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Frequency of occurrence of numbers in the World Wide Web

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Abstract

The distribution of numbers in human documents is determined by a variety of diverse natural and human factors, whose relative significance can be evaluated by studying the numbers' frequency of occurrence. Although it has been studied since the 1880's, this subject remains poorly understood. Here, we obtain the detailed statistics of numbers in the World Wide Web, finding that their distribution is a heavy-tailed dependence which splits in a set of power-law ones. In particular, we find that the frequency of numbers associated to western calendar years shows an uneven behavior: 2004 represents a 'singular critical' point, appearing with a strikingly high frequency; as we move away from it, the decreasing frequency allows us to compare the amounts of existing information on the past and on the future. Moreover, while powers of ten occur extremely often, allowing us to obtain statistics up to the huge 10^{127} , 'non-round' numbers occur in a much more limited range, the variations of their frequencies being dramatically different from standard statistical fluctuations. These findings provide a view of the array of numbers used by humans as a highly non-equilibrium and inhomogeneous system, and shed a new light on an issue that, once fully investigated, could lead to a better understanding of many sociological and psychological phenomena.

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1. Introduction

Already in the early 1880's, Newcomb [1] noticed a specific uneven distribution of the first digits of numbers, which is now known as Benford's law [2]. The observed form of this distribution indicates the wide, skewed shape of the frequency of occurrence of numbers in nature [3–5]—for illustration, and to clarify the question, note that in these first two sentences the numerals 1, 2, 3, 5 and 1880 all occur twice. Benford's law is directly derived by assuming that a number occurs with a frequency inversely proportional to it, meaning that the frequencies of numbers in the intervals (1, 10), (10, 100), (100, 1000), etc. are equal. Yet, this assumption lacks convincing quantitative support and understanding, in part due to scanty data available. In our days, this problem can be tackled by resorting (with the help of search engines) to the enormous database constituted by the World Wide Web.

One should note that the profoundly wide form of the distribution of numbers in human documents is determined by two sets of factors. The first includes general natural reasons of which the most important is the multi-scale organization of our world. The second are 'human factors' including the current technological level of the society, the structure of languages, adopted numeral and calendar systems, history, cultural traditions and religions, human psychology, and many others. By analyzing the occurrence frequency of numbers we can estimate the relative significance and role of these factors.

The frequency of occurrence of numbers in the World Wide Web pages (or, in other words, WWW documents) necessarily reflects the distribution of numbers in all human documents, allowing us to effectively study their statistics by using search engines, which usually supply the approximate number of pages containing the Arabic numeral that we are looking for. In this respect, the WWW provides us with huge statistics. Yet, the frequencies of occurrence of distinct kinds of numbers are very different [6]: for example, one can see that 777 and 1000 occur much more frequently than their neighbors (Table 1). Here we report on the markedly distinct statistics of different types of natural numbers (or, rather, positive integers) in the WWW documents, collected through the currently most popular search engine [7]. We consider separately (i) powers of 10 and (ii) non-round integers, and find that in both of these cases, the number $N(n)$ of pages containing an integer n decays as a power law, $N(n) \sim n^{-\beta}$, over many orders of magnitude. The observed values of the β exponent strongly differ for the different types of numbers, (i) and (ii), and also differ from 1, thus contradicting the above mentioned assumption of inverse proportionality for their frequency of occurrence.

Note that, previously, scale-free (i.e., power-law) distributions were observed for processes in the WWW [8,9] and its structural characteristics [10,11]. However, and in contrast to these studies, we use the WWW as a database for measuring one of the basic distributions in nature. In order to explain the observed distributions, we treat the global array of numbers as a non-equilibrium, evolving system with a specific influx of numbers, and, as a reflection of this non-equilibrium nature, we find a 'critical behavior' of $N(n)$ in the neighborhood of $n = 2004$ (the current year at the time the measurements were made): near this point, the frequency of WWW documents follows a power law, $N(n) \sim (2005 - n)^{-\alpha}$.

Table 1
Typical numbers with high frequencies of occurrence

Example	Description
1000	powers of 10
2460, 2465	'round' numbers: multiples of 10 and 5
666, ^a 131313	numbers easy to remember or symmetric
512 = 2 ⁹	powers of 2
666, ^a 777	numbers with strong associations
78701	popular zip codes
866, 877	toll free telephone numbers
1812	important historical dates
747, 8086	serial numbers of popular products
314159	beginning parts of mathematical constants

^aA number may occur simultaneously in several lines of the table.

Finally, we show that the statistics of variations of the frequencies of WWW pages which contain close numbers of the same kind, dramatically disagrees with the standard distribution of statistical fluctuations. We observe, namely, that the amplitude of these variations, $\delta N(n)$, is much greater than what would be expected for standard statistical fluctuations. Consequently, the frequencies of pages containing different numbers do not fluctuate independently, these fluctuations being a reflection of those of the influx of numbers.

2. Current-year singularity

In the second week of December 2004, we obtained the frequency of WWW documents corresponding to positive integers n in the range between 1 and 100,000 (Fig. 1a). This plot contains a set of regularly distributed peaks, which indicate that different types of numbers occur with very unlike frequencies. For example, the number of documents containing round (ending with 0) numbers is much higher than that for non-round numbers. Furthermore, the special number 2004 occurs with a remarkably high frequency: 3,030,000,000 pages. For comparison, among 8,058,044,651 WWW pages covered by the used search engine, a single character string a occurs in about 8,000,000,000 pages, while the numbers 0, 1 and 1000 occur in 2,180,000,000, 4,710,000,000 and 154,000,000 pages, respectively. The high asymmetric peak of $N(n)$ around $n = 2004$ (Fig. 1b) is naturally identified as the contribution of documents containing numbers associated to years; below $n = 2005$, this peak can be fitted by a power law, following $N(n) \sim (2005 - n)^{-\alpha}$, where $\alpha = 1.2 \pm 0.1$ (inset of Fig. 1b). Therefore, in the vicinity of 2004, $N(n)$ increases with n much faster than the total number of pages as the WWW grows with time, which indicates that there are many pages with numbers associated to years that disappear from the WWW (or at least, are updated) after a while. Indeed, our observations prove that the amount of pages holding a number $n < t$ (where t is time measured in

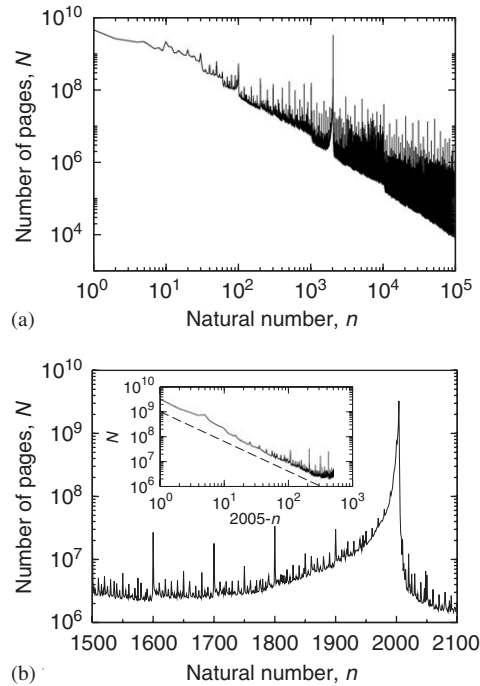


Fig. 1. (a) The frequencies $N(n)$ of WWW pages containing numbers n up to 100,000 on a log–log plot. Note the peak at $n = 2004$. (b) The part of the distribution around $n = 2004$ shown in more detail on a log–linear plot. The asymmetric form of the peak gives an idea about the relation between the stored volumes of information on the past and on the future: the former is much more referred to than the latter. In the inset, the low- n part of this peak is plotted versus the difference $2005 - n$ on a log–log plot ($1500 < n < 2005$). A power-law behavior is observed practically in the entire range where the contribution of numbers associated to years is main. The slope of the dashed line is -1.2 . It was not possible to find a reliable fit to the dependence for $n \geq 2005$. These plots also demonstrate a hierarchy of peaks for documents holding numbers of different kinds.

years) in the region of the ‘critical singularity’ decreases with t approximately following $N(n, t) \sim (t - n)^{-\alpha}$.

3. Power-law distributions

We find that the frequency of occurrence of natural numbers, considered without separating them into distinct classes (Fig. 1a), is a slowly decreasing dependence. Nevertheless, it can hardly be fitted by any power law because it is, in fact, the result of the superposition of distributions of distinct kinds of numbers, which, in turn, are power laws having different exponents. In order to proceed, we then compare the statistics of the WWW documents which hold two ‘extreme’ types of numbers: (i) powers of 10, which should occur with the highest frequencies due to the common

decimal numeral system, and, contrastingly, (ii) non-round numbers (i.e., those with a non-zero digit in the end) which are, on average, the most indistinctive ones, therefore occurring with the lowest frequencies. It is worth remarking that, even though the non-round include many peculiar numbers, such as 777 for example, we find that their contribution does not change the statistics noticeably.

The strikingly high frequency of occurrence of powers of 10 in the WWW allows us to obtain the statistics for numbers up to 10^{127} (Fig. 2a), a range that is restricted by the limited size of strings being accepted by the used search engine (128 characters). Two distinct regions are seen in the distribution. The region of relatively ‘small’ numbers, up to 10^{11} (Fig. 2b), is of a power-law form, $N(n) \sim n^{-\beta}$, where $\beta = 0.50 \pm 0.02$, hence close to the law $N(n) \sim 1/\sqrt{n}$; note that this exponent is much smaller than 1 and far smaller than the values of the exponents of typical Zipf’s law

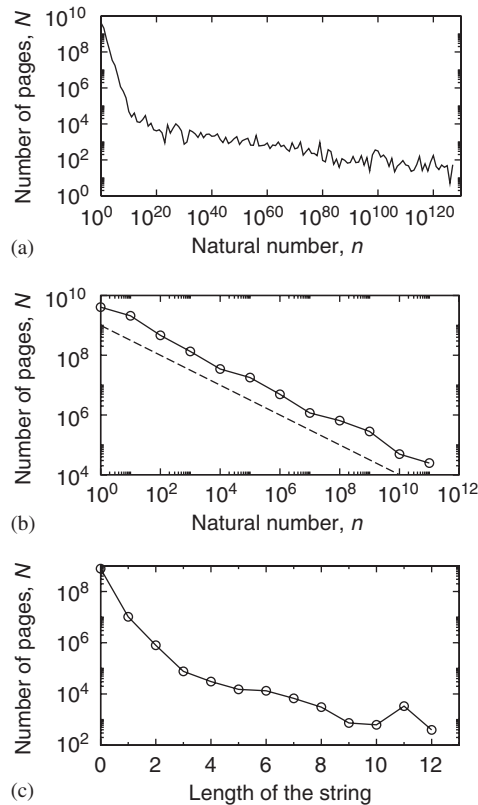


Fig. 2. The frequencies of WWW pages containing powers of 10. (a) The full log–log plot up to the maximal searchable 10^{127} . (b) The power-law-like part of the distribution. The slope of the dashed line is -0.5 . We emphasize that the power-law dependence is observed over 11 orders of magnitude, which is a uniquely wide range. (c) For comparison, the number of WWW documents containing a character string *baaa...a* of varying length on a log–linear plot (the length of the string is the equivalent to the exponent in the power of 10). Note the difference from (b).

distributions [11,12], these being mostly in the range between 2 and 3. For comparison, the occurrence frequencies of a character string $baaa\dots a$ of varying length were also measured, a quite different, far from straight line, dependence having been observed (Fig. 2c). For n larger than 10^{11} , we observe an extremely slow decrease of the frequency of occurrence of pages containing powers of 10 (Fig. 2a). It is worth noting that the crossover between these two regimes turns out to be rather close to the maximum 32 digit binary number, which is about 0.4×10^{10} .

For properly measuring the occurrence frequency of non-round numbers, we use a set of intervals selected in their wide range, each of which having a width of 50 numbers, so that the relative variation of the frequency of WWW pages inside a specific interval is sufficiently small. In addition, these intervals are chosen far from the powers of 10, whose close neighborhood includes numbers, such as, for instance, 1009, that occur more often and whose distribution does not follow a clear power law. Within each of these intervals, we take the average values of n and $N(n)$, and denote them by $\langle n \rangle$ and $\langle N \rangle$, respectively; the resulting dependence (Fig. 3) has a prominent power-law region with exponent $\beta = 1.3 \pm 0.05$, which strongly differs from that ascertained for powers of 10. As numbers grow, the ratio of the amount of WWW documents with powers of 10 to that with non-round numbers increases, following the $n^{0.8}$ dependence.

A few mechanisms generating power-law distributions [12] are known [13–17]. Most of these mechanisms explain power laws as a result of a specific self-organization of a non-equilibrium system, and we treat our observations in the spirit of these approaches. Evidently, the array of numbers in human documents is an evolving system, and the stochastic growth of this array is due to a permanent influx of numbers, added with new documents. The added numbers (among which may also occur new distinct ones, that were not employed previously) are chosen from a

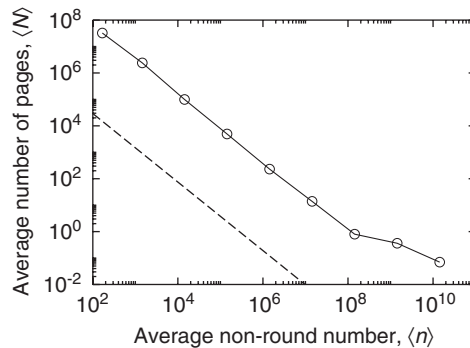


Fig. 3. Log–log plot of the frequencies of WWW pages holding non-round numbers. The circles show the average amounts of pages with non-round numbers taken from relatively narrow intervals (50 numbers). Each interval is centered at the $\langle n \rangle$ coordinate of a circle. The dashed line has slope -1.3 . Note that the power-law behavior is observed over 6 orders of magnitude. Non-round numbers occur much less frequently than powers of 10, which explains the essentially narrower range of numbers in this plot than in Fig. 2a. For instance, presently, and as far as search engines report, there are no WWW documents with the number 12345789013.

distribution which is determined by the one for the existing numbers. Here we do not discuss a specific model exploiting this mechanism and generating the observed complex distributions, but, instead, we explain the reason for the unusual small values of exponents which we observed— $\beta = 0.5$ and 1.3 (Figs. 2b and 3), while typical Zipf's law exponents are 2 and greater. At least, Zipf's law exponents must take values greater than 1. At first sight, this difference seems surprising, since the mechanisms of the power laws are quite similar. But, importantly, these two sets of exponents are defined for different distributions. In our non-traditional case, the observed power law describes the behavior of the frequency of WWW pages with a given natural number n , namely $N(n) \sim n^{-\beta}$. In contrast, typical Zipf's law exponent γ occurs in a power law for a quite different quantity: in our terms, this quantity is the amount, $m(N)$, of distinct numbers, where each of them occurs in each of N Web pages. So, we have the relation $m(N) \sim N^{-\gamma}$. One can show that the exponents β and γ satisfy a simple relation, $\beta = 1/(\gamma - 1)$ [18]. As a result, if the γ exponent is greater than 2, which is typical for simple linear growth processes, the β exponent is smaller than 1, as in Fig. 2b. On the other hand, non-linear growth may produce exponents γ below 2, which gives β greater than 1, as in Fig. 3.

4. Fluctuations of the number of WWW pages

The distributions reported here demonstrate that the frequencies of WWW pages holding numbers even of the same kind (for example, non-round numbers) strongly fluctuate from number to number. For documents containing non-round integers, we obtain the dependence of the fluctuations' amplitude (i.e., dispersion), $\sqrt{\langle(N - \langle N \rangle)^2\rangle} = \sqrt{\langle N^2 \rangle - \langle N \rangle^2}$, on the average frequency, $\langle N \rangle$, of these documents (Fig. 4). For calculating these dispersions and mean values, we used the same intervals as in Fig. 3. The resulting dependence turns out to be proportional,

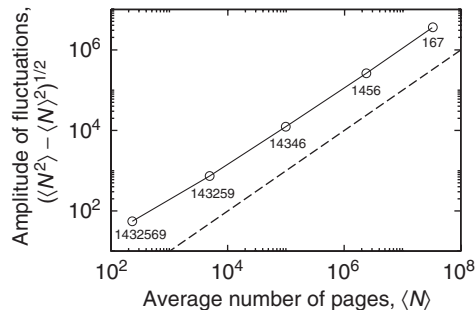


Fig. 4. Amplitude of the fluctuations, $\sqrt{\langle N^2 \rangle - \langle N \rangle^2}$, of the frequencies of pages containing non-round numbers versus their mean values, $\langle N \rangle$, on a log–log plot. The data (circles) were obtained resorting to the same intervals as in Fig. 3. Next to each circle the average (non-round) number, $\langle n \rangle$, for the corresponding interval is indicated. The dashed line has slope 1. One can see that $\sqrt{\langle N^2 \rangle - \langle N \rangle^2} \approx 0.1 \langle N \rangle$ for $\langle N \rangle > 10^3$.

$\sqrt{\langle N^2 \rangle - \langle N \rangle^2} \approx 0.1 \langle N \rangle$, over a broad region of values $\langle N \rangle$, which crucially differs from the square root behavior of standard statistical fluctuations [19]. The usual reason for such a strong difference is that the fluctuations of the quantities under study are not statistically independent [20,21]. In this respect, there is only one factor in the evolution of the array of numbers which can break the statistical independence of fluctuations, namely, the variation of the influx of numbers. So, the observed proportional law proves that the variations of the occurrence frequencies of numbers are an outcome of the fluctuations of their global influx in the WWW.

5. Discussion and conclusions

These observations suggest a new view of the array of integers in the WWW (and in nature) as a complex, evolving, inhomogeneous system. The statistics of numbers turns out to be far more rich and complex than one might expect based on classical Benford's law. Moreover, our findings provide a tool for extracting meaningful information from statistical data on the frequency of occurrence of numbers. As an illustration, consider the two integers, 666 and 777, with clear associations. We find that these numbers occur in the WWW with frequencies of 11,800,000 and 13,600,000 pages, respectively, which are 1.25 and 1.65 times higher than, on average, the occurrence frequencies of their non-round neighbors. These deviations are to a great extent higher than what one would anticipate from the relative amplitude of fluctuations, 0.1. Therefore, we can reasonably compare the amounts of pages containing 666 and 777 obtained after subtracting the numbers of pages holding the neighbors of these two integers. These subtractions give 2,400,000 and 5,400,000 pages for 666 and 777, respectively. It is the difference (or, rather, the relative difference) between the two last amounts that should be used as a starting point for a subsequent comparative analysis. The proposed approach is very suggestive. Indeed, by analyzing the frequencies of occurrence of specific 'popular' numbers with clear interpretations one could evaluate the relative significance of the corresponding underlining factors of this popularity.

Many more questions lie ahead: How do the occurrence frequencies of specific numbers vary in time? How do different numbers correlate and co-occur in WWW documents? It is well known that humans can easily memorize only up to rather limited sequences of digits [22,23], which are, therefore, many times replaced by words (like, for instance, the IP addresses of computers). Then, how does the statistics of numbers relate to the organization of human memory and to semantics? Our findings quantitatively show the key role of the common decimal numeral system—a direct consequence of the number of fingers. How do other numeral systems (the binary system, for example) influence the general statistics of numbers?

The global array of numbers is surmised to be a “numeric snapshot of the collective consciousness” [6]. So, the study of their statistics could lead to a better understanding of a wide circle of sociological and psychological phenomena. The distribution of numbers in human documents contains a wealth of diverse

information in an integrated form. The detailed analysis of the general statistics of numbers in the WWW could allow the effective extraction and evaluation of this hidden information.

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