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The Distribution of the Sum-of-Digits Function

par Michael DRMOTA et Johannes GAJDOSIK

RÉSUMÉ. Dans cet article, nous démontrons que la fonction "somme de chiffres" (relative à des récurrences linéaires finies et infinies particulières) satisfait à un théorème central limite. Nous obtenons aussi un théorème limite local.

ABSTRACT. By using a generating function approach it is shown that the sum-of-digits function (related to specific finite and infinite linear recurrences) satisfies a central limit theorem. Additionally a local limit theorem is derived.

1. Introduction

Let $G = (G_j)_{j\geq 0}$ be a strictly increasing sequence of integers with $G_0 = 1$. Then every non-negative integer n has a (unique) proper G-ary digital expansion

$$n = \sum_{j\geq 0} \epsilon_j(n) G_j$$

with integer digits $\epsilon_j(n) \geq 0$ provided that

$$\sum_{j<k} \epsilon_j(n) G_j < G_k$$

for all $k \geq 0$. The sum-of-digits functions $s_G(n)$ is given by

$$s_G(n) = \sum_{j\geq 0} \epsilon_j(n)$$

and the aim of this paper is to get an insight to the distribution of $s_G(n)$, i.e. to the behaviour of the numbers

$$a_{Nk} = |\{n < N : s_G(n) = k\}|.$$

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It is also very convenient to consider a related sequence of (discrete) random variables X_N, $N \geq 0$, defined by

$$\mathbf{P}r[X_N = k] = \frac{a_{Nk}}{N}.$$

Expected value and variance of X_N are given by

$$\mathbf{E}X_N = \frac{1}{N}\sum_{n<N} s_G(n) \quad \text{and by} \quad \mathbf{V}X_N = \frac{1}{N}\sum_{n<N}(s_G(n) - \mathbf{E}X_N)^2 \tag{1.1}$$

There is a vast literature concerning asymptotic properties of $\mathbf{E}X_N$ and $\mathbf{V}X_N$ and on the distribution of X_N.

Asymptotic and exact formulas for $\mathbf{E}X_N$ are due to Bush [3], Bellman and Shapiro [2], Delange [5], and Trollope [20] for q-ary digital expansions and due to Pethö and Tichy [17] and Grabner and Tichy [12, 13] for G-ary digital expansions with respect to linear recurrences. Corresponding formulas for higher moments $\mathbf{E}X_N^d$ and for the variance $\mathbf{V}X_N$ can be found in Coquet [4], Kirschenhofer [15], Kennedy and Cooper [14], Grabner, Kirschenhofer, Prodinger, and Tichy [11], and in Dumont and Thomas [7].

The asymptotic distribution of X_N and related problems are discussed in Schmidt [19], Schmid [18], Bassily and Katai [1], and in Dumont and Thomas [8].

The main purpose of this paper is to prove asymptotic normality (of the distribution of X_N) by the use of generating functions, where it is also possible to derive a local limit law. (A similar approach was used in [6].)

2. Results

In the present paper we will deal with basis sequences $G = (G_j)_{j\geq 0}$ which satisfy specific finite or infinite linear recurrences.

2.1. Finite Recurrences. In the first case we will make the following assumptions:

1. There exist non-negative integers a_i, $1 \leq i \leq r$, such that (for $j \geq r$)

$$G_j = \sum_{i=1}^{r} a_i G_{j-i}.$$

2. $\gcd\{i \geq 1 : a_i \neq 0\} = 1$.
3. For all $j > r$ and $1 \leq k < r$ we have

$$G_{j-k} \geq \sum_{i=k+1}^{r} a_i G_{j-i}.$$

In section 3 we will show that the above assumptions imply that the characterictic polynomial

$$P(u) = u^r - \sum_{i=1}^{r} a_i u^{r-i}$$

has a unique root α of maximal modulus which is real and positive (i.e. all other roots α' of $P(u)$ satisfy $|\alpha'| < \alpha$) and that

$$G_j \sim C\alpha^j \quad (j \to \infty)$$

for some constant $C > 0$.

Remark. Usually (e.g. see [12]) it is assumed that $a_1 \geq a_2 \geq \cdots \geq a_r > 0$ and that $G_j = \sum_{i=1}^{j} a_i G_{j-i} + 1$ for $j < r$. In this case all assumptions are satisfied. (Furthermore, $P(u)$ is irreducible and α is a Pisot number.)
If the sequence of a_i, $1 \leq i \leq r$, is not decreasing then the situation is more complicated, e.g. if $a_1 = a_r = 1$ and $a_i = 0$ for $i \neq 1, r$ then condition 3. is satisfied, too. However, if $r = 4$, $a_1 = a_3 = a_4 = 1$, and $a_2 = 0$ then 3. is violated.

2.2. **Infinite Recurrences.** In the second case our starting point is Parry's α-expansion of 1 (see [16])

$$1 = \frac{a_1}{\alpha} + \frac{a_2}{\alpha^2} + \frac{a_3}{\alpha^3} + \cdots,$$

where $\alpha > 1$ is a real number and a_i, $i \geq 1$ are positive integers. (In the case of ambiguity we take the infinite representation of 1.) The sequence $G = (G_j)_{j \geq 0}$ is now defined by

$$G_0 = 1, \; G_j = \sum_{i=1}^{j} a_i G_{j-i} + 1 \quad (j > 0). \tag{2.1}$$

If we further set

$$A(u) = \sum_{i \geq 1} a_i u^i \quad \text{and} \quad G(u) = \sum_{j \geq 0} G_j u^j$$

then

$$G(u) = \frac{1}{(1-u)(1-A(u))}$$

and it follows that $z_0 = 1/\alpha > 0$ is the only singularity on the circle of convergence $|z| = z_0$, which is a simple pole. Hence

$$G_j \sim C'\alpha^j \quad (j \to \infty)$$

and so we are in similar situation as above.

2.3. Asymptotic Properties. First we state a theorem concerning expected value and variance of X_N (defined) in (1.1). Actually this statement is more or less a collection of well known facts (see [5, 17, 13, 15, 7, 10]). More precisely, much more is known about the following $O(1)$-terms. Therefore we will not present a proof.

Theorem 2.1. *Suppose that $G = (G_j)_{j\ge 0}$ satisfies a finite or infinite linear recurrence of the above types. Set*

$$G(z,u) = \sum_{j\ge 1}\left(\sum_{l=0}^{a_j-1} z^l\right) z^{a_1+\cdots+a_{j-1}}u^j$$

and let $1/\alpha(z)$ denote the (analytic) solution $u = 1/\alpha(z)$ of the equation

$$G(u,z) = 1$$

for z in a sufficiently small (complex) neighbourhood of $z_0 = 1$ such that $\alpha(1) = \alpha$. Then

$$\mathbf{E}X_N = \frac{1}{N}\sum_{n<N} s_G(n) = \mu\frac{\log N}{\log \alpha} + O(1)$$

and

$$\mathbf{V}X_N = \frac{1}{N}\sum_{n<N}(s_G(n) - \mathbf{E}X_N)^2 = \sigma^2\frac{\log N}{\log\alpha} + O(1),$$

where

$$\mu = \frac{\alpha'(1)}{\alpha} \quad \text{and} \quad \sigma^2 = \frac{\alpha''(1)}{\alpha} + \mu - \mu^2.$$

Our main result concerns the distribution properties of X_N. We prove asymptotic normality in the weak sense and provide a local limit law.

Theorem 2.2. *Suppose that $G = (G_j)_{j\ge 0}$ satisfies a finite or infinite linear recurrence of the above types. If $\sigma^2 \ne 0$ then for every $\varepsilon > 0$*

$$(2.2)\quad \frac{1}{N}|\{n < N : s_G(n) < \mathbf{E}X_N + x\mathbf{V}X_N\}| = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{1}{2}t^2}\,dt + O((\log N)^{-1/2+\varepsilon})$$

uniformly for all real x as $N \to \infty$.
Furthermore

$$(2.3)\quad |\{n < N : s_G(n) = k\}| = \frac{N}{\sqrt{2\pi\mathbf{V}X_N}}\left(\exp\left(-\frac{(k-\mathbf{E}X_N)^2}{2\mathbf{V}X_N}\right) + O((\log N)^{-1/2+\varepsilon})\right)$$

uniformly for all non-negative integers k as $N \to \infty$.

In section 3. we collect some preliminaries which will be used in sections 4. and 5. for the proofs of (2.2) and (2.3).

3. Preliminaries

3.1. Finite Recurrences. We will first collect some basis facts which will be needed in the sequel.

Lemma 3.1. *Suppose that $G_0, G_1, \dots, G_{r-1}$ are positive, that $G_j = \sum_{i=1}^{r} a_i G_{j-i}$ for $j \geq r$, where $a_i \geq 0$, $1 \leq i \leq r$, and that* $\gcd\{i \geq 1 : a_i \neq 0\} = 1$. *Then the characterictic polynomial $P(u) = u^r - \sum\limits_{i=1}^{r} a_i u^{r-i}$ has a unique root α of maximal modulus which is real and > 1. Furthermore,*

$$G_j = C\alpha^j + O(\alpha^{(1-\delta)j}) \tag{3.1}$$

for a real constant $C > 0$ and some $\delta > 0$.

Proof. First we show that $P(u)$ has a unique positive real root $\alpha > 1$ of maximal modulus. Set $G(u) = 1 - u^r P(u^{-1}) = \sum\limits_{j=1}^{r} a_j u^j$. Then $G(u)$ is strictly increasing for real $u \geq 0$. Since $G(0) = 0$ and $\lim\limits_{u \to \infty} G(u) = \infty$ there uniquely exists $u_0 > 0$ with $G(u_0) = 1$. Since G_n is strictly increasing we have $\sum\limits_{j=1}^{r} a_j = G(1) > 1$ and consequently $u_0 < 1$. Furthermore, $G'(u_0) = \sum\limits_{j=1}^{r} j a_j u_0^{j-1} > 0$. Thus, $\alpha = 1/u_0 > 1$ is a simple root of $P(u)$.

If $|u| < u_0$ then

$$|G(u)| \leq G(|u|) < G(u_0) = 1.$$

Furthermore, if $|u| = u_0$ but $u \neq u_0$ then the gcd-condition $\gcd\{i \geq 1 : a_i \neq 0\} = 1$ implies that

$$|G(u)| < G(|u|) = 1.$$

Consequently, there are no roots of $P(u)$ other than α with modulus $\geq \alpha$.

Next it is clear that G_j has a representation of the form (3.1) for some real C. We only have to show that $C > 0$. For this purpose define $F_j(x_0, \dots, x_{r-1})$ by $F_j(x_0, \dots, x_{r-1}) = x_j$ if $0 \leq j < r$ and by

$$F_j(x_0, \dots, x_{r-1}) = \sum_{i=1}^{r} a_i F_{j-1}(x_0, \dots, x_{r-1})$$

for $j \geq r$. Then $F_j(x_0, \dots, x_{r-1})$ is multilinear and monotonic in all variables. Furthermore, $F_j(G_0, \dots, G_{r-1}) = G_j$ and $F_j(1, \alpha, \dots, \alpha^{r-1}) = \alpha^j$.

Hence, by setting $c_1 = \min\limits_{0 \le j < r} G_j \alpha^{-j}$ we obtain

$$c_1 \alpha^j = F_j(c_1, c_1\alpha, \dots, c_1\alpha^{r-1}) \le F_j(G_0, \dots, G_{r-1}) = G_j$$
$$= C\alpha^j + O(\alpha^{(1-\delta)j}).$$

Thus $C > 0$. □

Lemma 3.2. *Suppose that $G = (G_j)_{j \ge 0}$ satisfies the above conditions 1.–3. If $0 \le k < a_i$ (for $1 \le i \le r$), $0 \le m < G_{j-i}$, and $j \ge r$ then*

$$n = a_1 G_{j-1} + \cdots + a_{i-1} G_{j-i+1} + k G_{j-i} + m$$

has digits

$$\begin{aligned} \epsilon_l(n) &= \epsilon_l(m) \quad (0 \le l < j-i) \\ \epsilon_{j-i}(n) &= k \\ \epsilon_l(n) &= a_{j-l} \quad (j-i < l < j). \end{aligned}$$

Suppose that n has the digital expansion $n = \epsilon_L(n) G_L + \epsilon_{L-1}(n) G_{L-1} + \cdots + \epsilon_0(n) G_0$. If $j \le L$, $k < \epsilon_j(n)$, and $m < G_j$ then

$$n' = \epsilon_L(n) G_L + \epsilon_{L-1}(n) G_{L-1} + \cdots + \epsilon_{j+1}(n) G_{j+1} + k G_j + m$$

has digits

$$\begin{aligned} \epsilon_l(n') &= \epsilon_l(m) \quad (0 \le l < j) \\ \epsilon_j(n') &= k \\ \epsilon_l(n') &= \epsilon_l(n) \quad (j < l \le L). \end{aligned}$$

Proof. Since $kG_{j-i} + m < a_i G_i$ we obtain for $1 \le i' < i$ by condition 3.

$$n - \sum_{i''=1}^{i'} a_{i''} G_{j-i''} < G_j - \sum_{i''=1}^{i'} a_{i''} G_{j-i''} = \sum_{i''=i'+1}^{r} a_{i''} G_{j-i''} \le G_{j-i'}.$$

Thus, $\epsilon_l(n) = a_{j-l}$ for $j - i < l < j$. Similarly,

$$n - \sum_{i''=1}^{i-1} a_{i''} G_{j-i''} - k G_{j-i} = m < G_{j-i}$$

implies $\epsilon_{j-i}(n) = k$ and consequently $\epsilon_l(n) = \epsilon_l(m)$ for $0 \le l < j - i$. This completes the proof of the first part.

Since $kG_j + m < \epsilon_j(n) G_j$ we have for $0 \le i < L - j$

$$n' - \sum_{i'=0}^{i} \epsilon_{L-i'} G_{L-i'} < G_{L-i+1}$$

which gives $\epsilon_l(n') = \epsilon_l(n)$ for $j < l \le L$. Finally

$$n' - \sum_{i'=0}^{L-j-1} \epsilon_{L-i'} G_{L-i'} - kG_j < G_j$$

provides $\epsilon_j(n') = k$ and $\epsilon_l(n') = \epsilon_l(m)$ for $0 \le l < j$. □

Next let

$$b_{j,k} = a_{G_j k} = |\{n < G_j : s_G(n) = k\}|$$

and set

$$b_j(z) = \sum_{k \ge 0} b_{j,k} z^k$$

and

$$B(z,u) = \sum_{j \ge 0} b_j(z) u^j .$$

Lemma 3.3. *For $j \ge r$ we have*

$$b_j(z) = \sum_{i=1}^{r} \sum_{l=0}^{a_i - 1} z^{a_1 + \cdots + a_{i-1} + l} b_{j-i}(z). \tag{3.2}$$

Proof. First observe that the set $\{n \in \mathbf{Z} : 0 \le n < G_j\}$ $(j \ge r)$ can be represented as a disjoint union of the form

$$\bigcup_{i=1}^{r} \bigcup_{l=0}^{a_i-1} \left\{ \sum_{h=1}^{i-1} a_h G_{h-j} + lG_{j-i} + m : 0 \le m < G_{j-i} \right\}.$$

Thus by Lemma 3.2

$$b_{j,k} = \sum_{i=1}^{r} \sum_{l=0}^{a_i-1} b_{j-i, k-a_1-\cdots-a_{i-1}-l}.$$

which provides (3.2). □

Corollary. *We have*

$$B(z,u) = \frac{P(z,u)}{1 - G(z,u)},$$

in which $G(z,u)$ is defined in Theorem 2.1 and

$$P(z,u) = \sum_{j=1}^{r} b_j(z) \left(1 - \sum_{i=1}^{r-j} \left(\sum_{l=0}^{a_i-1} z^l \right) z^{a_1+\cdots+a_{i-1}} u^i \right) u^j .$$

3.2. **Infinite Recurrences.** In the case of digital expansions which are related to Parry's α-expansion we have similar properties.

Lemma 3.4. ([13]) *Let $G = (G_j)_{j\geq 0}$ be given by (2.1). Then a finite sequence $(\epsilon_0, \epsilon_1, \dots, \epsilon_L)$ of nonnegative integers constitute the G-ary digits $\epsilon_j = \epsilon_j(n)$ of $n = \sum_{j=0}^{L} \epsilon_j G_j$ if and only if*

$$(\epsilon_k, \epsilon_{k-1}, \dots, \epsilon_0, 0, 0, \dots) < (a_1, a_2, \dots) \tag{3.3}$$

for $k = 0, 1, \dots, L$, where "$<$" denotes the lexicographic order.

Remark. Note that (3.3) implies that Lemma 3.2 holds for the infinite case, too.

As above let

$$b_j(z) = \sum_{k\geq 0} b_{j,k} z^k,$$

where $b_{j,k} = a_{G_j k} = |\{n < G_j : s_G(n) = k\}|$, and

$$B(z,u) = \sum_{j\geq 0} b_j(z) u^j.$$

By using (3.3) (or the corresponding version of Lemma 3.2 for the infinite case) we obtain a similar representation of $B(z,u)$ as in Corollary of Lemma 3.3 in the case of finite recurrences.

Lemma 3.5. ([13]) *We have*

$$B(z,u) = \frac{P(z,u)}{1 - G(z,u)},$$

in which $G(z,u)$ is defined in Theorem 2.1 and

$$P(z,u) = 1 + \sum_{j\geq 1} z^{a_1 + \cdots + a_j} u^j.$$

3.3. **Composition.** A similar procedure which led us to recurrences for $b_{j,k}$ (resp. to generating function identities in Corollary of Lemma 3.3 and to Lemma 3.5) can also be used to extract a_{Nk} from $b_{j,k} = a_{G_j k}$.

Lemma 3.6. *Suppose that*

$$N = \sum_{l=0}^{L-1} e_l G_{j_l}$$

is the G-ary digital expansion of N, where $j_0 > j_1 > \cdots > j_{L-1}$ and $e_j > 0$. Then

$$\sum_{k\geq 0} a_{Nk} z^k = \sum_{l=0}^{L-1} b_{j_l}(z) z^{\sum_{h=0}^{l-1} e_h} \sum_{i=0}^{e_l - 1} z^i. \tag{3.4}$$

Proof. By Lemma 3.2 (which is also valid in the case of infinite recurrences) we have

$$
\begin{aligned}
a_{Nk} &= \sum_{l=0}^{L-1}\sum_{i=0}^{e_l-1}\left|\left\{m < G_{j_l} : s_G(m) = k - \sum_{h=0}^{l-1} e_h - i\right\}\right| \\
&= \sum_{l=0}^{L-1}\sum_{i=0}^{e_l-1} b_{j_l,k-\sum_{h=0}^{l-1} e_h - i}. \qquad (3.5)
\end{aligned}
$$

Thus (3.4) follows. □

4. Global Limit Law

The first step is to obtain proper information of $b_j(z)$.

Proposition 4.1. *Suppose that $G = (G_j)_{j\geq 0}$ satisfies a finite or infinite recurrence of the above types. Then*

$$b_j(z) = C(z)\alpha(z)^j + O\left(\alpha^{(1-\delta)j}\right) \qquad (4.1)$$

uniformly for z contained in a sufficiently small complex neighbourhood of $z_0 = 1$ as $j \to \infty$, where $\alpha(z)$ is defined in Theorem 2.1 and $C(z)$ is an analytic function with $C(1) = C$ resp. $C(1) = C'$.

Proof. Firstly, let G_n satisfy a finite linear recurrence of the above type. Then $1 - G(1,u) = u^r P(u^{-1})$, where $P(u)$ is the characteristic polynomial. Thus $G(1,\alpha^{-1}) = 0$. Furthermore, since $\frac{\partial}{\partial u}G(z,u) < 0$ for real and non-negative z,u there exists an analytic function $\alpha(z)$ (for z in a sufficiently small complex neighbourhood of $z_0 = 1$) with $G(z, 1/\alpha(z)) = 0$ and $\alpha(1) = \alpha$. Similarly we have $G(1,\alpha^{-1}) = 0$ and $\frac{\partial}{\partial u}G(z,u) < 0$ in the case of infinite linear recurrence. Thus, there also exists an analytic function $\alpha(z)$ with $G(z,1/\alpha(z)) = 0$ and $\alpha(1) = \alpha$.

In both cases there exist analytic functions $G_1(z,u), R(z,u), R_1(z,u)$ such that

$$
\begin{aligned}
&1 - G(z,u) = \left(u - \frac{1}{\alpha(z)}\right) G_1(z,u), \\
&G_1(z,1/\alpha(z)) \neq 0, \\
&\qquad \frac{P(z,u)}{G_1(z,u)} = \frac{P(z,1/\alpha(z))}{G_1(z,1/\alpha(z))} + \left(u - \frac{1}{\alpha(z)}\right) R_1(z,u)
\end{aligned}
$$

for z,u in a complex neighbourhood of $z_0 = 1, u_0 = \alpha$. Since $1/\alpha = 1/\alpha(1)$ is the unique (and simple) zero of $G(1,u) = 0$ on the circle $|u| = 1/\alpha$ and since there are no zeroes for $|u| < 1/\alpha$ the function $G_1(z,u)$ can be analytically continued to $|u| < 1/\alpha + \varepsilon$ (for some sufficiently small $\varepsilon > 0$) if z varies in a (sufficiently small) neighbourhood of $z_0 = 1$. Withoug loss of generality we may assume that $|1/\alpha(z)| \le 1/\alpha + \varepsilon/4$. Hence, $R_1(z,u)$ can be analytically continued to the same region and we obtain for $|u| < 1/\alpha+\varepsilon$

$$\frac{P(z,u)}{1-G(z,u)} = \frac{C(z)}{1-u\alpha(z)} + R_1(z,u),$$

where $C(z) = -\alpha(z)P(z,1/\alpha(z))/G_1(z,1/\alpha(z))$. Finally, by Cauchy's formula we get

$$\begin{aligned} b_j(z) &= \frac{1}{2\pi i} \int\limits_{|u|=1/\alpha+\varepsilon/2} \frac{P(z,u)}{1-G(z,u)} \frac{du}{u^{j+1}} \\ &= C(z)\alpha(z)^j + \frac{1}{2\pi i} \int\limits_{|u|=1/\alpha+\varepsilon/2} R_1(z,u) \frac{du}{u^{j+1}} \\ &= C(z)\alpha(z)^j + O\left(\alpha^{(1-\delta)j}\right), \end{aligned}$$

with some $\delta > 0$. This completes the proof of Proposition 4.1. □

With help of Proposition 4.1 and Lemma 3.6 we can prove asymptotic normality of X_N. Observe that

$$\frac{1}{N}\sum_{k\ge 0} a_{Nk}e^{ikt} = \mathbf{E}e^{itX_N}$$

is the characteristic function of X_N.

Proposition 4.2. *Suppose that* $\sigma^2 \ne 0$ *and set* $\mu_N = \mathbf{E}X_N$ *and* $\sigma_N^2 = \mathbf{V}X_N$. *Then for every* $\varepsilon > 0$ *we have uniformly for* $|t| \le (\log N)^{1/2-\varepsilon}$

$$e^{-it\mu_N/\sigma_N}\frac{1}{N}\sum_{k\ge 0} a_{Nk}e^{ikt/\sigma_N} = e^{-t^2/2} + O((\log N)^{-1/2+\varepsilon}). \tag{4.2}$$

Proof. Set $f(z) = \log\alpha(e^z)$ in an open neighbourhood of $z=0$. Then we have

$$\alpha(e^{it}) = \alpha e^{i\mu t - \sigma^2 t^2/2 + O(t^3)},$$

with $\mu = f'(0) = \alpha'(1)/\alpha$ and $\sigma^2 = f''(0) = \alpha''(1)/\alpha + \mu - \mu^2$ (see Theorem 2.2). Hence, by using Proposition 4.1

$$b_j(e^{it}) = G_j e^{j(i\mu t-\sigma^2t^2/2)} e^{O(t+jt^3+(1-\delta)^j)} + O\left(\alpha^{(1-\delta)j}\right)$$

in an open neighbourhood of $t=0$ in $\mathbf{R}$. Now suppose that $N = \sum\limits_{l=0}^{L-1} e_l G_{j_l}$ with $j_0 > j_1 > \cdots > j_{L-1}$ and $e_l > 0$ is the G-ary expansion of N. Then by Lemma 3.6 and the trivial estimate $\sum_{s=0}^{e_l-1} e^{its} = e_l(1+O(t))$ we have

$$\begin{aligned}\sum_{k\ge 0} a_{Nk}e^{ikt} &= \sum_{l=0}^{L-1} b_{j_l}(e^{it})e^{it\sum_{h=0}^{l-1} e_h} \sum_{s=0}^{e_l-1} e^{its} \\ &= \sum_{l=0}^{L-1} e_l G_{j_l} e^{ij_l\mu t - j_l\sigma^2 t^2/2 + it\sum_{h=0}^{l-1} e_h} e^{O(t+j_l t^3 + (1-\delta)^{j_l})} + O(N^{(1-\delta)}).\end{aligned}$$

Now observe that

$$\frac{it}{\sigma_N} = \frac{it}{\sigma\, j_0^{1/2}}\left(1+O(j_0^{-1})\right),$$

and that

$$e^{-it\mu_N/\sigma_N} = e^{-it(\mu/\sigma)j_0^{1/2}(1+O(j_0^{-1}))}.$$

Hence

$$\begin{aligned}\mathbf{E}e^{it(X_N-\mu_N)/\sigma_N} &= e^{-it\mu_N/\sigma_N}\frac{1}{N}\sum_{k\ge 0} a_{Nk}e^{ikt/\sigma_N} \\ &= e^{-t^2/2}\sum_{l=0}^{L-1}\frac{e_l G_{j_l}}{N} e^{it/(\sigma j_0^{1/2})(\sum_{h=0}^{l-1} e_h - \mu(j_0-j_l)) - t^2(j_l-j_0)/(2j_0)} \\ &\qquad\times e^{O\left(j_0^{-1/2}(|t|+|t|^3)+(1-\delta)^{j_l}\right)} + O(N^{-\delta}).\end{aligned}$$

Let $\varepsilon > 0$ be a (small) real number and let κ be defined by $j_{\kappa-1} > j_0 - j_0^{\varepsilon} \ge j_\kappa$. Then $\kappa \le j_0 - j_\kappa < j_0^{\varepsilon}$ and consequently

$$\begin{aligned}\mathbf{E}e^{it(X_N-\mu_N)/\sigma_N} &= e^{-t^2/2}\sum_{l=0}^{\kappa-1}\frac{e_l G_{j_l}}{N} e^{O\left(|t|\sigma j_0^{\varepsilon-1/2} + t^2 j_0^{\varepsilon-1} + j_0^{-1/2}(|t|+|t|^3) + (1-\delta)^{j_0 - j_0^{\varepsilon}}\right)} \\ &\quad + O\left(\sum_{l=\kappa}^{L-1}\frac{G_{j_l}}{N}\right) + O(N^{-\delta}) \\ &= e^{-t^2/2} e^{O\left(|t|\sigma j_0^{\varepsilon-1/2} + t^2 j_0^{\varepsilon-1} + |t|^3 j_0^{-1/2} + (1-\delta)^{j_0-j_0^{\varepsilon}}\right)} + O(\alpha^{-j_0^{\varepsilon}}).\end{aligned}$$

Since $j_0 = (\log N)/(\log\alpha) + O(1)$ this implies (4.2) directly for $|t| \le (\log N)^{\varepsilon/3}$. Furthermore, since

$$e^{-t^2/2 + O(|t^3|j_0^{-1/2})} \le e^{-cj_0^{2\varepsilon/3}} = O(j_0^{-1})$$

for $(\log N)^{\varepsilon/3} \le |t| \le (\log N)^{1/2-\varepsilon}$ and a sufficiently small $c > 0$ we finally obtain the full version of (4.2). □

We can now use Proposition 4.2 to prove the first part of Theorem 2.2.

Proof. Set

$$\Delta_N(t) = e^{-t^2/2} - \mathbf{E}e^{it(X_N-\mu_N)/\sigma_N}.$$

Then by Esseen's [9, p. 32] inequality we have

$$\begin{aligned}(4.3)\quad &\frac{1}{N}|\{n<N : s_G(n) < \mathbf{E}X_N + x\mathbf{V}X_N\}| \\ &\qquad = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{1}{2}t^2}\,dt + O\left(\frac{1}{T} + \int_{-T}^{T}\left|\frac{\Delta_N(t)}{t}\right|dt\right).\end{aligned}$$

Choosing $T = (\log N)^{1/2-\varepsilon}$ we directly obtain from Proposition 4.2 and by applying the estimate

$$e^{-it\mu_N/\sigma_N}\frac{1}{N}\sum_{k\ge 0} a_{Nk}e^{ikt/\sigma_N} = 1 + O(t^2)$$

for $|t| \le (\log N)^{-2}$ that

$$\int_{-T}^{T}\left|\frac{\Delta_N(t)}{t}\right|dt = O\left((\log N)^{-1/2+\varepsilon}(\log\log N)\right).$$

Hence, (2.2) follows. □

5. Local Limit Law

In order to prove a local limit law for X_N, i.e. the second part or Theorem 2.2, we need more precise information on the behaviour of $b_j(z)$.

Proposition 5.1. *Suppose that $G = (G_j)_{j\ge 0}$ satisfies a finite or infinite recurrence of the above types. Then there exist $\eta > 0$ and $\delta > 0$ such that*

$$b_j(e^{it}) = C(e^{it})\alpha(e^{it})^j + O\left(\alpha^{(1-\delta)j}\right) \tag{5.1}$$

uniformly for $|t| \le \eta$, where $C(z)$ and $\alpha(z)$ are as in Proposition 4.1, and

$$b_j(e^{it}) = O\left(\alpha^{(1-\delta)j}\right) \tag{5.2}$$

uniformly for $\eta \le |t| \le \pi$.

Proof. Obviously, (5.1) follows from (4.1) for some $\eta > 0$.

For the proof of (5.2) we just have to observe that $|G(z,u)| < G(|z|,|u|) \le 1$ if $|z| \le 1$, $z \ne 1$, and $|u| \le 1/\alpha$. Hence, by continuity there exist $\varepsilon > 0$ and $\tau > 0$ such that $|1 - G(u, e^{it})| \ge \tau$ uniformly for (real) t with $\eta \le |t| \le \pi$ and (complex) u with $|u| \le 1+\varepsilon$. Thus, $B(e^{it}, u)$ is analytic (and therefore bounded) in this range and we obtain

$$\begin{aligned} b_j(e^{it}) &= \frac{1}{2\pi i} \int\limits_{|u|=1/\alpha+\varepsilon} B(e^{it}, u) \frac{du}{u^{j+1}} \\ &= O\left(\alpha^{(1-\delta)j}\right), \end{aligned}$$

with some $\delta > 0$. □

With help of Proposition 5.1 it is possible to derive asymptotic expansions for $b_{j,k}$ via saddle point approximations.

Proposition 5.2. *We have*

$$b_{j,k} = \frac{G_j}{\sqrt{2\pi j \sigma^2}} \left(\exp\left(-\frac{(k - j\mu)^2}{2j\sigma^2} \right) + O(j^{-1/2}) \right)$$

uniformly for all $j, k \geq 0$.

Proof. We again use Cauchy's formula

$$b_{j,k} = \frac{1}{2\pi} \int_{-\pi}^{\pi} b_j(e^{it}) e^{-ikt}\, dt.$$

Since

$$\int_{\eta \leq |t| \leq \pi} |b_j(e^{it})|\, dt = O\left(\alpha^{(1-\delta)j}\right) = O(G_j/j)$$

we just have to evaluate

$$I = \frac{1}{2\pi} \int_{|t| \leq j^{-\varepsilon}} b_j(e^{it}) e^{-ikt}\, dt + \frac{1}{2\pi} \int_{j^{-\varepsilon} \leq |t| \leq \eta} b_j(e^{it}) e^{-ikt}\, dt = I_1 + I_2,$$

where $0 < \varepsilon < \frac{1}{6}$. From $\alpha(e^{it}) = \alpha e^{i\mu t - \sigma^2 t^2/2 + O(t^3)}$ it follows that there exists a constant $c > 0$ such that $|\alpha(e^{it})| \leq e^{-ct^2}$ for $|t| \leq \eta$. Hence,

$$\begin{aligned} I_2 &\leq \frac{1}{\pi} \int_{j^{-\varepsilon}}^{\infty} e^{-cjt^2}\, dt + O\left(\alpha^{(1-\delta)j}\right) = O\left(e^{-cj^{1-2\varepsilon}}\right) + O\left(\alpha^{(1-\delta)j}\right) \\ &= O(G_j/j) \end{aligned}$$

Finally,

$$\begin{aligned}
I_1 &= \frac{1}{2\pi}\int_{|t|\le j^{-\varepsilon}} C\alpha^j e^{it(j\mu-k)-j\sigma^2t^2/2}\left(1+O(j|t^3|+|t|)\right)dt + \\
&\qquad\qquad O\left(\alpha^{(1-\delta)j}\right) \\
&= \frac{1}{2\pi}\int_{-\infty}^{\infty} C\alpha^j e^{it(j\mu-k)-j\sigma^2t^2/2}\,dt + O\left(\int_{|t|>j^{-\varepsilon}} C\alpha^j e^{-j\sigma^2t^2/2}\,dt\right) \\
&\quad + O\left(\int_{|t|\le j^{-\varepsilon}} C\alpha^j e^{-j\sigma^2t^2/2}(j|t^3|+|t|)\,dt\right) + O\left(\alpha^{(1-\delta)j}\right) \\
&= \frac{C\alpha^j}{\sqrt{2\pi j\sigma^2}}\exp\left(-\frac{(k-j\mu)^2}{2j\sigma^2}\right) + O(\alpha^j/j) \\
&= \frac{G_j}{\sqrt{2\pi j\sigma^2}}\exp\left(-\frac{(k-j\mu)^2}{2j\sigma^2}\right) + O(G_j/j).
\end{aligned}$$

This completes the proof of Proposition 5.2. □

Finally Proposition 5.2 and Lemma 3.6 can be used to complete the proof of Theorem 2.2.

Proof. As in the proof of Proposition 4.2 we suppose that $N = \sum\limits_{l=0}^{L-1} e_l G_{j_l}$ (with $j_0 > j_1 > \cdots > j_{L-1}$ and $e_l > 0$) is the G-ary expansion of N. Furthermore, let $\varepsilon > 0$ be a (small) real number and let κ be defined by $j_{\kappa-1} > j_0 - j_0^{\varepsilon} \ge j_\kappa$. Then by (3.5)

$$\begin{aligned}
a_{Nk} &= \sum_{l=0}^{L-1}\sum_{i=0}^{e_l-1} b_{j_l,k-\sum_{h=0}^{l-1}e_h-i} \\
&= \sum_{l=0}^{\kappa-1}\sum_{i=0}^{e_l-1} b_{j_l,k-\sum_{h=0}^{l-1}e_h-i} + O\left(\sum_{l=\kappa}^{L-1}\frac{G_{j_l}}{j_l^{1/2}}\right) \\
&= \sum_{l=0}^{\kappa-1}\sum_{i=0}^{e_l-1} \frac{G_{j_l}}{\sqrt{2\pi j_l\sigma^2}}\exp\left(-\frac{\left(k-\sum_{h=0}^{l-1}e_h - ij_l\mu\right)^2}{2j_l\sigma^2}\right) + O(G_{j_0}/j_0).
\end{aligned}$$

If $l < \kappa$ and $|k - \mu_N| = O(j_0^{1/2} \log j_0)$ then

$$\begin{aligned}
\frac{(k-\mu_N)^2}{2\sigma_N^2} - \frac{\left(k - \sum_{h=0}^{l-1} e_h - ij_l\mu\right)^2}{2j_l\sigma^2}
&= \frac{(k-\mu_N)^2 - \left(k - \sum_{h=0}^{l-1} e_h - ij_l\mu\right)^2}{2\sigma_N^2} \\
&\qquad + \left(k - \sum_{h=0}^{l-1} e_h - ij_l\mu\right)^2 \left(\frac{1}{2\sigma_N^2} - \frac{1}{2j_l\sigma^2}\right) \\
&= O\left(j_0^{\varepsilon-1/2} \log j_0\right) + O\left(j_0^{-1}(\log j_0)^2\right),
\end{aligned}$$

where we have used $\mu_N = j_0\mu + O(1)$ and $\sigma_N^2 = j_0\sigma^2 + O(1)$. Hence, from

$$\sqrt{\frac{j_0 + O(1)}{j_l}} \exp\left(\frac{(k-\mu_N)^2}{2\sigma_N^2} - \frac{\left(k - \sum_{h=0}^{l-1} e_h - ij_l\mu\right)^2}{2j_l\sigma^2}\right) = 1 + O\left(j_0^{\varepsilon-1/2} \log j_0\right)$$

we obtain

$$\begin{aligned}
a_{Nk} &= \frac{N}{\sqrt{2\pi\sigma_N^2}} \exp\left(-\frac{(k-\mu_N)^2}{2\sigma_N^2}\right) \sum_{l=0}^{k-1} \frac{e_l G_{j_l}}{N} \left(1 + O\left(j_0^{\varepsilon-1/2} \log j_0\right)\right) \\
&\qquad + O(G_{j_0}/j_0) \\
&= \frac{N}{\sqrt{2\pi\sigma_N^2}} \left(\exp\left(-\frac{(k-\mu_N)^2}{2\sigma_N^2}\right) + O\left(j_0^{\varepsilon-1/2} \log j_0\right)\right).
\end{aligned}$$

If $|k - \mu_N| \geq j_0^{1/2} \log j_0$ then we have for $l < \kappa$

$$\begin{aligned}
b_{j_l, k - \sum_{h=0}^{l-1} e_h - i} &= O\left(\alpha^{j_l} j_0^{-1/2} \exp\left(-\frac{(\log j_0)^2}{4\sigma^2}\right)\right) \\
&= O\left(\alpha^{j_l} j_0^{-1}\right)
\end{aligned}$$

which finally gives

$$\begin{aligned}
a_{Nk} &= O((\alpha^{j_0} j_0^{-1}) + O\left(\sum_{l=\kappa}^{L-1} \frac{G_{j_l}}{j_l^{1/2}}\right) \\
&= O(G_{j_0}/j_0).
\end{aligned}$$

This completes the proof of Theorem 2.2. $\square$

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