Relative clock demonstrates the endogenous heterogeneity of human dynamics

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Abstract. - The heavy-tailed inter-event time distributions are widely observed in many human-activated systems, which may result from both endogenous mechanisms like the highest-priority-first protocol and exogenous factors like the varying global activity versus time. To distinguish the effects on temporal statistics from different mechanisms is this of theoretical significance. In this Letter, we propose a new timing method by using a relative clock, where the time length between two consecutive events of an individual is counted as the number of other individuals’ events appeared during this interval. We propose a model, in which agents act either in a constant rate or with a power-law inter-event time distribution, and the global activity either keeps unchanged or varies periodically versus time. Our analysis shows that the heavy tails caused by the heterogeneity of global activity can be eliminated by setting the relative clock, yet the heterogeneity due to real individual behaviors still exists. We perform extensive experiments on four large-scale systems, the search engine by AOL, a social bookmarking system—Delicious, a short-message communication network, and a microblogging system—Twitter. Strong heterogeneity and clear seasonality of global activity are observed, but the heavy tails cannot be eliminated by using the relative clock. Our results suggest the existence of endogenous heterogeneity of human dynamics.

Introduction. – Characterizing and understanding human activity patterns are necessary to explain many socioeconomic phenomena and could find significant applications ranging from resource allocation to transportation control, from epidemic prediction to interface design for Internet users [1,2]. One of the most attractive observations is the heavy-tailed nature of human temporal activities, with the inter-event time distribution usually being approximate to a power-law form. Example include the email communication [3], the surface mail communication [4,5], the cell-phone communication [6–8], the online activities [9–12], and so on, to name just a few.

Many endogenous mechanisms of human activities have been put forward to explain the observed heavy-tailed statistics, such as the task priority [3,13], the varying interest [14,15], the memory effects [16], the human interacting [17,19], and so on. Besides the efforts on digging out endogenous mechanisms, a litter pessimistic argument is that the observed heavy-tailed statistics are hardly to reveal significant ingredients or provide insights on human activity patterns yet may originate from some trivial exogenous factor[4]. In particular, the heterogeneity and seasonality[2] of human activities has recently been recognized as one candidate to explain the heavy-tailed inter-event time distribution [20,21]. Putting the mathematics

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Here we use the word “exogenous” to stand for the factors not related to the essential motivations or stimulations from the actions or other people.

Denote by $M(T)$ the global activity of the population (i.e., the number of events during the $T$’s time window), the heterogeneity lies in the heterogeneity of the distribution of $M$, and the seasonality is evidenced by $M(T) \approx M(T + P)$, where $P$ is the time period, normally being a day and/or a week in our daily behaviors.
In this Letter, we propose a new timing method that can filter out the effects caused by the exogenous hybrid mechanisms—some of them are endogenous like the highest-priority-first rule [3], while others are exogenous like activity heterogeneity [20] and seasonality [21].

In this Letter, we propose a new timing method that can eliminate the heavy tails in the inter-event time distribution caused by the activity heterogeneity. We analyze a model, in which agents act with either an exponential or a power-law inter-event time distribution, and the global activity either keeps unchanged or varies periodically versus time. Simulation results show that the heavy tails caused by the heterogeneity of activity can be eliminated by setting the relative clock, yet the heterogeneity due to endogenous individual behaviors still exists. Comparing the modeling results to the experiments on four large-scale real systems, we conclude that the temporal activity contains endogenous heterogeneity that cannot be explained by Poissonian agent assumption with seasonality.

**Relative Clock.** — The heterogeneity of human activity versus time has been observed for many online systems. For example, we will later show four real systems in Fig. 5. As we have mentioned above, the statistics about inter-event time at the population level may result from hybrid mechanisms, and thus it is valued to design a method that can filter out the effects caused by the exogenous heterogeneity. In the traditional way, the inter-event time is defined as the time interval between two consecutive events. Figure 1 illustrates a simple example where the individual A acts at time \(t_A = 2\), \(t_B = 5\), \(t_C = 8\), \(t_D = 14\), and \(t_E = 36\), and thus the four time intervals are \(t_A - t_B, t_B - t_C, t_C - t_D\) and \(t_D - t_E\). This timing method is called absolute clock in this Letter. Considering a system with strong heterogeneity of human activity versus time. For example, in a short-message communication network, an individual may send in average more than ten messages in the noon yet less than one message during the midnight. As a time interval, 1 hour is relatively long in the noon yet 10 hours is usual across the midnight. Therefore, the absolute clock is highly affected by the activity heterogeneity and thus may fail to capture the endogenous human activity patterns. Accordingly, we propose a new timing method by using a relative clock, where the time length between two consecutive events of an individual is counted as the number of other individuals’ events appeared during this interval. Considering the population A, B and C shown in Fig. 1, the inter-event time of the events happened at \(t_A\) and \(t_B\) for individual A is counted as the number of events in between \(t_A\) and \(t_B\) for individuals B and C. Table 1 presents the results of two definitions of the inter-event time for individual A. Compared with the absolute clock, the relative clock, running faster at the time with frequent events, can be considered as a kind of time rescaling method that can eliminate the heavy tails of inter-event time distribution caused by the activity heterogeneity.

|           | \((t_1, t_2)\) | \((t_2, t_3)\) | \((t_3, t_4)\) | \((t_4, t_5)\) |
|-----------|----------------|----------------|----------------|----------------|
| Absolute  | 3              | 53             | 27             | 11             |
| Relative  | 1              | 10             | 3              | 3              |

**Table 1: Inter-event times for individual A in figure 1.** The upper row corresponds to the results based on the absolute clock while the lower row on the relative clock. In the case of relative clock, we use the number plus one to avoid zero interval.

**Model.** — To see the difference between absolute and relative clocks, we first study a theoretical model. This model spans over 10 days, with a second resolution, namely it contains 864000 time steps. Each day is divided into 24 hours, and for simplicity, the global activity inside an hour keeps unchanged. Accordingly, for each hour \(i\), we denote its activity as \(\lambda_i\). For the first day, the value of \(\lambda\) for each of the 24 hours is sampled from a given distribution \(\Phi(\lambda)\). To account for the seasonality, the following 9 days will repeat the activity pattern of the first day, that is, \(\lambda_i = \lambda_{i+24}\). All the \(N\) individuals in the model have the same temporal statistics. We consider four cases: (i) Every individual follows a Poissonian process with rate \(r\), that is, at each second, an arbitrary individual \(A\) will act with probability \(r\lambda_i\), where \(i\) denotes the current hour. We assume a constant global activity, say \(\lambda_1 = \lambda_2 = \cdots = \lambda_{24} = \lambda\). (ii) Same to the case (i), but \(\lambda_i (i = 1, 2, \cdots, 24)\) are independently sampled from a uniform distribution in the range \((0, 1)\), say \(\Phi(\lambda) = U(0, 1)\). (iii) Every individual acts with an endogenous power-law inter-event time distribution \(\Phi(t) \sim t^{-\beta}\). In the beginning, each individual will sample an inter-event time \(t\) from \(\Phi(t)\), and will indeed act at time \(t/\lambda_1\). Then, after each act, the individual will resample an inter-event time \(t'\) from \(\Phi(t)\) and act after \(t'/\lambda_2\) seconds, where \(i\) denotes the current hour. This rule reflects the fact that...
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Fig. 2: How the global activity $A_i$, quantified by the number of events happened during the $i$’s hour, changes with time. The four plots respectively correspond to cases (i), (ii), (iii) and (iv). The parameters are $N = 100, r = 0.2, \lambda = 0.5$ and $\beta = 2$. Strong heterogeneity and clear daily seasonality are observed for cases (ii) and (iv) yet only random fluctuations are associated with cases (i) and (iii).

in an inactive time period, the inter-event time tends to be longer, and vice verse. If the time interval spans over more than one hour, only the activity of the starting hour affects the real length of the time interval. We assume $\lambda_1 = \lambda_2 = \cdots = \lambda_{24} = \lambda$. (iv) Same to the case (iii), but $\lambda_i$ ($i = 1, 2, \cdots, 24$) are independently sampled from the uniform distribution $U(0, 1)$.

Figure 2 displays the global activity $A_i$ ($i = 1, 2, \cdots, 240$) for the 240 hours, where $A_i$ is the number of total events in the $i$’s hour. For the cases (i) and (iii), the global activity is homogeneous, and thus the relative clock will not change the overall statistical regularities although it can to some extent reduce the fluctuation. The heterogeneity of global activity is a necessary condition for the elimination of the heavy tail by using the relative clock, yet not a sufficient condition.

Figure 3 reports the simulation results for the toy model, from which we conclude that: (i) As shown in Fig. 3(c), a power-law-like inter-event time distribution could result from the heterogeneity of global activity, although all individuals are the same and each individual obeys a Poissonian process in each hour. This is supportive to the theoretical analyses of Refs. [20][21]. In fact, endogenous factor, exogenous factors and the hybrid of them can generate heavy tails in $p(\tau)$, as shown in Fig. 3(d), 3(f) and 3(h). (ii) As shown in Fig. 3(d), the inter-event time distribution based on the relative clock follows an exponential form, that is to say, the heavy-tail resulted from the heterogeneity of global activity can be effectively eliminated by using the proposed timing method. (iii) Com-

$^{3}$We introduce a periodical global activity to the model to mimic the seasonality observed in the real systems [10][12][21]. However, the seasonality does not essentially contribute to the heavy tail in the inter-event time distribution. For example, if we assume $\lambda_i$ ($i = 1, 2, \cdots, 240$) are independently sampled from $U(0, 1)$, then the seasonality will be eliminated yet the heavy tail in the distribution $p(\tau)$ still exists.

Fig. 3: Comparison of inter-event time distributions $p(\tau)$ based on the absolute and relative clocks. All the distributions presented in this figure come from the theoretical model: case (i)–(a)(b), case (ii)–(c)(d), case (iii)–(e)(f), case (iv)–(g)(h). The left and right plots correspond to the distributions on absolute and relative clocks, respectively. Plots (a), (b) and (d) are of log-linear scale, while plots (c), (e), (f), (g) and (h) are of log-log scale. The parameters are $N = 100, r = 0.2, \lambda = 0.5$ and $\beta = 2$. The power-law sampling on $\Phi(t)$ follows the method in Ref. [23].

Fig. 4: (Color online) Analytical results about the inter-event time distributions on relative clock. The plots (a) and (b) correspond to Fig. 2(b) and 2(f) respectively, with black circles representing the simulation results and red curves standing for the analytical solutions.

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comparing Fig. 3(f) with 3(e), as well as 3(h) with 3(g), it is clear that the endogenous heterogeneity, embodied in the power-law distribution $\Phi(t) \sim t^{-\beta}$, could not be eliminated by the timing with relative clock. (iv) A peak near the head of $p(\tau)$ will emerge in all the cases when using the relative clock.

To explain the existence of a peak, we calculate the inter-event time distribution $p(\tau)$ on relative clock. Notice that, since the relative clock could eliminate the heterogeneity of global activity, the idiosyncratic form of $\Psi(\lambda)$ almost has nothing to do with $p(\tau)$ (as an evidence, the distributions shown in Fig. 3(b) and Fig. 3(d) are almost the same, and the distributions shown in Fig. 3(f) and Fig. 3(h) are almost the same). Considering two independent stochastic processes, the actions of an individual and the actions of all others. Given a monitored individual $i$, we assuming that her acting frequency (i.e., the number of events during a unit time) is $f_i$, and the total acting frequency of other individuals is $f = \sum_{j \neq i} f_j$, then the probability density of the inter-event time of individual $i$ is:

$$p(t) = f_i e^{-f_i t}. \quad (1)$$

Notice that, here we assume the individual $i$ at most act once in one time step, namely $f_i < 1$ and in each time step $i$ will activate an event with probability $f_i$. In principle, we can assume the time resolution is elaborate enough and thus at each time step there is at most one event from all other individuals, and the happening probability is $f_i$. During $t$ time steps, the probability density of the cumulative number of events of all other individuals reads

$$q(a) = C_a^t f_i^t (1 - f_i)^{t-a}, \quad (2)$$

where $C_a^t = \frac{t!}{(t-a)!}$. When the activity of individual can be approximated as a Poisson process, we can get the probability distribution of the inter-event time on relative clock through the joint probability distribution:

$$p(\tau) = \int_0^\infty \frac{f_i^t}{(\tau-1)!} e^{-f_i \tau} e^{-f_i t} dt. \quad (3)$$

Even when $f_i > 1$, We have checked numerically that Eq. (3) can well reproduced the front peak in $p(\tau)$. For example, in the case shown in Fig. 4(a), $f_i = 0.1$ and $f_i = 9.9$. Similar to the Poissonian cases, when the endogenous time interval follows a power-law distribution, the probability distribution of the inter-event time on relative clock is:

$$p(\tau) = \int_0^\infty f_i^t \frac{(f_i - t)^{\tau-1}}{(\tau-1)!} e^{-f_i \tau} dt. \quad (4)$$

where $\beta$ is the exponential power. Figure 4 reports the analytical solutions Eq. (3) and Eq. (4), which agree very well with the simulations.

**Data.** – This Letter analyzes four large-scale real systems, and for fair comparison, every data set presented here spans over 10 days. Followed please find the data description, with basic statistics shown in Table 2. (i) **AOL.** – It is previously known as America Online, which is a company providing Internet services and media, etc. This data set is about the searching behaviors of Internet users, with time resolution being second. The date starts from March 10, 2006 to March 20, 2006. The inter-event time is defined as the time interval between two consecutive queries by a user. (ii) **Delicious.** – It is a web site aiming at helping users in collecting the tastiest bookmarks in the web. The data set contains the bookmarks add by users with seconds resolution, starting from September 5, 2009, last for 10 days. Each record (i.e., event) contains the operation time, the users ID, the Universal Resource Locator (URL), and so on. The inter-event time is defined as the time interval between two consecutive collections of bookmarks by a user. (iii) **SM.** – Short Message is probably the most widely used electronic communication tool in people’s daily life. This data set starts from December 10, 2010 to December 20, 2010, with time resolution being second. Each record consists of three elements: a sender ID, a receiver ID, and the time stamp. The inter-event time is defined as the time intervals between two consecutive short messages sent by the same user. (iv) **Twitter.** – It is a microblogging system in which users could upload their posts (i.e., microblogs) and other users, especially their
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followers, may comment and/or transfer these posts. The date starts from November 10, 2009, last for 10 days, with time resolution being second, recording only the uploading time of original posts. The inter-event time is defined as the time interval between two consecutive posts by a user.

**Experimental Results.** – Figure 5 reports the global activity $M(T)$ versus the time $T$, where the whole data is divided into 14400 segments, each of which lasts one minute. That is to say, $M(T)$ is the number of event of the population in $T$’s minute. It is observed that every system displays strong heterogeneity and daily seasonality.

The inter-event time distributions based on absolute clock are shown in Fig. 6. For AOL and Delicious, exclusive of slightly drooping heads, their distributions can be well approximated by power laws. The distributions for SM and Twitter are more complicated, with only the middle parts following power laws. The whole distributions cannot be accurately fitted by power laws, and the solid lines are only for eye guidance. In fact, we are not interested in whether these distributions are power-law, but we have noticed that the distributions typically span over six orders of magnitude, which is more than enough to demonstrate the burstiness of temporal activities.

Compared with Fig. 3(c), 3(d) and Fig. 2, the observed broad inter-event time distribution may mainly result from the heterogeneity of activity shown in Fig. 5. If so, the distribution $p(\tau)$ should be narrowed when using the relative clock. Figure 7 reports the results of $p(\tau)$ by using the relative clock. In accordance with the fourth point and Fig. 4 obtained from the theoretical model, every distribution has a peak near to the head (SM and Twitter are more remarkable). However, different from Fig. 3(c) and 3(d), the heavy tails in $p(\tau)$ cannot be weakened or eliminated by using the relative clock. These results strongly suggest that the observed heavy-tailed nature cannot be simply explained by the activity heterogeneity or seasonality.

**Discussion.** – In this Letter, we proposed a new timing method based on the so-called relative clock, where the time interval between two consecutive events of an individual is quantified by the number of other individuals’ events appeared during this interval. This method is expected to be able to eliminate the effects of heterogeneity of global activity on the inter-event time distribution. The simulation results on the theoretical model have demonstrated the effectiveness of our method, and by comparing the performances of simulations with experiments, we conclude that the observed heavy-tailed nature in human online temporal activities could not be well explained by Poissonian agents with activity heterogeneity, no matter whether the seasonality gets embodied in the activity time series.

Human behavior is one of the most complex and complicated things, driven by countless unknown factors. Therefore, given a certain statistical feature, to distinguish the effects from different factors is very significant. Our method could successfully filter out the effects caused by activity heterogeneity, yet it is not omnipotent. For example, our method may lead to bias when there exists strong trend of global activity, and thus in these cases, detrend

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4The typical difference of the peaked and low-lying values of $M$ is about 10^2 in AOL, Delicious and SM. This is really a huge. Even for Twitter, the peaked value of $M$ can be as twice large as the low-lying one.

5Here we mainly concentrate on the daily seasonality, yet for longer data, we could also observe the weekly seasonality (see, e.g., the weekly seasonality in Netflix).

6In online systems, usually as the number of users increases, the global activity will also increase, and a certain length of absolute time interval will thus become larger and larger on relative clock.
algorithms [25, 27] have to be associated with our method. In addition, the effects of heterogeneity among individuals (i.e., different individuals act with different rates) could not be filtered out by our method, which is also a known candidate that may contribute to the heavy-tailed inter-event distribution [20]. The rescaling method [12, 28] according to the average inter-event time may be helpful in judging whether the active and inactive individuals act with essentially different patterns ⑦.

As a starting point of designing effective tools to distinguish the effects of different factors on the statistical regularities of human dynamics, the present method is simple and imperfect, yet it may largely complement the current understanding of our behavioral patterns. In summary, the main contributions of this Letter are threefold. Firstly, by using a theoretical model, we show the heavy-tailed nature in population level may result from an exogenous factor—the activity heterogeneity, and the timing method based on relative clock can successfully eliminate such exogenous effects. Secondly, extensive empirical analysis reveals the heavy-tailed inter-event time distributions of typical online systems, and suggests the existence of endogenous mechanisms that can not be explained by the activity heterogeneity or seasonality versus time. Lastly, this Letter reports many novel empirical results to the scientific community, which could facilitate the studies on human dynamics. Although our knowledge about human behavior increases incessantly, it never gets sufficient. We believe this work has added new insights and rich empirical materials into our knowledge.

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⑦Radicchi [12] suggested that the active and inactive users are of the same activity patterns since the inter-event time distributions of high-active group and low-active group will collapses to a single curve. Our empirical studies show that for some data sets like FriendFeed, the rescaling performance is not good [29]. In fact, the Internet users may have different behaving patterns, for example, in online resource-sharing systems, new users tend to visit popular things yet old users tend to dig out cool objects [29].