Heterogenous Human Dynamics in Intra and Inter-day Time Scale

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Abstract. - In this paper, we study two large data sets containing the information of two different human behaviors: blog-posting and wiki-revising. In both cases, the interevent time distributions decay as power-laws at both individual and population level. As different from previous studies, we put emphasis on time scales and obtain heterogeneous decay exponents in intra- and inter-day range for the same dataset. Moreover, we observe opposite trend of exponents in relation to individual Activity. Further investigations show that the presence of intra-day activities mask the correlation between consecutive inter-day activities and lead to an underestimate of Memory, which explain the contradicting results in recent empirical studies. Removal of data in intra-day range reveals the high values of Memory and lead us to convergent results between wiki-revising and blog-posting.

Introduction. – Thanks to the development of the information technology, comprehensive data available from the internet give us valuable insights into the pattern of human behaviors. Many recent studies of human behavior focus on the distributions of inter-event time or waiting time and report a heavy-tail both at the individual and population level. Examples of empirical studies including communication patterns of electronic mails \cite{2,17} and surface mail \cite{18}, web surfing \cite{6,7}, short message \cite{8}, movie rating \cite{9}.

In all the above systems, the observed distributions of interevent time goes as $\tau^\alpha$ with exponents ranging from 1 to 3. Various mechanisms were suggested to explain the underlying dynamics. One main class of mechanism is the priority-queue model \cite{2,17}, which yields power-law waiting-time distributions $p(\tau) = \tau^a$ with universal exponents a=1.0 and 1.5. Other mechanisms include the adaptive interesting model \cite{11}, the memory model \cite{12} and the interaction model \cite{13}. A crucial assumption of all these models and empirical studies is that the mechanisms driving human behaviors are identical in all time scales. According to this assumption, interevent time with length in minutes and in days are generated by the same mechanism and follow the same scaling law. Even in the cascading nonhomogeneous Poisson process \cite{3,4} which emphasizes external factors such as circadian and weekly cycles, the distributions still follow power-laws with identical exponent over the whole range.

Table 1 shows a collection of recent empirical results, including the exponents and the unit of interevent time and the time range where the power-laws were observed. In this table, we simply classify the results into intra- and inter-day behaviors. As we can see, for those data with unit in second or minute, the studies are often focused on the intra-day interevent time distribution; for those with unit in hour or day, only the inter-day range was studied. None of these studies investigated both the intra and inter-day behavior, though some noticed a hump in the interevent time distribution caused by the circadian rhythm \cite{14}. One case that had been studied intensively is email and letter based communications, where some studies suggested that mechanisms of the two activities are different, based on the different exponents observed \cite{2}; others suggested that the two are essentially the same based on the data collapse of interevent time distributions \cite{3}. Limited attention has been paid on the different time range in the two activities, as the timestamp of email and letters communications are respectively in the unit of second and day, and exponents are thus extracted from different

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Table 1: Comparison of the exponents from different human activities. The unit of interevent times and the time range in these studies are shown in the table. ∗ corresponds to the average of exponents from individual distributions; △ corresponds to the exponent from a single user; others are the ones from global distribution.

| Human activity                        | Unit | Range     | Exponent |
|---------------------------------------|------|-----------|----------|
| Email [2][14]                         | sec  | intra-day | 1*, 0.9  |
| Correspondence [12][15]               | day  | inter-day | 2.37△, 2.1△ |
| Library loans [2]                     | min  | intra-day | 1*       |
| Printing behavior [16]                | sec  | intra-day | 1.3△     |
| Visits of a web portal [2]            | sec  | intra-day | 1*       |
| Visits to the same URL [6]            | sec  | intra-day | 1.25     |
| Visits to any page [8]                | sec  | intra-day | 1.2      |
| Queries on AOL [7]                    | hour | inter-day | 1.9      |
| Message on Ebay [7]                   | hour | inter-day | 1.9      |
| Logging actions on Wikipedia [7]      | hour | inter-day | 1.2      |
| Movie rating [9]                      | day  | inter-day | 2.08     |

Data sets description.

Wikipedia. Wikipedia (Wiki) is a free encyclopedia written in multiple languages and collaboratively created by volunteers. Wiki contains millions of articles which is produced by tens thousands of online volunteers. When an article is revised by an user, a new version is created by this user. The database we consider contains the timestamp and the authors of all the revisions in the Chinese Wiki. This data set is composed of 9641842 revisions made by 81823 users between 26/10/2002 and 7/6/2009.

Fig. 1: (Color online) The global distribution of interevent time spanning the intra- and inter-day range. n is frequency. We fit the distributions with the “shifted power-law”: $y \sim (x + a)^{-\beta}$ [24]. Figure (a) and (c) shows the distributions of the intra-day range of wiki-revising and blog-posting [18]. The heavy-tails are found in both intra- and inter-day part of the distributions from these two activities. Our results show that even for the same activity the exponents of these two ranges are different.

Further evidences are obtained by examining the dependence of decay exponent on individual Activity, the measure of how frequent the action is taken. Zhou et al. [9] found that the exponent increases with Activity, which was further confirmed by Radicchi [7]. It is noted that both analyses are conducted in the inter-day range. In our case, we found the same dependence in the inter-day range but remarkably a different behavior in the intra-day range. It further demonstrates that the mechanisms underlying intra- and inter-day human dynamics are different.

On the other hand, weak memory in human behaviors are observed in system such as library loans and printing [18]. However, other studies show significant memory in some systems driven by human [16][18][20]. For wiki page revision, we found seemingly weak memory. However, we observe a strong memory comparable to that of blog-posting [18] by removal of intra-day intervals and consider the inter-day ones only. It shows that the memory of inter-day activities is underestimated as intra-day activity mask the correlation between inter-day activities in analysis. We suggest that it is the reason behind the apparent weak memory in some human behaviors.

Blog. Blog is a kind of so-called web2.0 applications emerging in recent years, on which people post, read
and comment articles from each other [22,23]. Our data was collected from the campus blog website of Nanjing university [http://bbs.nju.edu.cn/blogall]. Most users are current or former students and teachers of Nanjing university. As of 01/09/2009, there are 1627697 articles posted by 20379 users in this website. The first post is at 25/03/2003 when the blog was established.

Empirical analysis.

The global distribution of interevent time in intra-day and inter-day range. The timestamp of both the data sets is in precision of one minute. Here, the interevent time τ is time interval between consecutive actions, i.e. revising a wiki-page by the same user in wiki or posting an article by the same user in blog. The global distributions of τ for both data sets are shown in figure 1. As we can see, the distributions can be divided into two parts: For the intra-day range, the curves clearly show the heavy-tails; for the inter-day range, they all show oscillation because of the circadian periodicity that make it hard to observe the scaling law.

Even in the intra-day range, the power-law behavior is not homogeneous in all time scale and a slight hump is observed at τ ≈ 100 (see fig. 1(a) and (c) and fig 4 for clearer evidence). We thus apply a piecewise fitting curve to show the change in power-law exponents. For the range with τ < 100 (within about 1 hour), the exponents of blogging and wiki-revising activities are 1.20 and 1.88; for the range with τ > 100(beyond 1 hour and within 1 day), lower values of 0.66 and 1.32 are found.

Figure 1(b) and (d) shows the distribution of inter-day interevent time where a unit of one day is employed to eliminate the oscillation. The heavy-tails in the intra-day range are shown clearly in these two distribution. The exponent of blogging activity is 2.02 which is significantly higher than the ones in intra-day range, in agreement with the results obtained by comparing different empirical studies in table 1. On the other hand, the intra-day exponent of wiki-revising seem to be close to the inter-day one. However, as we will see in following section, the empirical analysis at group and individual levels demonstrate the different activity pattern between the two ranges.

Heterogenous Dependence on Activity. In this section, we will investigate further the features of intra- and inter-day activity pattern. Firstly, we measure the average Activity Aᵢ of user i as Aᵢ = nᵢ/dᵢ, where nᵢ is the total number of actions of user i and dᵢ is the time between the first and the last actions. We then sort users in an ascending order of Activity and divide the entire population into 10 groups, each of which have M users (M ≈ N/10 where N is the total number of users). The first M users in the list belong to group 1, and the last M users are belong to group 10, etc. We only consider users with nᵢ·dᵢ > 10.

As different from previous studies [7,9] which only focus on the inter-day range, we investigate the dependence of the exponent on Activity in both the intra- and inter-day range. In fig. 2, we plot the interevent time distribution of wiki-revising at a group level (group 3 and group 9). For distribution in the intra-day range, the range of fitting is from 1 to 70. (a) and (c) correspond to the intra-day range and (b) and (d) correspond to the inter-day range. The decay exponents are β ≃ 2.00 in (a), β ≃ 1.16 in (b), β ≃ 1.75 in (c), β ≃ 2.21 in (d).

Interevent time distribution for individuals. To show further evidences for our conjecture, we look in detail the
behavior of individual agents. Figure 4 shows the cumulative distribution of interevent time from four users, two are from the data set of wiki and two are from the blog data set. An obvious trend change is observed at τ ≃ 1 day. For the inter-day range, all these distributions follow power-laws. The wiki users often revise one page many times within a day but blog users seldom post several articles in one day. Therefore, it is hard to study the intra-day activity of blog-posting at the individual level as data is insufficient in this range. For wiki-revising, the distributions are even heterogeneous within the intra-day range (see fig 4(a)), which is consistent with the global one and shows further complexity in the mechanism of human activity.

![Fig. 4: (Color online) The cumulative distribution of interevent time from four users, two are from the data set of wiki and two are from the blog data set. An obvious trend change is observed at τ ≃ 1 day. For the inter-day range, all these distributions follow power-laws. The wiki users often revise one page many times within a day but blog users seldom post several articles in one day. Therefore, it is hard to study the intra-day activity of blog-posting at the individual level as data is insufficient in this range. For wiki-revising, the distributions are even heterogeneous within the intra-day range (see fig 4(a)), which is consistent with the global one and shows further complexity in the mechanism of human activity.](image1)

The consecutive interevent times of these users are plotted in fig 5 which helps us to visualize the dynamics of their activities. For the blog user (see fig 5(a)), we observe the clustering of extremely long interevent times which is also called mountain-valley-structure found in many complex systems [25, 26]. For the wiki user, fig 5(b) shows similar clustering but the interevent time longer than one day are separated by many short intra-day interevent times which are rare in blog-posting (compared with fig 5(a)). The consequence is that the values of Memory become rather small. The definition of Memory is as follow [19]:

\[
M_k = \frac{1}{n_\tau - 1} \sum_{i=1}^{n_\tau-1} \frac{(\tau_i - m_1)(\tau_{i+k} - m_2)}{\sigma_1 \sigma_2},
\]

where \(\tau_i\) is the interevent time values and \(n_\tau\) is the number of interevent time and \(m_1(m_2)\) and \(\sigma_1(\sigma_2)\) are sample mean and sample standard deviation of \(\tau_i's\) (\(\tau_{i+k}'s\)). The two interevent times \(\tau_i\) and \(\tau_{i+k}\) are separated by \(k\) events.

![Fig. 5: The interevent time of consecutive events (a) User 3 in figure 4c. (b) User 1 in figure 4a. (c) User 1 after deleting short interevent times which is less than 1000 mins. The Memory \(M_1\) of the blog user is 0.13 but the one of the wiki user is only 0.02. The average \(M_1\) of all qualified users with \(k\) ranging from 1 to 35 is shown in fig 6. Average \(M_1\) of wiki-revising is 0.13 which is obviously less than 0.21, the \(M_1\) in blog-posting. This result is in agreement with the one found in fig 5(a) and (b). As there are different mechanisms in human activity in the intra- and inter-day range, we find a way to study the memory of these mechanisms separately. We remove the interevent times of wiki-revising which is less than 1000 minutes (about 1 day) and analyze the remaining series which only contain the inter-day intervals. This allows us to consider only the memory in the interday intervals and ignore the actions within one day. Figure 5(c) shows the interevent time series after data removal, of which \(M_1\) is 0.12. Correspondingly, we also find a significant increase in the average \(M_1\) of wiki-revising through this procedure. As shown in the inset of fig 6, average \(M_1\) increases to 0.20 which is very close to the one in blogposting. Moreover, the decay curve is similar to that of blog-posting: when \(k < 10\), it decays asymptotically as a power law; when \(k > 10\), it decreased exponentially.

Discussion. – We conclude by remarking two concrete evidences which support our conjecture that human activity patterns are significantly different in different time scale. Firstly, the exponents of interevent time distribution is different in the intra- and inter-day range. In addition to comparison with the previous empirical studies, we show difference at the individual and global level by investigating the activity patterns of wiki-revising and blog-posting. The second evidence is the different dependence on Activity: for the inter-day range, the exponents increase with Activity; for the intra-day range, the exponents decrease with Activity and in smaller magnitude. On the other hand, we show the behavioral similarity be-
Fig. 6: (Color online) The average $M_k$ of all qualified users in blog-posting and wiki-revising after data removal with different $k$. The comparison between the results before and after data removal is shown in the inset. For the one of blog-posting, $M_k$ decays as a power law when $k < 10$: $M_k = 0.23 * k^{-0.45}$, when $k > 10$, it decays exponentially: $M_k = 0.1 * e^{-k/23.22}$. For the original data, it decays as a power law over whole range: $M_k = 0.13 * k^{-0.47}$. After data removal, when $k < 9$: $M_k = 0.61 * k^{-0.21}$, when $k > 9$: $M_k = 0.10 * e^{-k/12.76}$. To avoid characterizing users whose number of actions is too small, we consider only the qualified users of the two data sets and calculate the memory of all these users with $k$ ranging from 1 to 35 (for wiki, a total of 809 users with number of revisions more than 800 and frequency of long intervals ($> 1000$ mins) more than 100 are considered; for blog, a total of 2126 users with more than 200 posts and frequency of long intervals ($> 1000$ mins) more than 200 are considered.

We finally remark again the interesting behaviors in both the intra- and inter-day range. There are interesting details within both intra- and inter-day range. A slight hump is observed in $P(\tau)$ at $\tau \approx 1$ hours. For inter-day range, the decay of memory is power-law when $k < 10$ and became exponential beyond this range. Is there a relationship between time units (such as minute, hour, week, month) and the dynamics underlying human activities? For example, trend change observed in $P(\tau)$ at one hour may due to the timing of tasks in hours.

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