)$$

and

$$\Phi_{l,n} = \frac{1}{q^l} \sum_{A \in P_l} |\Phi_n(A)|^2.$$

Lemma 3.4. *Suppose that $|\Phi_k(R)| < 1$. Then*

$$\begin{aligned} & \left| \frac{1}{q^l} \sum_{H \in P_l} \left| \frac{1}{q^n} \sum_{A \in P_n} E \left(\frac{R}{M} (f(A+H) - f(A)) \right) \right| \right|^2 \\ & \ll \exp \left(- \min\{n, l\} \frac{1 - |\Phi_k(R)|^2}{kq^k} \right). \end{aligned}$$

Proof. We begin by establishing some recurrence relations for Φ_n and $\Phi_{l,n}$, namely

$$(3.8) \quad \Phi_{k+n}(QK + R) = \Phi_k(R)\Phi_n(K)$$

for polynomials K, R with $R \in P_k$. By using the relation $g(AQ + B) = g(A)g(B)$ and splitting the sum defining $\Phi_{k+n}(QK + R)$ according to the residue class of A modulo Q we obtain

$$\begin{aligned} q^{k+n}\Phi_{k+n}(QK + R) &= \sum_{I \in P_k} \sum_{A \in P_n} \overline{g(AQ + I)} g(AQ + I + QK + R) \\ &= \sum_{I \in P_k} \sum_{A \in P_n} \overline{g(A)} \overline{g(I)} g(A + K) g(I + R) \\ &= \sum_{I \in P_k} \overline{g(I)} g(I + R) \sum_{A \in P_n} \overline{g(A)} g(A + K) \\ &= q^k \Phi_k(R) q^n \Phi_n(K). \end{aligned}$$

This proves (3.8).

Next observe that

$$\begin{aligned} q^{k+l}\Phi_{k+l,k+n} &= \sum_{I \in P_k} \sum_{A \in P_l} \overline{\Phi_{k+n}(QA + I)} \Phi_{k+n}(QA + I) \\ &= \sum_{I \in P_k} \sum_{A \in P_l} \overline{\Phi_k(I)\Phi_n(A)} \Phi_k(I)\Phi_n(A) \\ &= \sum_{I \in P_k} \overline{\Phi_k(I)} \Phi_k(I) \sum_{A \in P_l} \overline{\Phi_n(A)} \Phi_n(A) \\ (3.9) \quad &= q^k \Phi_{k,k} q^l \Phi_{l,n}. \end{aligned}$$

Thus

$$(3.10) \quad \Phi_{k+l,k+n} = \Phi_{k,k} \Phi_{l,n}$$

and consequently

$$(3.11) \quad \Phi_{ik+l, ik+n} = (\Phi_{k,k})^i \Phi_{l,n}.$$

Since $|\Phi_{l,n}| \leq 1$ we also get $|\Phi_{ik+l, ik+n}| \leq |\Phi_{k,k}|^i$.

Hence, if n and l are given then we can represent them as $n = ik + r, l = ik + s$ with $i = \min([n/k], [l/k])$ and $\min(r, s) < k$. By definition we have

$$\Phi_{k,k} = \frac{1}{q^k} \sum_{A \in P_k} |\Phi_k(A)|^2$$

with $|\Phi_k(A)| \leq 1$ for all A . Since $|\Phi_k(R)| < 1$ we also have

$$\Phi_{k,k} \leq 1 - \frac{1 - |\Phi_k(R)|^2}{q^k} \leq \exp\left(-\frac{1 - |\Phi_k(R)|^2}{q^k}\right) < 1$$

and consequently

$$|\Phi_{l,n}| \leq |\Phi_{k,k}|^i \ll \exp\left(-\min\{l, n\} \frac{1 - |\Phi_k(R)|^2}{kq^k}\right).$$

□

Remark. We want to remark that $|\Phi_k(R)| = 1$ is a *rare* event. In particular, we have

$$\begin{aligned} \forall R : |\Phi_k(R)| = 1 &\Leftrightarrow \forall R \forall A \in P_k : \overline{g(A)}g(A + R) \text{ is constant} \\ &\Leftrightarrow \forall R, \forall A, B \in P_k : \overline{g(A)}g(A + R) = \overline{g(B)}g(B + R) \\ &\Leftrightarrow \forall A, B \in P_k : g(A + B) = g(A)g(B). \end{aligned}$$

Thus, there exists R with $|\Phi_k(R)| < 1$ if and only if there exist $A, B \in P_k$ with $g(A)g(B) \neq g(A + B)$.

Next we prove a pre-version of Proposition 3.1.

Lemma 3.5. *Let $Q_1, Q_2, \dots, Q_d \in \mathbb{F}_q[T]$ be pairwise coprime polynomials, $M_1, M_2, \dots, M_d \in \mathbb{F}_q[T]$, and $R = (R_1, R_2, \dots, R_d) \in P_{m_1} \times \dots \times P_{m_d}$ such that $|\Phi_{k_j}(R_j)| < 1$ for at least one $j = 1, \dots, d$. Then*

$$(3.12) \quad \lim_{l \rightarrow \infty} \frac{1}{q^l} \sum_{A \in P_l} g_R(A) = 0,$$

where $g_R(A) = \prod_{j=1}^d g_{R_j}(A)$ with $g_{R_j}(A) = E\left(\frac{R_j}{M_j} f_j(A)\right)$.

Proof. Set $B_j = Q_j^{t_j}$ and suppose that $b_j = t_j \deg Q_j$ satisfies that $r \leq b_j \leq 2r$ with $r = \frac{l}{3d}$. Given $S = (S_1, S_2, \dots, S_d)$ and B_1, B_2, \dots, B_d , we define $N_S := \{A \in P_l : A \equiv S_1 \pmod{B_1}, \dots, A \equiv S_d \pmod{B_d}\}$. By the Chinese remainder theorem we have for $l \geq \sum_{j=1}^d b_j$

$$|N_S| = \frac{q^l}{\prod_{j=1}^d q^{b_j}} = q^{l - \sum_{j=1}^d b_j}$$

Furthermore set $\mathcal{S} := P_{b_1} \times \dots \times P_{b_d}$. By Lemma 3.3 we obtain for $D \in P_r \setminus \{0\}$:

$$\begin{aligned} \sum_{A \in P_l} \overline{g_R(A)} g_R(A + D) &= \sum_{S \in \mathcal{S}} \sum_{A \in N_S} \overline{g_R(A)} g_R(A + D) \\ &= \sum_{S \in \mathcal{S}} \sum_{A \in N_S} \prod_{j=1}^d \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D) \\ &= \sum_{S \in \mathcal{S}} \prod_{j=1}^d \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D) \sum_{A \in N_S} 1 \\ &= \prod_{j=1}^d \sum_{S_j \in P_{b_j}} \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D) \frac{q^l}{\prod_{j=1}^d q^{b_j}} \\ &= q^l \prod_{j=1}^d \frac{1}{q^{b_j}} \sum_{S_j \in P_{b_j}} \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D). \end{aligned}$$

According to Lemma 3.2 we obtain for $r \leq l$

$$\begin{aligned} \left| \sum_{A \in P_l} g_R(A) \right|^2 &\leq q^{2l-r} + q^{l-r} \sum_{D \in P_r \setminus \{0\}} \left| \sum_{A \in P_l} \overline{g_R(A)} g_R(A + D) \right| \\ &= q^{2l-r} \sum_{D \in P_r \setminus \{0\}} \underbrace{\left| \prod_{j=1}^d q^{-b_j} \sum_{S_j \in P_{b_j}} \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D) \right|}_{\Sigma_1} \\ &\quad + O(q^{2l-r}). \end{aligned}$$

Hölder's inequality gives

$$\begin{aligned} \Sigma_1 &\leq q^{r/(d+1)} \prod_{j=1}^d \left(\sum_{D \in P_r \setminus \{0\}} \left| q^{-b_j} \sum_{S_j \in P_{b_j}} \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D) \right|^{d+1} \right)^{1/(d+1)} \\ &\leq q^r \prod_{j=1}^d \left(q^{-r} \sum_{D \in P_r \setminus \{0\}} \left| q^{-b_j} \sum_{S_j \in P_{b_j}} \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D) \right|^2 \right)^{1/(d+1)}. \end{aligned}$$

For some j we have $|\Phi_{k_j}(R_j)| < 1$, so that Lemma 3.4 is applicable and thus

$$q^{-r} \sum_{D \in P_r \setminus \{0\}} \left| q^{-b_j} \sum_{S_j \in P_{b_j}} \overline{g_{R_j}(S_j)} g_{R_j}(S_j + D) \right|^2 \rightarrow 0$$

as $r = l/(3d) \rightarrow \infty$. For all other j we trivially estimate by ≤ 1 and obtain

$$(3.13) \quad \frac{1}{q^l} \left| \sum_{A \in P_l} g_R(A) \right| \rightarrow 0$$

as $l \rightarrow \infty$. □

3.3. Proof of Proposition 3.1. As above we set $g_R(A) = \prod_{j=1}^d g_{R_j}(A) = E \left(\sum_{j=1}^d \frac{R_j}{M_j} f_j(A) \right)$. We split up the proof into several cases.

Case 1: There exist j and $A, B \in P_{k_j}$ with $g_{R_j}(A)g_{R_j}(B) \neq g_{R_j}(A + B)$.

This case is covered by Lemma 3.5 (compare with the remark following Lemma 3.4).

Case 2: For all j and for all $A, B \in P_{k_j}$ we have $g_{R_j}(A)g_{R_j}(B) = g_{R_j}(A + B)$.

In this case we also have (due to the additivity property) $g_{R_j}(A)g_{R_j}(B) = g_{R_j}(A + B)$ for all $A, B \in \mathbb{F}_q[T]$ and consequently $g(A)g(B) = g(A + B)$ for all $A, B \in \mathbb{F}_q[T]$.

Case 2.1: In addition we have $g(A) = 1$ for all $A \in \mathbb{F}_q[T]$.

This case is the first alternative in Proposition 3.1.

Case 2.2: In addition there exists $A \in \mathbb{F}_q[T]$ with $g(A) \neq 1$.

For simplicity we assume that q is a prime number. Thus, if $A = \sum_{i \geq 0} a_i T^i$ then we have $g(A) = \prod_{i \geq 0} g(T^i)^{a_i}$. Consequently there exists $i \geq 0$ with $g(T^i) \neq 1$. Furthermore

$$\sum_{a=0}^{q-1} g(T^j)^a = \begin{cases} q & \text{if } g(T^j) = 1 \\ 0 & \text{if } g(T^j) \neq 1. \end{cases}$$

Hence, if $l > i$ we surely have

$$\begin{aligned} \sum_{A \in P_l} g(A) &= \sum_{a_0=0}^{q-1} \sum_{a_1=0}^{q-1} \cdots \sum_{a_{l-1}=0}^{q-1} g(T^0)^{a_0} g(T^1)^{a_1} \cdots g(T^{l-1})^{a_{l-1}} \\ &= \left(\sum_{a_0=0}^{q-1} g(T^0)^{a_0} \right) \cdots \left(\sum_{a_{l-1}=0}^{q-1} g(T^{l-1})^{a_{l-1}} \right) \\ (3.14) \quad &= 0 \end{aligned}$$

If q is a prime power the can argue in a similar way. This completes the proof of Proposition 3.1.

3.4. Completion of the Proof of Theorem 2.1. We define two (additive) groups

$$G := \{R = (R_1, R_2, \dots, R_d) \in P_{m_1} \times \cdots \times P_{m_d} : \forall A \in \mathbb{F}_q[T] \ g_R(A) = 1\}$$

and

$$H_0 := \left\{ S \in P_{m_1} \times \cdots \times P_{m_d} : \forall R \in G \ E \left(\sum_{i=1}^d -\frac{S_i R_i}{M_i} \right) = 1 \right\}.$$

Furthermore, set

$$(3.15) \quad F(S) := \frac{1}{|G|} \sum_{R \in G} E \left(\sum_{i=1}^d -\frac{S_i R_i}{M_i} \right).$$

Now, by applying Proposition 3.1 we directly get

$$\begin{aligned}
 & \frac{1}{q^l} \#\{A \in P_l : f_1(A) \equiv S_1 \pmod{M_1}, \dots, f_d(A) \equiv S_d \pmod{M_d}\} = \\
 &= \frac{1}{q^l} \sum_{A \in P_l} \frac{1}{q^{\sum_{j=1}^d m_j}} \sum_{R \in P_{m_1} \times \dots \times P_{m_d}} E \left(\sum_{j=1}^d \frac{R_j}{M_j} (f_j(A) - S_j) \right) \\
 &= \frac{1}{q^{\sum_{j=1}^d m_j}} \sum_{R \in P_{m_1} \times \dots \times P_{m_d}} \left[E \left(\sum_{j=1}^d -\frac{S_j R_j}{M_j} \right) \cdot \frac{1}{q^l} \sum_{A \in P_l} g_R(A) \right] \\
 &= \frac{1}{q^{\sum_{j=1}^d m_j}} \sum_{R \in G} E \left(\sum_{j=1}^d -\frac{S_j R_j}{M_j} \right) + o(1) \\
 &= \frac{|G|}{q^{\sum_{j=1}^d m_j}} F(S) + o(1).
 \end{aligned}$$

More precisely the coefficient $F(S)$ characterizes H_0 .

Lemma 3.6. *We have*

- (1) $F(S) = 1$ for $S \in H_0$
- (2) $F(S) = 0$ for $S \notin H_0$.

Furthermore $|G| \cdot |H_0| = |P_{m_1} \times \dots \times P_{m_d}| = q^{m_1 + \dots + m_d}$.

Proof. It is clear that $F(S) = 1$ if $S \in H_0$.

Now suppose that $S \notin H_0$. Then there exists $R^0 = (R_1^0, R_2^0, \dots, R_d^0) \in G$ with $E \left(\sum_{i=1}^d -\frac{S_i R_i^0}{M_i} \right) \neq 1$. Since

$$\begin{aligned}
 \sum_{R \in G} E \left(\sum_{i=1}^d -\frac{S_i R_i}{M_i} \right) &= \sum_{R \in G} E \left(\sum_{i=1}^d -\frac{S_i (R_i + R_i^0)}{M_i} \right) \\
 &= E \left(\sum_{i=1}^d -\frac{S_i R_i^0}{M_i} \right) \sum_{R \in G} E \left(\sum_{i=1}^d -\frac{S_i R_i}{M_i} \right)
 \end{aligned}$$

it follows that $F(S) = 0$.

Finally, by summing up over all $S \in P_{m_1} \times \dots \times P_{m_d}$ it follows that $|G| \cdot |H_0| = |P_{m_1} \times \dots \times P_{m_d}|$. \square

In fact we have now shown that (as $l \rightarrow \infty$)

$$\frac{1}{q^l} \#\{A \in P_l : f_1(A) \equiv S_1 \pmod{M_1}, \dots, f_d(A) \equiv S_d \pmod{M_d}\} = \frac{1}{|H_0|} + o(1)$$

if $S = (S_1, \dots, S_d) \in H_0$ and (as $l \rightarrow \infty$)

$$\frac{1}{q^l} \#\{A \in P_l : f_1(A) \equiv S_1 \pmod{M_1}, \dots, f_d(A) \equiv S_d \pmod{M_d}\} = o(1)$$

if $S = (S_1, \dots, S_d) \notin H_0$. The final step of the proof of Theorem 2.1 is to show that

$$H = \{(f_1(A) \bmod M_1, \dots, f_d(A) \bmod M_d) : A \in \mathbb{F}_q[T]\} = H_0.$$

In fact, if $S \in H_0$ then we trivially have $S \in H$.

Conversely, if $S \in H$ then there exists $A \in \mathbb{F}_q[T]$ with $f_1(A) \equiv S_1 \bmod M_1, \dots, f_d(A) \equiv S_d \bmod M_d$. In particular, it follows that

$$g_R(A) = E \left(\sum_{j=1}^d \frac{R_j}{M_j} f_j(A) \right) = E \left(\sum_{j=1}^d \frac{R_j S_j}{M_j} \right).$$

Moreover, for all $R \in G$ we have

$$E \left(\sum_{j=1}^d \frac{R_j S_j}{M_j} \right) = 1.$$

Consequently, $S \in H_0$. This proves $H = H_0$ and also completes the proof of Theorem 2.1.

4. Proof of Theorem 2.2

4.1. Preliminaries. The first lemma shows how we can extract a digit $D_{Q,j}(A)$ with help of exponential sums.

Lemma 4.1. *Suppose that $Q \in \mathbb{F}_q[T]$ with $\deg Q = k \geq 1$. Set*

$$c_{H,D} = \frac{1}{q^k} E \left(-\frac{DH}{Q} \right).$$

Then

$$\sum_{H \in P_k} c_{H,D} E \left(\frac{AH}{Q^{j+1}} \right) = \begin{cases} 1 & \text{if } D_{Q,j}(A) = D \\ 0 & \text{if } D_{Q,j}(A) \neq D. \end{cases}$$

Proof. Consider the Q -ary expansion

$$(4.1) \quad A = \sum_{j \geq 0} D_{Q,j}(A) Q^j \quad \text{with} \quad D_{Q,j}(A) \in P_k.$$

Then it follows that for $H \in P_k$

$$E \left(\frac{AH}{Q^{j+1}} \right) = E \left(\frac{D_{Q,j}(A)H}{Q} \right).$$

Consequently, for every $D \in P_k$ we obtain

$$\begin{aligned} \sum_{H \in P_k} c_{H,D} E\left(\frac{AH}{Q^{j+1}}\right) &= \frac{1}{q^k} \sum_{H \in P_k} E\left(-\frac{DH}{Q}\right) E\left(\frac{AH}{Q^{j+1}}\right) \\ &= \frac{1}{q^k} \sum_{H \in P_k} E\left(\frac{H}{Q}(D_{Q,j}(A) - D)\right) \\ &= \begin{cases} 1 & \text{if } D_{Q,j}(A) = D, \\ 0 & \text{if } D_{Q,j}(A) \neq D. \end{cases} \end{aligned}$$

□

The next two lemmas are slight variations of estimates of [2].

Lemma 4.2. *Suppose that $Q \in \mathbb{F}_q[T]$ has degree $\deg Q = k \geq 1$ and that $P \in \mathbb{F}_q[T]$ is a polynomial of degree $\deg P = r \geq 1$. Then*

$$(4.2) \quad \frac{1}{q^n} \left| \sum_{A \in P_n} E\left(\frac{H}{Q^{j+1}}P(A)\right) \right| \ll n^{2^2-r} \max\left(q^{-(j+1)k2^{-r}}, q^{-n2^{-r}}, q^{(j+1)k2^{-r}-nr2^{-r}}\right)$$

Corollary 4.1. *Let $n^{1/3} \leq j+1 \leq \frac{rn}{k} - n^{1/3}$. Then there exists a constant $c > 0$ such that uniformly in that range*

$$\frac{1}{q^n} \left| \sum_{A \in P_n} E\left(\frac{H}{Q^{j+1}}P(A)\right) \right| \ll e^{-cn^{1/3}}.$$

A similar estimate holds for monic irreducible polynomials I_n of degree $< n$. Note that $|I_n| = q^n / ((q-1)n) + O(q^{n/2}) \sim q^n / ((q-1)n)$.

Lemma 4.3. *Let $\frac{2r}{k}n^{1/3} \leq j+1 \leq \frac{rn}{k} - \frac{2r}{k}n^{1/3}$, and H be a polynomial coprime to Q . Then*

$$(4.3) \quad \frac{1}{|I_n|} \left| \sum_{A \in I_n} E\left(\frac{H}{Q^{j+1}}P(A)\right) \right| \ll (\log n) \cdot n^{4/3+2^{-2-2r}} q^{-r2^{-2r}n^{1/3}}.$$

With help of these estimates we can prove the following frequency estimates.

Lemma 4.4. *Let m be a fixed integer and $\frac{2r}{k}n^{1/3} \leq j_1 < j_2 < \dots < j_m \leq \frac{nr}{k} - \frac{2r}{k}n^{1/3}$. Then*

$$\begin{aligned} &\frac{1}{q^n} \cdot \#\{A \in P_n : D_{Q,j_1}(P(A)) = D_1, \dots, D_{Q,j_m}(P(A)) = D_m\} \\ &= \frac{1}{q^{km}} + O\left(e^{-cn^{1/3}}\right) \end{aligned}$$

and

$$\begin{aligned} & \frac{1}{|I_n|} \cdot \#\{A \in I_n : D_{Q,j_1}(P(A)) = D_1, \dots, D_{Q,j_m}(P(A)) = D_m\} \\ &= \frac{1}{q^{km}} + O\left(e^{-cn^{1/3}}\right) \end{aligned}$$

uniformly for all $D_1, \dots, D_m \in P_k$ and for all j_1, \dots, j_m in the mentioned range.

Proof. By Lemma 4.1 we have

$$\begin{aligned} & \frac{1}{q^n} \#\{A \in P_n : D_{Q,j_1}(P(A)) = D_1, \dots, D_{Q,j_m}(P(A)) = D_m\} = \\ &= \frac{1}{q^n} \sum_{A \in P_n} \prod_{i=1}^m \left(\sum_{H_i \in P_k} c_{H_i, D_i} E\left(\frac{H_i}{Q^{j_i+1}} P(A)\right) \right) \\ &= \sum_{H_1, \dots, H_m \in P_k} \prod_{i=1}^m c_{H_i, D_i} \frac{1}{q^n} \sum_{A \in P_n} E\left(P(A) \left(\frac{H_1}{Q^{j_1+1}} + \dots + \frac{H_m}{Q^{j_m+1}}\right)\right) \\ &= c_{0, D_1} \cdots c_{0, D_m} \\ &+ \sum_{H_1, \dots, H_m \in P_k}^* \prod_{i=1}^m c_{H_i, D_i} \frac{1}{q^n} \sum_{A \in P_n} E\left(P(A) \left(\frac{H_1}{Q^{j_1+1}} + \dots + \frac{H_m}{Q^{j_m+1}}\right)\right) \\ &= \frac{1}{q^{km}} + S, \end{aligned}$$

where \sum^* denotes that we sum just over all $(H_1, \dots, H_m) \neq (0, \dots, 0)$. In order to complete the proof we just have to show that $S = O(e^{-cn^{1/3}})$.

Let l be the largest i with $H_i \neq 0$ then

$$\frac{1}{q^n} \sum_{A \in P_n} E\left(P(A) \left(\frac{H_1}{Q^{j_1+1}} + \dots + \frac{H_m}{Q^{j_m+1}}\right)\right) = \frac{1}{q^n} \sum_{A \in P_n} E\left(P(A) \frac{H}{Q^{j_l+1}}\right)$$

where $H = H_l + H_{l-1}Q^{j_l-j_{l-1}} + \dots + H_1Q^{j_l-j_1}$. By our assumption we have $\frac{2r}{k}n^{1/3} \leq j_l \leq \frac{nr}{k} - \frac{2r}{k}n^{1/3}$. Hence by Lemma 4.2 the first result follows.

The proof for $A \in I_n$ is completely the same. \square

4.2. Weak Convergence. The idea of the proof of Theorem 2.2 is to compare the distribution of $g(P(A))$ with the distribution of sums of independent identically distributed random variables. Let Y_0, Y_1, \dots be independent identically distributed random variables on P_k with $\mathbb{P}[Y_j = D] = q^{-k}$ for all $D \in P_k$. Then Lemma 4.4 can be rewritten as

$$\begin{aligned} & \frac{1}{q^n} \# \{A \in P_n : D_{Q,j_1}(P(A)) = D_1, \dots, D_{Q,j_m}(P(A)) = D_m\} \\ &= \mathbb{P}[Y_{j_1} = D_1, \dots, Y_{j_m} = D_m] + O\left(e^{-cn^{1/3}}\right). \end{aligned}$$

Note further that this relation is also true if j_1, \dots, j_m vary in the range $\frac{2r}{k}n^{1/3} \leq j_1, j_2, \dots, j_m \leq \frac{nr}{k} - \frac{2r}{k}n^{1/3}$ and are not ordered. It is even true if some of them are equal.

In fact, we will use a moment method, that is, we will show that the moments of $g(P(A))$ can be compared with moments of the normal distribution. Finally this will show that the corresponding (normalized) distribution function of $g(P(A))$ converges to the normal distribution function $\Phi(x)$.

It turns out that we will have to cut off the first and last few digits, that is, we will work with

$$\tilde{g}(P(A)) := \sum_{\frac{2r}{k}n^{1/3} \leq j \leq \frac{nr}{k} - \frac{2r}{k}n^{1/3}} g(D_{Q,j}(P(A)))$$

instead of $g(P(A))$.

Lemma 4.5. *Set*

$$\mu = \frac{1}{q^k} \sum_{H \in P_k} g(H) = \mathbb{E}g(Y_j).$$

Then the m -th (central) moment of $\tilde{g}(P(A))$ is given by

$$\begin{aligned} & \frac{1}{q^n} \sum_{A \in P_n} \left(\tilde{g}(P(A)) - \left(\frac{nr}{k} - 2\frac{2r}{k}n^{1/3} \right) \mu \right)^m = \\ &= \mathbb{E} \left(\sum_{\frac{2r}{k}n^{1/3} \leq j \leq \frac{nr}{k} - \frac{2r}{k}n^{1/3}} (g(Y_j) - \mu) \right)^m + O\left(n^m e^{-cn^{1/3}}\right). \end{aligned}$$

Proof. For notational convenience we just consider the second moment:

$$\begin{aligned}
& \frac{1}{q^n} \sum_{A \in P_n} \left(\tilde{g}(P(A)) - \left(\frac{nr}{k} - \frac{2r}{k} n^{1/3} \right) \mu \right)^2 = \\
& = \sum_{j_1, j_2} \sum_{D_1, D_2} g(D_1)g(D_2) \frac{1}{q^n} \#\{A \in P_n : D_{Q, j_i}(P(A)) = D_i, i = 1, 2\} \\
& \quad - \sum_{j_1} \sum_{D_1} g(D_1) \frac{1}{q^n} \#\{A \in P_n : D_{Q, j_1}(P(A)) = D_1\} \cdot \sum_{j_2} \mu \\
& \quad - \sum_{j_1} \mu \sum_{j_2} \sum_{D_2} g(D_2) \frac{1}{q^n} \#\{A \in P_n : D_{Q, j_2}(P(A)) = D_2\} + \sum_{j_1, j_2} \mu^2 \\
& = \sum_{j_1, j_2} \sum_{D_1, D_2} g(D_1)g(D_2) \mathbb{P}[Y_{j_1} = D_1, Y_{j_2} = D_2] + O\left(n^2 e^{-cn^{1/3}}\right) \\
& \quad - \sum_{j_1} \sum_{D_1} g(D_1) \mathbb{P}[Y_{j_1} = D_1] \sum_{j_2} \mu \\
& \quad - \sum_{j_1} \mu \sum_{j_2} \sum_{D_2} g(D_2) \mathbb{P}[Y_{j_2} = \varepsilon_2] + \sum_{j_1} \sum_{j_2} \mu^2 \\
& = \mathbb{E} \left(\sum_j (g(Y_j) - \mu) \right)^2 + O\left(n^2 e^{-cn^{1/3}}\right).
\end{aligned}$$

The very same procedure works in general and completes the proof of the lemma. \square

Since the sum of independent identically distributed random variables converges (after normalization) to the normal distribution it follows from Lemma 4.5

$$\frac{1}{q^n} \#\left\{ A \in P_n : \frac{\tilde{g}(P(A)) - \left(\frac{nr}{k} - \frac{2r}{k} n^{1/3} \right) \mu}{\sqrt{\left(\frac{nr}{k} - \frac{2r}{k} n^{1/3} \right) \sigma^2}} \leq x \right\} = \Phi(x) + o(1)$$

Because of

$$|\tilde{g}(P(A)) - g(P(A))| \ll n^{1/3}$$

and $n^{1/3}/n^{1/2} = n^{-1/6} \rightarrow 0$ it also follows that

$$\frac{1}{q^n} \#\left\{ A \in P_n : \frac{g(P(A)) - \frac{nr}{k} \mu}{\sqrt{\frac{nr}{k} \sigma^2}} \leq x \right\} = \Phi(x) + o(1).$$

This completes the proof of Theorem 2.2.

5. Proof of Theorem 2.3

5.1. Preliminaries. As usual, let $\nu\left(\frac{A}{B}\right) = \deg(B) - \deg(A)$ be the valuation on $\mathbb{F}_q(T)$.

Lemma 5.1. For $a, b \in \mathbb{F}_q(T)$ we have

$$(5.1) \quad \nu(a + b) \geq \min\{\nu(a), \nu(b)\}.$$

Moreover, if $\nu(a) \neq \nu(b)$, then

$$(5.2) \quad \nu(a + b) = \min\{\nu(a), \nu(b)\}.$$

Furthermore, we will use the following easy property (see [10]) that is closely related to Lemma 3.1.

Lemma 5.2. Suppose that $\nu\left(\frac{B}{C}\right) > 0$ and that $n \geq \nu\left(\frac{B}{C}\right)$, then

$$(5.3) \quad \sum_{A \in P_n} E\left(\frac{B}{C}A\right) = 0.$$

Another important tool is Mason's theorem (see [16]).

Lemma 5.3. Let K be an arbitrary field and $A, B, C \in K[T]$ relatively prime polynomials with $A + B = C$. If the derivatives A', B', C' are not all zero then the degree $\deg C$ is smaller than the number of different zeros of ABC (in a proper algebraic closure of K).

We will use Mason's theorem in order to prove the following property.

Lemma 5.4. Let $Q_1, Q_2 \in \mathbb{F}_q[T]$ be coprime polynomials with degrees $\deg(Q_i) = k_i \geq 1$ such that at least one of the derivatives Q'_1, Q'_2 is non-zero. Then there exists a constant c such that for all polynomials $H_1 \in P_{k_1}$ and $H_2 \in P_{k_2}$ with $(H_1, H_2) \neq (0, 0)$ and for all integers $m_1, m_2 \geq 1$ we have

$$\deg(H_1Q_2^{m_2} + H_2Q_1^{m_1}) \geq \max\{\deg(H_1Q_2^{m_2}), \deg(H_2Q_1^{m_1})\} - c.$$

Proof. Set $A = H_1Q_2^{m_2}$, $B = H_2Q_1^{m_1}$, and $C = A + B$. If A and B are coprime by Mason's theorem we have $\deg(A) \leq n_0(ABC) - 1$ and $\deg(B) \leq n_0(ABC) - 1$, where $n_0(F)$ is defined to be the number of distinct zeroes of F . Hence

$$\begin{aligned} \max\{\deg(A), \deg(B)\} &\leq n_0(ABC) - 1 \\ &= n_0(H_1H_2Q_1Q_2C) - 1 \\ &\leq \deg(H_1H_2Q_1Q_2) + \deg(C) - 1 \end{aligned}$$

and consequently

$$(5.4) \quad \deg(C) \geq \max\{\deg(A), \deg(B)\} - \deg(H_1H_2Q_1Q_2) + 1.$$

This shows that (in the present case) $c = 2k_1 + 2k_2$ is surely a proper choice.

If A and B are not coprime then by assumption the common factor D is surely a divisor of H_1H_2 . Furthermore, there exists $m' \geq 0$ such that D^2 is a divisor of $H_1H_2(Q_1Q_2)^{m'}$. Consequently we have

$$(A/D)(B/D) = (H_1H_2(Q_1Q_2)^{m'}/D^2)Q_1^{m_1-m'}Q_2^{m_2-m'}$$

and by a reasoning as above we get

$$\begin{aligned} \deg(C/D) &\geq \\ &\max\{\deg(A/D), \deg(B/D)\} - \deg((H_1H_2(Q_1Q_2)^{m'}/D^2)Q_1Q_2) + 1. \end{aligned}$$

or

$$\deg(C) \geq \max\{\deg(A), \deg(B)\} - \deg((H_1H_2(Q_1Q_2)^{m'}/D^2)Q_1Q_2) + 1.$$

Since there are only finitely possibilities for H_1, H_2 , and D the lemma follows. \square

5.2. Convergence of Moments. The idea of the proof of Theorem 2.3 is completely the same as that of Theorem 2.2. We prove weak convergence by considering moments. The first step is to provide a generalization of Lemma 4.4.

Lemma 5.5. *Let m_1, m_2 be fixed integers. Then there exists a constant $c' > 0$ such that for all $0 \leq i_1 < i_2 < \dots < i_{m_1} \leq \frac{n}{k_1} - c'$ and $0 \leq j_1 < j_2 < \dots < j_{m_2} \leq \frac{n}{k_2} - c'$ we have*

$$\begin{aligned} &\frac{1}{q^n} \#\left\{ A \in P_n : D_{Q_1, i_1}(A) = D_1, \dots, D_{Q_1, i_{m_1}}(A) = D_{m_1}, \right. \\ &\quad \left. D_{Q_2, j_1}(A) = E_1, \dots, D_{Q_2, j_{m_2}}(A) = E_{m_2} \right\} \\ &= \frac{1}{q_1^{k_1 m_1} q_2^{k_2 m_2}}. \end{aligned}$$

Instead of giving a complete proof of this lemma we will concentrate on the cases $m_1 = m_2 = 1$ and $m_1 = m_2 = 2$. The general case runs along the same lines (but the notation will be terrible).

First let $m_1 = m_2 = 1$. Here we have

$$\begin{aligned} & \frac{1}{q^n} \#\left\{A \in P_n : D_{Q_1, i}(A) = D_1, D_{Q_2, j}(A) = E_1\right\} \\ &= \frac{1}{q^n} \sum_{A \in P_n} \sum_{H_1 \in P_{k_1}} c_{H_1, Q_1, D_1} E\left(\frac{AH_1}{Q_1^{i+1}}\right) \sum_{H_2 \in P_{k_2}} c_{H_2, Q_2, E_1} E\left(\frac{AH_2}{Q_2^{j+1}}\right) \\ &= \frac{1}{q^{k_1+k_2}} \\ &+ \sum_{(H_1, H_2) \neq (0,0)} c_{H_1, Q_1, D_1} c_{H_2, Q_2, E_1} \frac{1}{q^n} \sum_{A \in P_n} E\left(A\left(\frac{H_1}{Q_1^{i+1}} + \frac{H_2}{Q_2^{j+1}}\right)\right). \end{aligned}$$

Now we can apply Lemma 5.4 and obtain

$$\begin{aligned} \nu\left(\frac{H_1}{Q_1^{i+1}} + \frac{H_2}{Q_2^{j+1}}\right) &= \nu\left(\frac{H_1 Q_2^{j+1} + H_2 Q_1^{i+1}}{Q_1^{i+1} Q_2^{j+1}}\right) \\ &\leq k_1(i+1) + k_2(j+1) \\ &\quad - \max\{\deg(H_1) + k_2(j+1), \deg(H_2) + k_1(i+1)\} \\ &\quad + c \\ &\leq \min\{k_1(i+1), k_2(j+1)\} + c. \end{aligned}$$

Thus, there exists a constant $c' > 0$ such that

$$\min\{k_1(i+1), k_2(j+1)\} + c \leq n$$

for all i, j with $0 \leq i \leq \frac{n}{k_1} - c'$ and $0 \leq j \leq \frac{n}{k_2} - c'$. Hence, by Lemma 5.2

$$\sum_{A \in P_n} E\left(A\left(\frac{H_1}{Q_1^{i+1}} + \frac{H_2}{Q_2^{j+1}}\right)\right) = 0.$$

This completes the proof for the case $m_1 = m_2 = 1$.

Next suppose that $m_1 = m_2 = 2$. Here we have

$$\begin{aligned}
& \frac{1}{q^n} \# \left\{ A \in P_n : D_{Q_1, i_1}(A) = D_1, D_{Q_1, i_2}(A) = D_2, \right. \\
& \quad \left. D_{Q_2, j_1}(A) = E_1, D_{Q_2, j_2}(A) = E_2 \right\} \\
&= \frac{1}{q^n} \sum_{A \in P_n} \left(\sum_{H_{11} \in P_{k_1}} c_{Q_1, H_{11}, D_1} E \left(\frac{H_{11}}{Q_1^{i_1+1}} A \right) \right) \times \\
& \quad \left(\sum_{H_{12} \in P_{k_1}} c_{Q_1, H_{12}, D_2} E \left(\frac{H_{12}}{Q_1^{i_2+1}} A \right) \right) \times \\
& \quad \left(\sum_{H_{21} \in P_{k_2}} c_{Q_2, H_{21}, E_1} E \left(\frac{H_{21}}{Q_2^{j_1+1}} A \right) \right) \times \\
& \quad \left(\sum_{H_{22} \in P_{k_2}} c_{Q_2, H_{22}, E_2} E \left(\frac{H_{22}}{Q_2^{j_2+1}} A \right) \right) \\
&= \sum_{H_{11}, H_{12} \in P_{k_1}, H_{21}, H_{22} \in P_{k_2}} c_{Q_1, H_{11}, D_1} c_{Q_1, H_{12}, D_2} c_{Q_2, H_{21}, E_1} c_{Q_2, H_{22}, E_2} \\
& \quad \times \frac{1}{q^n} \sum_{A \in P_n} E \left(A \left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}} + \frac{H_{22}}{Q_2^{j_2+1}} \right) \right)
\end{aligned}$$

Of course, if $H_{11} = H_{12} = H_{21} = H_{22} = 0$ then we obtain the *main term* $q_1^{-2k_1} q_2^{-2k_2}$.

For the remaining cases we will distinguish between four cases. Note that we only consider the case where all polynomials $H_{11}, H_{12}, H_{21}, H_{22}$ are non-zero. If some (but not all) of them are zero the considerations are still easier.

Case 1. $i_2 - i_1 \leq c_1, j_2 - j_1 \leq c_2$ for properly chosen constants $c_1, c_2 > 0$.

In this case we proceed as in the case $m_1 = m_2 = 1$ and obtain

$$\begin{aligned}
& \nu \left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}} + \frac{H_{22}}{Q_2^{j_2+1}} \right) \\
&= \nu \left(\frac{(H_{11} Q_1^{i_2-i_1} + H_{12}) Q_2^{j_2+1} + (H_{21} Q_2^{j_2-j_1} + H_{22}) Q_1^{i_2+1}}{Q_1^{i_2+1} Q_2^{j_2+1}} \right)
\end{aligned}$$

$$\begin{aligned} &\leq k_1(i_2 + 1) + k_2(j_2 + 1) \\ &\quad - \max\{\deg(H_{11}Q_1^{i_2-i_1} + H_{12}) + k_2(j_2 + 1), \\ &\quad \deg(H_{21}Q_2^{j_2-j_1} + H_{22}) + k_1(i_2 + 1)\} + c(c_1, c_2) \\ &\leq \min\{k_1(i_1 + 1), k_2(j_1 + 1)\} + \tilde{c}(c_1, c_2) \end{aligned}$$

for some suitable constants $c(c_1, c_2)$ and $\tilde{c}(c_1, c_2)$.

Case 2. $i_2 - i_1 > c_1, j_2 - j_1 > c_2$ for properly chosen constants $c_1, c_2 > 0$

First we recall that

$$\nu\left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{21}}{Q_2^{j_1+1}}\right) \leq \min\{k_1(i_1 + 1), k_2(j_1 + 1)\} + c.$$

Furthermore

$$\begin{aligned} \nu\left(\frac{H_{12}}{Q_1^{i_2+1}}\right) &\geq k_1(i_2 + 1) - \deg H_{12} \\ &\geq k_1(i_2 - i_1) + k_1 i_1 > k_1(i_1 + c_1) \\ \nu\left(\frac{H_{22}}{Q_2^{j_2+1}}\right) &> k_2(j_1 + c_2) \end{aligned}$$

Thus, if c_1 and c_2 are chosen that $(c_1 - 1)k_1 > c$ and $(c_2 - 1)k_2 > c$ then

$$\nu\left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{21}}{Q_2^{j_1+1}}\right) < \min\left\{\nu\left(\frac{H_{12}}{Q_1^{i_2+1}}\right), \nu\left(\frac{H_{22}}{Q_2^{j_2+1}}\right)\right\}$$

and consequently by Lemma 5.1

$$\begin{aligned} \nu\left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}} + \frac{H_{22}}{Q_2^{j_2+1}}\right) &= \nu\left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{21}}{Q_2^{j_1+1}}\right) \\ &\leq \min(k_1(i_1 + 1), k_2(j_1 + 1)) + c \end{aligned}$$

Case 3. $i_2 - i_1 \leq c_1, j_2 - j_1 > c_2$ for properly chosen constants $c_1, c_2 > 0$

First we have

$$\begin{aligned} &\nu\left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}}\right) \\ &= \nu\left(\frac{(H_{11}Q_1^{i_2-i_1} + H_{12})Q_2^{j_1+1} + H_{21}Q_1^{i_2+1}}{Q_1^{i_2+1}Q_2^{j_1+1}}\right) \\ &\leq k_1(i_2 + 1) + k_2(j_1 + 1) \\ &\quad - \max\{k_1(i_2 - i_1) + k_2(j_1 + 1), k_1(i_2 + 1)\} + c(c_1) \\ &= \min\{k_1(i_1 + 1), k_2(j_1 + 1)\} + c(c_1). \end{aligned}$$

Furthermore,

$$\begin{aligned} \nu \left(\frac{H_{22}}{Q_2^{j_2+1}} \right) &\geq k_2(j_2 + 1) - \deg(H_{22}) \\ &\geq k_2(j_2 - j_1) + k_2 j_1 > k_2(j_1 + c_2). \end{aligned}$$

Hence, if c_2 is sufficiently large then

$$\begin{aligned} \nu \left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}} + \frac{H_{22}}{Q_2^{j_2+1}} \right) &= \nu \left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}} \right) \\ &< \min(k_1(i_1 + 1), k_2(j_1 + 1)) \\ &\quad + c(c_1) \end{aligned}$$

Case 4. $i_2 - i_1 > c_1, j_2 - j_1 \leq c_2$ for properly chosen constants $c_1, c_2 > 0$

This case is completely symmetric to case 3.

Putting these four cases together they show that (with suitably chosen constants c_1, c_2) there exists a constant \tilde{c} such that for all polynomials $(H_{11}, H_{12}, H_{21}, H_{22}) \neq (0, 0, 0, 0)$ we have

$$\nu \left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}} + \frac{H_{22}}{Q_2^{j_2+1}} \right) \leq \min(k_1(i_1 + 1), k_2(j_1 + 1)) + \tilde{c}.$$

Thus, there exists a constant $c' > 0$ such that

$$\min\{k_1(i_1 + 1), k_2(j_1 + 1)\} + \tilde{c} \leq n$$

for all i_1, j_1 with $0 \leq i_1 \leq \frac{n}{k_1} - c'$ and $0 \leq j_1 \leq \frac{n}{k_2} - c'$. Hence, by Lemma 5.2

$$\sum_{A \in P_n} E \left(A \left(\frac{H_{11}}{Q_1^{i_1+1}} + \frac{H_{12}}{Q_1^{i_2+1}} + \frac{H_{21}}{Q_2^{j_1+1}} + \frac{H_{22}}{Q_2^{j_2+1}} \right) \right) = 0.$$

This completes the proof for the case $m_1 = m_2 = 2$.

As in the proof of Theorem 2.2 we can rewrite Lemma 5.5 as

$$\begin{aligned} &\frac{1}{q^n} \# \{ A \in P_n : D_{Q_1, i_1}(A) = D_1, \dots, D_{Q_1, i_{m_1}}(A) = D_{m_1}, \\ &\quad D_{Q_2, j_1}(A) = E_1, \dots, D_{Q_2, j_{m_2}}(A) = E_{m_2} \} \\ &= \mathbb{P}[Y_{i_1} = D_1, \dots, Y_{i_{m_1}} = D_{m_1}, Z_{j_1} = E_1, \dots, Z_{j_{m_2}} = E_{m_2}], \end{aligned}$$

where Y_i and Z_j are independent random variables that are uniformly distributed on P_{k_1} resp. on P_{k_2} .

If we define

$$\begin{aligned}\tilde{g}_1(A) &:= \sum_{j_1 \leq \frac{n}{k_1} - c'} g_1(D_{Q_1, j_1}(A)), \\ \tilde{g}_2(A) &:= \sum_{j_2 \leq \frac{n}{k_2} - c'} g_2(D_{Q_2, j_2}(A))\end{aligned}$$

then Lemma 5.5 immediately translates to

Lemma 5.6. *For all positive integers m_1, m_2 we have for sufficiently large n*

$$\begin{aligned}& \frac{1}{q^n} \sum_{A \in P_n} \left(\tilde{g}_1(A) - \frac{n}{k_1} \mu_{g_1} \right)^{m_1} \left(\tilde{g}_2(A) - \frac{n}{k_2} \mu_{g_2} \right)^{m_2} \\ &= \mathbb{E} \left(\sum_{j_1 \leq \frac{n}{k_1} - c'} (g_1(Y_{j_1}) - \mu_{g_1}) \right)^{m_1} \mathbb{E} \left(\sum_{j_2 \leq \frac{n}{k_2} - c'} (g_2(Z_{j_2}) - \mu_{g_2}) \right)^{m_2}.\end{aligned}$$

Of course this implies that the joint distribution of \tilde{g}_1 and \tilde{g}_2 is asymptotically Gaussian (after normalization). Since the differences $g_1(A) - \tilde{g}_1(A)$ and $g_2(A) - \tilde{g}_2(A)$ are bounded the same is true for the joint distribution of g_1 and g_2 . This completes the proof of Theorem 2.3.

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Michael DRMOTA
Inst. of Discrete Math. and Geometry
TU Wien
Wiedner Hauptstr. 8–10
A-1040 Wien, Austria
E-mail : michael.drkota@tuwien.ac.at
URL: <http://www.dmg.tuwien.ac.at/drmota/>

Georg GUTENBRUNNER
Inst. of Discrete Math. and Geometry
TU Wien
Wiedner Hauptstr. 8–10
A-1040 Wien, Austria
E-mail : georg@gutenbrunner.com