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SOME FURTHER STATISTICAL PROPERTIES OF THE DIGITS IN CANTOR'S SERIES

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By

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Dedicated to G. ALEXITS *on the occasion of his 60th birthday*

Introduction

Let $q_1, q_2, \ldots, q_n, \ldots$ be an arbitrary sequence of positive integers, restricted only by the condition $q_n \geqq 2$. We can develop every real number x $(0 \leqq x \leqq 1)$ into Cantor's series

(1) $$x = \sum_{n=1}^{\infty} \frac{\varepsilon_n(x)}{q_1 q_2 \cdots q_n}$$

where the n-th "digit" $\varepsilon_n(x)$ may take on the values $0, 1, \ldots, q_n - 1$ $(n = 1, 2, \ldots)$. The representation (1) is clearly a straightforward generalization of the ordinary decimal (or q-adic) representation of real numbers, to which it reduces if all q_n are equal to 10 (or to q, resp.).

In a recent paper [3] (see also [2] for a special case of the theorem) it has been shown that the classical theorem of BOREL [1] (according to which for almost all real numbers x the relative frequency of the numbers $0, 1, \ldots, 9$ among the first n digits of the decimal expansion of x tends for $n \to +\infty$ to $\frac{1}{10}$) can be generalized for all those representations (1) for which $\sum_{n=1}^{\infty} \frac{1}{q_n}$ is divergent. The generalization obtained in [2] can be formulated as follows: Let $f_n(k, x)$ denote the number of those among the digits $\varepsilon_1(x), \varepsilon_2(x), \ldots, \varepsilon_n(x)$ which are equal to k $(k = 0, 1, \ldots)$, i. e. put

(2) $$f_n(k, x) = \sum_{\substack{\varepsilon_j(x) = k \\ 1 \leqq j \leqq n}} 1.$$

Let us put further

(3a) $$Q_n = \sum_{j=1}^{n} \frac{1}{q_j}$$

and

(3b) $$Q_{n,k} = \sum_{\substack{j=1 \\ q_j > k}}^{n} \frac{1}{q_j}.$$

Then for all non-negative integers k for which

(4) $$\lim_{n \to +\infty} Q_{n,k} = +\infty,$$

we have for almost all x

(5) $$\lim_{n\to+\infty} \frac{f_n(k,x)}{Q_{n,k}} = 1.$$

For those values of k for which $Q_{n,k}$ is bounded, $f_n(k,x)$ is bounded for almost all x. (For other related results see [4] and [5].)

In the present paper we consider the behaviour of

(6) $$M_n(x) = \operatorname*{Max}_{(k)} f_n(k,x),$$

i. e. of the frequency of the most frequent number among the first n digits.

We shall discuss the three most important types of behaviour of $M_n(x)$:

Type 1. $\lim\limits_{n\to\infty} \frac{M_n(x)}{Q_n} = 1$ for almost all x. This is the case if q_n is constant or bounded, but also if e. g. $q_n \sim cn^\beta$ with $c>0$ and $0<\beta<1$ (see Theorem 1).

Type 2. $\lim\limits_{n\to+\infty} \frac{M_n(x)}{Q_n} = C$ for almost all x where $1<C<+\infty$. This is the case e. g. if $q_n \sim cn$ with $c>0$ (see Theorem 2).

Type 3. $\lim\limits_{n\to+\infty} \frac{M_n(x)}{Q_n} = +\infty$ for almost all x. This is the case e. g. if $q_n \sim n(\log n)^\alpha$ with $0<\alpha\leqq 1$ (see Theorem 3).

There exist, of course, sequences q_n for which $\lim\limits_{n\to\infty} \frac{M_n(x)}{Q_n}$ does not exist for almost all x, but we do not consider such cases in the present paper. We shall deal with the case when $\sum \frac{1}{q_n} < +\infty$ and with some other questions on Cantor's series in another paper.

All results obtained are based on the evident fact that the digits $\varepsilon_n(x)$, considered as random variables on the probability space $[\Omega, \mathcal{A}, \mathbf{P}]$, where Ω is the interval $(0,1)$, $\mathcal{A}$ the set of all measurable subsets of Ω and $\mathbf{P}(A)$ is for $A\in\Omega$ the Lebesgue measure of A, are independent and have the probability distribution

(7) $$\mathbf{P}(\varepsilon_n(x)=k) = \frac{1}{q_n} \qquad (k=0,1,\ldots,q_n-1).$$

§ 1. Type 1 behaviour of $M_n(x)$

In case q_n is bounded, $q_n\leqq K$, we have by (5)

$$\lim_{n\to\infty} \frac{N_n(0,x)}{Q_n} = 1 \quad \text{and} \quad \overline{\lim_{n\to\infty}} \frac{N_n(k,x)}{Q_n} \leqq 1 \quad \text{for} \quad k\geqq 1$$

and thus, as in this case $M_n(x) = \max_{0 \leqq k < K} f_n(k, x)$, we obtain for almost all x

$$\lim_{n \to +\infty} \frac{M_n(x)}{Q_n} = 1. \tag{8}$$

We shall show that (8) is valid under more general conditions. We prove in this direction the following

THEOREM 1. *If*

$$\lim_{n \to +\infty} \frac{Q_n}{\log n} = +\infty, \tag{9}$$

then we have for almost all x

$$\lim_{n \to +\infty} \frac{M_n(x)}{Q_n} = 1. \tag{10}$$

PROOF OF THEOREM 1. Let $\mathfrak{A}$ denote the set of those numbers n for which $q_n < n^3$. Let us denote the elements of the complementary set $\overline{\mathfrak{A}}$ of $\mathfrak{A}$ by n_j $(n_j < n_{j+1};\ j = 1, 2, \ldots)$, then we have $n_j \geqq j$ and therefore $q_{n_j} \geqq n_j^3 \geqq j^3$.

Then we have for any k

$$\sum_{j \in \overline{\mathfrak{A}}} \mathbf{P}(\varepsilon_j(x) = k) = \sum_j \mathbf{P}(\varepsilon_{n_j}(x) = k) = \sum_j \frac{1}{q_{n_j}} \leqq \sum_{j=1}^{\infty} \frac{1}{j^3} < +\infty$$

and therefore, by the Borel—Cantelli lemma for almost every x, every k occurs only a finite number of times in the sequence $\varepsilon_{n_j}(x)$. On the other hand, the probability that a number k occurs more than once in the sequence $\varepsilon_{n_j}(x)$ $(j = 1, 2, \ldots)$ does not exceed

$$W_k = \sum_{\substack{q_{n_i} > k \\ q_{n_j} > k \\ j > i}} \frac{1}{q_{n_i} q_{n_j}}$$

and we have

$$\sum_{k=0}^{\infty} W_k = \sum_{i<j} \sum \frac{\min(q_{n_i}, q_{n_j})}{q_{n_i} q_{n_j}} = \sum_{i=1}^{\infty} \sum_{j>i} \frac{1}{q_{n_j}} \leqq \sum_{i=1}^{\infty} \sum_{j=i+1}^{\infty} \frac{1}{j^3} < +\infty.$$

Thus, using again the Borel—Cantelli lemma, it follows that for almost all x only a finite number of integers k may occur more than once in the sequence $\varepsilon_{n_i}(x)$. This, together with what has been proved above, implies that for almost every x in the sequence $\varepsilon_{n_i}(x)$ only a finite number of values occur more than once and these values occur also only a finite number of times. By other words, in proving Theorem 1 we may suppose that

$$q_n < n^3 \quad \text{for all values of } n \tag{11}$$

without the restriction of generality.

Clearly, we have

$$\frac{M_n(x)}{Q_n} \geqq \frac{f_n(0, x)}{Q_n}$$

and thus, taking into account that owing to (9) condition (4) is fulfilled for $k=0$, it follows by (5) that

$$\varliminf_{n\to+\infty} \frac{M_n(x)}{Q_n} \geqq 1.$$

Thus to prove Theorem 1 it suffices to show that for almost all x

$$\varlimsup_{n\to+\infty} \frac{M_n(x)}{Q_n} \leqq 1. \tag{12}$$

As by (4) we have for any k_0

$$\varlimsup_{n\to+\infty} \frac{\operatorname*{Max}_{0\leqq k\leqq k_0} f_n(k, x)}{Q_n} \leqq 1,$$

(12) will be proved if we show that for any $\varepsilon>0$ and for some k_0 which may depend on ε, putting

$$M_n^{(k_0)}(x) = \operatorname*{Max}_{k>k_0} f_n(k, x), \tag{13}$$

we have

$$\varlimsup_{n\to\infty} \frac{M_n^{(k_0)}(x)}{Q_n} \leqq 1+\varepsilon. \tag{14}$$

To prove (14) we start by calculating the probability $\mathbf{P}(f_n(k,x)=j)$. In what follows $c_1, c_2, \ldots$ denote positive absolute constants. We evidently have

$$\mathbf{P}(f_n(k,x)=j) = \Bigg(\sum_{\substack{1\leqq i_1<i_2<\cdots<i_j\leqq n\\ q_{i_r}>k;\ r=1,2,\ldots,j}} \frac{1}{(q_{i_1}-1)\cdots(q_{i_j}-1)}\Bigg)\cdot \prod_{\substack{h=1\\ q_h>k}}^{n}\left(1-\frac{1}{q_h}\right). \tag{15}$$

It follows that

$$\mathbf{P}(f_n(k,x)=j) \leqq e^{-Q_{n,k}} \frac{(Q^*_{n,k})^j}{j!} \tag{16}$$

where

$$Q^*_{n,k} = \sum_{\substack{j\leqq n_j\\ q_j>k}} \frac{1}{q_j-1}. \tag{17}$$

Using the well-known identity

$$e^{-\lambda}\sum_{j=N}^{\infty}\frac{\lambda^j}{j!} = \frac{1}{N!}\int_0^{\lambda} t^N e^{-t}\,dt$$

we obtain for $0<\lambda<\dfrac{N}{1+\varepsilon}$

$$e^{-\lambda}\sum_{j=N}^{\infty}\frac{\lambda^j}{j!} \leqq \frac{c_1}{\varepsilon\sqrt{N}} e^{-\frac{(N-\lambda)^2}{2N}}. \tag{18}$$

Thus we obtain for $0<\varepsilon<1$, in view of

$$Q^*_{n,k} \leqq Q_{n,k}\left(1+\frac{1}{k}\right) \leqq Q_n\left(1+\frac{1}{k}\right), \tag{19}$$

that

$$\mathbf{P}(f_n(k,x) \geqq (1+\varepsilon)Q_n) \leqq \frac{c_1}{\varepsilon\sqrt{Q_n}}\, e^{\frac{Q_n}{k}}\, e^{-\frac{Q_n\left(\varepsilon-\frac{1}{k}\right)^2}{4}}. \tag{20}$$

We obtain from (20) for $k \geqq \frac{8}{\varepsilon^2}$

$$\mathbf{P}(f_n(k,x) \geqq (1+\varepsilon)Q_n) \leqq \frac{c_1}{\varepsilon\sqrt{Q_n}}\, e^{-\frac{\varepsilon^2 Q_n}{16}}. \tag{21}$$

This implies, putting $k_0=\left[\frac{8}{\varepsilon^2}\right]+1$ and taking (11) into account,

$$\mathbf{P}(M_n^{(k_0)}(x) \geqq (1+\varepsilon)Q_n) \leqq \sum_{k=k_0}^{n^3} \mathbf{P}(f_n(k,x) \geqq (1+\varepsilon)Q_n) \leqq \frac{c_1 n^3}{\varepsilon\sqrt{Q_n}}\, e^{-\frac{\varepsilon^2 Q_n}{16}}. \tag{22}$$

As by (9) we have for $n \geqq n_0$ $Q_n > \frac{80}{\varepsilon^2}\log n$, it follows that

$$\mathbf{P}(M_n^{(k_0)}(x) \geqq (1+\varepsilon)Q_n) \leqq \frac{c_2}{n^2}. \tag{23}$$

Thus

$$\sum_{n=1}^{\infty} \mathbf{P}(M_n^{(k_0)}(x) \geqq (1+\varepsilon)Q_n) < +\infty \tag{24}$$

and therefore by the lemma of Borel—Cantelli, the inequality $M_n^{(k_0)}(x) \geqq (1+\varepsilon)Q_n$ can be satisfied for almost all x only for a finite number of values of n. This implies (14) for almost all x which proves Theorem 1.

§ 2. Type 2 behaviour of $M_n(x)$

In this § we shall prove the following rather surprising

THEOREM 2. *If*

$$0<c_2 \leqq \frac{q_n}{n} \leqq c_3 \qquad (n=1,2,\ldots) \tag{25}$$

and

$$\lim_{n\to+\infty} \frac{Q_n}{\log n} = \alpha > 0, \tag{26}$$

then we have for almost all x

$$\lim_{n\to+\infty} \frac{M_n(x)}{Q_n} = y(\alpha) \tag{27}$$

where $y=y(\alpha)>1$ *is the unique (real) solution of the equation*

$$y\log y=\frac{1}{\alpha}. \tag{28}$$

PROOF OF THEOREM 2. We start from the inequality, which follows simply from Stirling's formula,

$$e^{-\lambda}\sum_{j=N}^{\infty}\frac{\lambda^j}{j!}\leqq c_4\left(\frac{\lambda e}{N}\right)^N e^{-\lambda} \tag{29}$$

for $N>\beta\lambda$ with fixed $\beta>1$ where c_4 depends on β.

Now evidently (25) and (26) imply that

$$Q_{n,k}=\alpha\log\frac{n}{k}+o(\log n). \tag{30}$$

Thus, by virtue of (16), we have, if $Y>y(\alpha)$ where $y(\alpha)$ denotes the solution of the equation (28), for any ε with $0<\varepsilon<\alpha Y\log Y-1$ and $n\geqq n_0(\varepsilon)$

$$\sum_{k=1}^{c_3 n}\mathbf{P}(f_n(k,x)\geqq YQ_n)\leqq\frac{c_5}{n^{\alpha Y\log Y-1-\varepsilon}}. \tag{31}$$

Thus

$$\mathbf{P}(M_n(x)>YQ_n)\leqq\frac{c_5}{n^{\delta}}\quad\text{for}\quad n\geqq n_0(\varepsilon) \tag{32}$$

where $\delta=\alpha Y\log Y-1-\varepsilon>0$. It follows that

$$\sum_{s=1}^{\infty}\mathbf{P}(M_{2^s}(x)>YQ_{2^s})<+\infty \tag{33}$$

and therefore by the Borel—Cantelli lemma the number of those values of s for which $M_{2^s}(x)>YQ_{2^s}$ is finite for almost every x. If $2^{s-1}<n<2^s$, let us choose an arbitrary number Y_1 such that $y(\alpha)<Y<Y_1$, then

$$\frac{M_n(x)}{Q_n}\leqq\frac{M_{2^s}(x)}{Q_{2^{s-1}}}\leqq\frac{Y_1}{Y}\frac{M_{2^s}(x)}{Q_{2^s}}$$

if $s\geqq s_0$. Thus, if for such an n $M_n(x)>Y_1Q_n$, then $M_{2^s}(x)>YQ_{2^s}$. As the last inequality can be valid for almost all x only for a finite number of values of s, it follows that $M_n(x)>Y_1Q_n$ is valid for almost all x only for a finite number of values of n. As Y_1 may be equal to any number greater than $y(\alpha)$, this implies that for almost all x

$$\overline{\lim_{n\to\infty}}\frac{M_n(x)}{Q_n}\leqq y(\alpha). \tag{34}$$

It remains to prove that we have also

$$\underline{\lim_{n\to\infty}}\frac{M_n(x)}{Q_n}\geqq y(\alpha) \tag{35}$$

for almost all x.

As for any sequence of positive numbers $b_1, b_2, \ldots, b_N$ we have

$$\sum_{1\leqq i_1<i_2<\ldots<i_j\leqq N} b_{i_1}b_{i_2}\cdots b_{i_j} \geqq \frac{\left(\sum_{i=1}^{N} b_i\right)^j}{j!} - \frac{1}{2}\left(\sum_{i=1}^{N} b_i^2\right)\frac{\left(\sum_{i=1}^{N} b_i\right)^{j-2}}{(j-2)!},$$

we obtain from (15)

$$\mathbf{P}(f_n(k,x)=j) \geqq c_6 e^{-Q_{n,k}}\left(\frac{Q_{n,k}^j}{j!} - \frac{Q_{n,k}^{j-2}\sum_{q_i>k,\, i\leqq n}\frac{1}{q_i^2}}{2(j-2)!}\right). \tag{36}$$

Taking into account that

$$\sum_{i\leqq n,\, q_i>k}\frac{1}{q_i^2} \leqq \frac{c_7}{k}$$

and that for $j=yQ_n$ and $k\leqq n^{1-\varepsilon}$

$$\frac{j^2}{(Q_{n,k})^2} \leqq \frac{c_8}{\varepsilon^2}$$

if $1<y<y(\alpha)$ where $y(\alpha)$ denotes the solution of (28) and $0<\varepsilon<1-\alpha y\log y$, it follows that

$$\sum_{\log^2 n\leqq k<n}\mathbf{P}(f_n(k,x)\geqq yQ_n) \geqq c_9 n^\delta \quad \text{for} \quad n\geqq n_0(\varepsilon) \tag{37}$$

where $\delta = 1-\alpha y\log y-\varepsilon>0$.

Now it is easy to see that

$$\begin{aligned}\mathbf{P}(f_n(k_1,x)=j_1, f_n(k_2,x)=j_2) &\leqq \\ \leqq \left(1+\frac{j_1}{k_1}\right)\left(1+\frac{j_2}{k_2}\right)&\mathbf{P}(f_n(k_1,x)=j_1)\mathbf{P}(f_n(k_2,x)=j_2).\end{aligned} \tag{38}$$

It follows that for $k_1\geqq\log^3 n$, $k_2\geqq\log^3 n$ we have for any y with $1<y<y(\alpha)$, where $y(\alpha)$ is the solution of the equation (28),

$$\begin{aligned}&\mathbf{P}(f_n(k_1,x)\geqq yQ_n, f_n(k_2,x)\geqq yQ_n)\leqq \\ &\leqq \mathbf{P}(f_n(k_1,x)\geqq yQ_n)\mathbf{P}(f_n(k_2,x)\geqq yQ_n)\left(1+O\left(\frac{1}{\log^2 n}\right)\right).\end{aligned}$$

If we define $\eta_n=\eta_n(x)$ as the number of those values of k for which $\log^2 n\leqq k\leqq n$ and $f_n(k,x)\geqq yQ_n$, we have, denoting by $\mathbf{M}(\eta_n)$ the mean value and by $\mathbf{D}^2(\eta_n)$ the variance of η_n,

$$\mathbf{M}(\eta_n)\geqq c_9 n^\delta \tag{39}$$

and

$$\mathbf{D}^2(\eta_n)\leqq c_{10}\frac{\mathbf{M}^2(\eta_n)}{\log^2 n}. \tag{40}$$

It follows by the inequality of Chebyshev

$$\mathbf{P}(\eta_n=0)\leqq\mathbf{P}(|\eta_n-\mathbf{M}(\eta_n)|\geqq\mathbf{M}(\eta_n))\leqq\frac{c_{10}}{\log^2 n} \tag{41}$$

and thus

$$\sum_{n=1}^{\infty}\mathbf{P}(\eta_{2^n}=0)<+\infty. \tag{42}$$

It follows by the Borel—Cantelli lemma that we have for almost all x

$$M_{2^n}(x)\geqq yQ_{2^n}\quad\text{for}\quad n\geqq n_0(x).$$

Thus for any $\varepsilon>0$ and for $n\geqq n_1(x,\varepsilon)$ and $2^n\leqq N<2^{n+1}$ we have

$$M_N(x)\geqq M_{2^n}(x)\geqq yQ_{2^n}\geqq(y-\varepsilon)Q_N. \tag{43}$$

This implies that for almost all x

$$\varliminf_{n\to\infty}\frac{M_n(x)}{Q_n}\geqq y. \tag{44}$$

As y may be any number not exceeding $y(\alpha)$, we obtain from (44) that (35) is also valid for almost all x. Thus the proof of Theorem 2 is complete.

§ 3. Type 3 behaviour of $M_n(x)$

Now we shall prove a theorem which deals with conditions under which $\frac{M_n(x)}{Q_n}$ tends to $+\infty$ for almost every x.

THEOREM 3. *Let us suppose that*

$$\lim_{n\to+\infty}\frac{q_n}{n}=+\infty, \tag{45}$$

but at the same time

$$\lim_{n\to+\infty}Q_n=+\infty. \tag{46}$$

Then we have for almost every x

$$\lim_{n\to+\infty}\frac{M_n(x)}{Q_n}=+\infty. \tag{47}$$

PROOF OF THEOREM 3. The proof follows the same pattern as the second half of the proof of Theorem 2 (i. e. the proof of (35)).

We have from (45)

$$Q_n=\sum_{i=1}^{n}\frac{1}{q_i}=\sum_{i=1}^{n}\frac{1}{i}\,\frac{i}{q_i}=o(\log n), \tag{48}$$

further for any $A>0$

$$\sum_{q_j<e^{AQ_n}} \frac{1}{q_j} = o(\log e^{AQ_n}) = o(Q_n) \tag{49}$$

and thus

$$Q_{n,k} \geqq Q_n(1-o(1)) \quad \text{for} \quad k \leqq e^{AQ_n}. \tag{50}$$

It follows from (36) that for any $N>N_0>1$

$$\mathbf{P}(f_n(k,x) \geqq NQ_n) \geqq e^{-N\log N\cdot Q_n}. \tag{51}$$

Now let us choose $A=3N\log N$, then we have

$$\sum_{Q_n^2 \leqq k \leqq e^{AQ_n}} \mathbf{P}(f_n(k,x) \geqq NQ_n) \geqq e^{2N\log N\cdot Q_n}.$$

On the other hand, we have from (38)

$$\mathbf{P}(f_n(k_1,x) \geqq NQ_n, f_n(k_2,x) \geqq NQ_n) \leqq$$
$$\leqq \mathbf{P}(f_n(k_1,x) \geqq NQ_n)\mathbf{P}(f_n(k_2,x) \geqq NQ_n)\left(1+O\left(\frac{1}{Q_n}\right)\right)$$

and thus, defining $\eta_n=\eta_n(x)$ as the number of those values of k for which $Q_n^2 \leqq k \leqq e^{AQ_n}$ and $f_n(k,x)>NQ_n$, we have $\mathbf{M}(\eta_n)\to+\infty$ and

$$\mathbf{D}^2(\eta_n) \leqq c_{12}\frac{\mathbf{M}^2(\eta_n)}{Q_n}.$$

Similarly as in the proof of Theorem 2 we obtain that

$$\varlimsup_{n\to\infty} \frac{M_n(x)}{Q_n} \geqq N$$

for almost all x. As N may be chosen arbitrarily large, Theorem 3 follows.

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