

Correlated dynamics in human printing behavior

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Arrival times of requests to print in a student laboratory were analyzed. Inter-arrival times between subsequent requests follow a universal scaling law relating time intervals and the size of the request, indicating a scale invariant dynamics with respect to the size. The cumulative distribution of file sizes is well-described by a modified power law often seen in non-equilibrium critical systems. For each user, waiting times between their individual requests show long range dependence and are broadly distributed from seconds to weeks. All results are incompatible with Poisson models, and may provide evidence of critical dynamics associated with voluntary thought processes in the brain.

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Since the early work of Berger and Mandelbrot [1] examining error clustering in telephone circuits, it has been recognized that standard Poisson models may be inadequate to describe electronic information networks. This was confirmed, for instance by Leland et al. [2], who studied network traffic and found that packet traces show scaling behavior. Observations of scaling behavior raise a number of questions about how to model these systems, optimize performance, or improve design. Significant effects include an increase in response times, required buffer sizes, etc. In Ref. [3] the authors show how the file size distribution of a web server affects the resulting network traffic. Large fluctuations (which are inherent in critical systems) in packet traffic or demand for resources in computer networks can significantly degrade worst case performance [4]. Scaling behavior has been found not only in the size distribution of files stored in computer systems [5], and the sizes of web server requests [6], but also in the physical structure of the internet [7] and the hyper-link structure of the world-wide web [8, 9]. So far, no definitive causes have been established for the complexity of the modern information network. Of course, humans interact when they build the internet, make hyper-link connections, and send and receive information. Like traffic jams [10] on roads, internet jams are produced by humans who act and react, often in response to information originating within the network or outside it. Various parts of the information network/user system are themselves complex systems, and one of the problems in modeling modern information networks is how to disentangle these effects.

One recognizes that psychological experiments have demonstrated that correlated dynamics occurs in individual human behavior [11, 12, 13, 14, 15], even in situations where interactions with other humans are minimal [16, 17, 18]. For instance, Ref. [17] describes an experiment where subjects had to estimate the duration of time intervals from memory. The time series of errors in the estimates exhibits a $1/f$ power spectrum, showing that the errors are correlated in time. In contrast, the se-

quence of reaction times to an event showed no long range correlation. The authors proposed that long range dependence is associated with voluntary thought processes in the brain [17]. Similar observations were made for the dynamics of moods [14] and psychotic states. For instance the distribution of time intervals between subsequent hospitalizations for schizophrenia is approximately power-law [13]. A physical basis for these behaviors may be related to scale-free functional networks in the brain, which have recently been observed in situ [19].

In order to better describe individual human behavior in a networked computing environment, we study a simple case where the use or demand is primarily associated with individual choice rather than with group dynamics. The particular quantity we focus on is the inter-arrival times between subsequent print requests made by users in a computing laboratory for university students. We find evidence of long range correlations in the inter-arrival times for individual users to send requests, as well as a broad distribution of inter-arrival times. The totality of print requests from all users reveals a scaling law relating inter-arrival times and the sizes of the print request. This law indicates that the same (re-scaled) dynamics is responsible for requests to print small and large documents. This law is similar to that recently observed for waiting times between successive earthquakes [20, 21, 22] or solar flares [23]. The scaling function for the re-scaled inter-arrival times is approximately log-normal. The cumulative distribution of the sizes of print requests is well-described by a modified power law, which is referred to as the χ^2 distribution of superstatistics [24, 25], or the q-exponential of non extensive statistical mechanics [26, 27]. An elementary stochastic process is studied that reproduces some, but not all, of the observed features. Our results are supportive of the hypothesis that the brain operates at or near a self-organized critical state [28]. It also suggests the possibility of using data collected via the modern information network to systematically investigate models of human behavior.

The Department of Computing at Imperial College

London maintains a networked printing system for staff and students. The student labs offer about 300 computer work spaces, and are divided into different rooms, the largest one accommodating up to 150 students. The printers are networked and accessible from any machine in the department. A user selects a printer and submits her print job to a central server. The server records the time a request is submitted with a resolution of one second. It also records the size of the request, the user name and the intended printer. This investigation focuses on requests sent to the printer, *chrome*, that is located in the largest room. The labs are closed between 23:00 and 7:00, but users can print during closure times when logged in remotely. The data used here include the entire year of 2003 and closure times have been included in the analysis. Table 1 gives relevant parameters for the data set studied, which can be accessed at [29].

number of users	1122
number of users issuing more than three requests	1001
number of requests per year	73853
mean document size	1.2 Mbytes
mean time between requests	7.1 min
minimum time resolution	1.0 sec

TABLE I: Parameters of the user and printing system in 2003.

We first analyze the distribution of inter-arrival times between subsequent print requests for the entire year. Time differences from the logged event times T_i^S are measured as

$$t_i^S = T_{i+1}^S - T_i^S, \text{ where } 0 \leq i \leq N^S. \quad (1)$$

The superscript S refers to the size of the print request in bytes and indicates that this set of times only includes requests that are larger than S . The quantity N^S is the number of print requests that are larger than S . Time intervals of length zero are neglected from the analysis. For each chosen threshold S we estimate $P_S(t)$, which is the probability of a certain time interval t between subsequent requests of size S or larger. To display this distribution we count the number of time differences in exponentially growing bins and normalize the count by the bin size. Fig. 1 shows that the shape of the waiting time distribution depends on the size threshold, S , of the documents. This could indicate different dynamical processes responsible for the small and large documents. However, all distributions are broad and show an anomaly near one day. The anomaly is related to the overnight closure of the labs.

To determine if a different dynamics is responsible for requests of different sizes, we implement a scaling argument similar to one recently put forward by Bak *et al* [20] to describe the waiting time statistics of earthquakes. The average time between requests $\langle t \rangle_S$ may

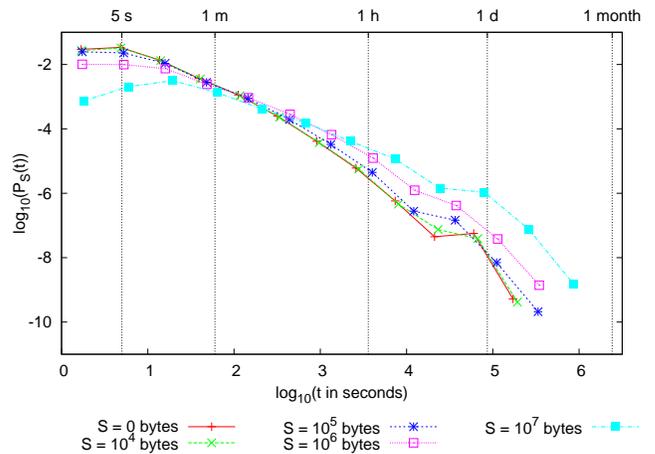


FIG. 1: Distribution of inter-arrival between subsequent requests to the printer "chrome" in 2003. Different curves are for different threshold sizes of the requests.

provide a rescaling factor for the inter-arrival times, so that the distributions measured with different size thresholds, S , collapse onto a single scaling function. Of course, $\langle t \rangle_S = \frac{T}{N_{>S}} = \frac{1}{R(S)}$. Here T is the time span of the record and $R(S)$ is the rate of requests larger than S . $N(>S)$ is the cumulative number of requests larger than size S . As shown in the inset of Fig. 2, $N(>S)$ is well described by a modified power law [24, 25, 26, 27]:

$$N(>S) \sim \frac{1}{(1 + (S/S^*))^{\gamma-1}} \quad (2)$$

where $S^* = (7.9 \pm 0.5) \times 10^5$ and $\gamma - 1 = 0.76 \pm 0.03$.

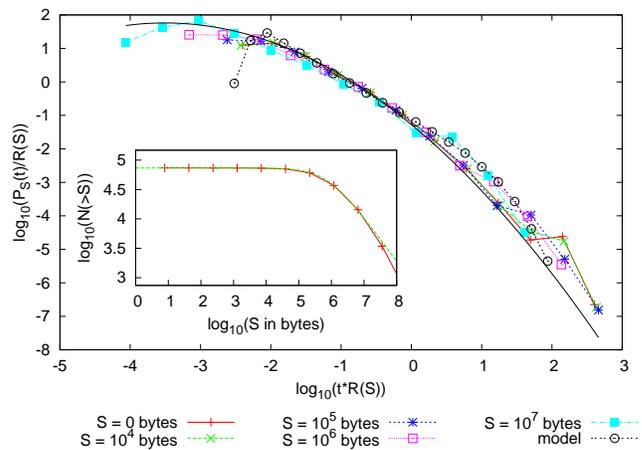


FIG. 2: Universal scaling law for the inter-arrival times between requests larger than size S , according to Eq. 3. The solid line is a fit to a log-normal function as described in the text. Data from the numerical simulation is also shown. The inset displays the cumulative distribution of requests sizes.

We test the *ansatz*

$$P_S(t) \sim R(S)g(tR(S)) \quad , \quad (3)$$

where $g(x)$ is a scaling function and $x = tR(S)$ is a scaling variable. Fig. 2 shows the results of rescaling the different curves in Fig. 1 by their average rate. We see that the scaling *ansatz* of Eq. 3 appears to hold over a wide range, about seven orders of magnitude in the scaling variable. This indicates that the same scale invariant dynamics operates when users send requests of any size. The slight deviation from data collapse at short times is due to the finite temporal resolution of our data (one second). There is an additional deviation due to the diurnal distribution. The scaling function g is close to a log-normal distribution:

$$g(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left(-\frac{(\ln(x) - m)^2}{2\sigma^2}\right) \quad (4)$$

with $m = -3.41 \pm 0.07$ and $\sigma = 2.16 \pm 0.04$, as also shown in Fig. 2. This feature is also found in numerical simulations of a stochastic process described later.

The inter-arrival times for all users do not necessarily give a good estimate for the times that pass between subsequent requests issued by a *single* user. To this end we study the inter-arrival times t_i^u for each user u printing more than three documents over the one year period. In the discussion below we set the threshold $S = 0$.

$$t_i^u = T_{i+1}^u - T_i^u, \text{ where } 0 \leq i \leq N^u. \quad (5)$$

Each user's list of inter-arrival times is concatenated to determine the probability $P_{\text{ind}}(t)$ of single user inter-arrival times, shown in Fig. 3. This distribution is approximately a power law over several decades ranging from one minute to about a day, with an exponent $\alpha \approx 1.3$. We also analyze the inter-arrival times for the busiest single user, which is similar. For comparison we show in Fig. 3 an exponential distribution for a Poisson event process that has the same average rate, $\lambda = 3.4 \times 10^{-5}/\text{sec}$, as the process of the busiest single user. A critical system with a power-law distribution of intervals is a more accurate description of the data than a Poisson model of print requests.

To decide if inter-arrival times are correlated, we measured the auto correlation function of waiting times for single users. The autocorrelation $a_u(\tau)$ at lag step τ is defined as

$$a_u(\tau) = \frac{1}{N_u - \tau} \sum_{i=1}^{N_u - \tau} s_i^u s_{i+\tau}^u \quad (6)$$

where $s_i^u = t_i^u - \frac{1}{N_u} \sum_{j=1}^{N_u} t_j^u$. If the inter-arrival times are uncorrelated and independent, the arrival process of individual requests to print can be modeled as a fractal renewal process [30, 31]. Analyzing data separately for the three most busy users, we find that the auto correlation function decays as $1/\tau^\delta$ with $\delta \approx 0.6$. When the order of the inter-arrival times for an individual user are shuffled randomly this power law disappears, and the waiting times become uncorrelated, with $a_u(\tau)$ independent of τ for $\tau \geq 1$. The sequence of inter-arrival times

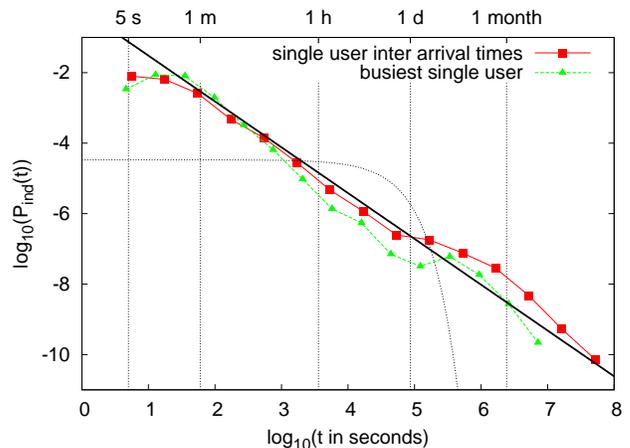


FIG. 3: Single user inter-arrival time distribution, averaged over all users and for the single busiest user. The solid, straight line indicates a power law distribution, $P_{\text{ind}}(t) \sim t^{-\alpha}$ with $\alpha = 1.3$. For comparison, an exponential distribution with the same rate as the busiest user is shown as a dashed curve.

for individual users are correlated over the entire time span of our data set.

Our data shows that models of criticality are relevant for describing individual human behavior in the modern information network. Lacking, at present, a microscopic dynamical model, we compare our observations with results from a simple stochastic process. Consider N arrival streams of print requests. In each stream, time intervals between subsequent requests are independent random variables chosen from a truncated Pareto distribution. We neglect correlations between intervals. All intervals have the same probability distribution

$$P_{\text{ind}}(x) = \frac{1}{C} k x^{-1-k} \text{ where } 1 \leq a \leq x \leq b \quad (7)$$

where a and b are the points where the Pareto distribution is truncated and C is a normalization constant. We choose the parameter $k = 0.3$ motivated by the results in Fig. 3. The short time cut-off $a = 2.5$ sec is set to reflect the fact that in some application users must wait before a subsequent print job can be sent off. Most students leave after at most 8 years, so $b = 8$ years appears to be a reasonable choice. Generating approximately 73,000 requests in a year fixes the number of users close to $N = 1000$.

At the start of the numerical simulation we schedule an arrival event for each stream according to Eq. 7. Upon each arrival, the next arrival time is scheduled using the same distribution. The system takes about 5 years with the above parameters to reach a statistically stationary state. As shown in Fig. 2, the inter arrival times measured in the simulation compare fairly well with the real data. However the real data has significantly larger variance.

We also examined the time series defined by the number of print requests in each second. We calculated the power spectrum $S(f)$ of this time series and find $1/f^\alpha$ behavior, as shown in Fig. 4. The exponent α observed in the numerical simulation is fixed by the value of k in Eq. 7, and is $\alpha = 0.3$ [31, 32]. The real data show instead a larger value $\alpha \approx 0.5$, which indicates, just as the autocorrelation function $a_u(\tau)$, that the real arrival process is more complicated than a fractal renewal process. A more accurate model of individual user behavior in a computing network may be that of Davidsen and Schuster [33].

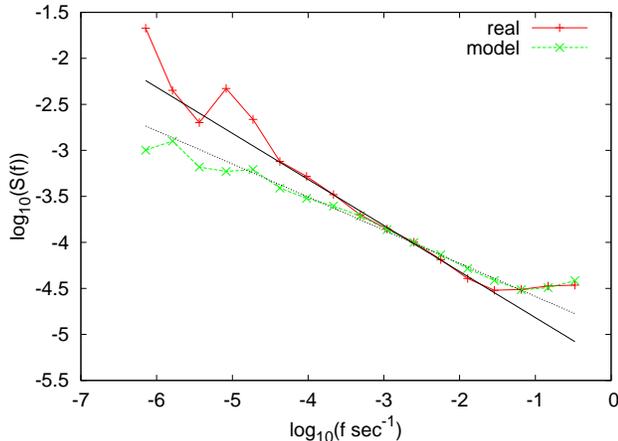


FIG. 4: Power spectrum of the time series defined by the print requests per second based on the real arrival data and the simulated arrivals in the fifth year. The solid line is a fit for the real data, the dashed one for the simulation results, see text.

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