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Punctuated equilibrium dynamics in human communications

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HIGHLIGHTS

- This model is based on the interaction and activation between individuals.
- This model links punctuated equilibrium models and queueing models.
- Rich non-Poisson properties in spatial–temporal patterns are created.
- A novel explanation for bimodal distribution is proposed.
- Our model shed light on non-Poisson phenomena in many complex systems.

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ABSTRACT

A minimal model based on network incorporating individual interactions is proposed to study the non-Poisson statistical properties of human behavior: individuals in system interact with their neighbors, the probability of an individual acting correlates to its activity, and all the individuals involved in action will change their activities randomly. The model reproduces varieties of spatial–temporal patterns observed in empirical studies of human daily communications, providing insight into various human activities and embracing a range of realistic social interacting systems, particularly, intriguing bimodal phenomenon. This model bridges priority queueing theory and punctuated equilibrium dynamics, and our modeling and analysis is likely to shed light on non-Poisson phenomena in many complex systems.

1. Introduction

In the recent decade, along with the fast development of online social services, the understanding and predicting of human behavior has attracted much attention of researchers. One of the remarkable features of statistical patterns of human behavior is the wide-spread non-Poisson property [1–13], which usually shows heavy-tail distribution on temporal statistics or spatial patterns and sharply differs from the Poissonian picture in traditional understanding [14,15]. Several mechanisms based on separated individuals have been proposed to explain the origin of bursts and heavy tails, including priority-queueing processes [1,5,16,17], Poisson processes modulated by circadian and weekly cycles [18–20], adaptive interests [5,21], preferential linking [5], and memory effects [22]. However, one major concern of behavior types in human dynamics is the interaction and communication behavior between individuals. Such human actions have a strong impact on

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resource allocation, circulation of information, even evolution of social network structure, therefore it has been the focus of research. In real life, everyone is influenced by the surrounding social environment, for instance, the interval between sending two consecutive E-mails is influenced by the actions of this individual and other communicating partners. Researchers achieved a breakthrough first in the simplest model of two interacting bodies [23]. A minimal model of interacting priority queues is proposed to discuss bimodal phenomenon observed in Short Message correspondence [24]: inter-event time distribution was neither completely Poisson nor power law but a bimodal combination of them. Notably, this bimodal phenomenon was also observed in inter-event time distribution of the calling activity of mobile phone users [25], two consecutive transactions made by a stock broker [16], successive transactions of experimental futures exchange [26], *etc*. Indeed, some purported power-law distributions in complex systems may not be power laws at all. In fact, strict power-law distribution is rarely observed in empirical studies albeit bursts and heavy tails are widespread. In addition to the widespread bimodal distribution, human activity patterns may be power-law distribution followed by distinct cutoff [10,27–30], multimodal distribution of power-law with different scaling exponents [30–33], in some instances it is more consistent with Mandelbrot distribution [34], and so on. Human activity patterns exhibit such a wealth of statistical properties. How to quantitatively understand human dynamics, does there exist a universal fundamental governing human dynamics and individuals? The understanding about these questions needs to be studied deeply.

In this paper, a simple model based on network, incorporating solely individual interactions, is proposed to explain and develop human dynamics, especially the origin of bursts and heavy tails. Our model links punctuated equilibrium models and queueing models, and reproduces varieties of distributions on spatial–temporal patterns observed in empirical researches, *e.g.*, exponential distributions, power-law distributions, and bimodal properties.

2. The model

In real life, a certain type of activity of an individual is influenced by the actions of this agent and other communicating partners. For example, one person may reply in no time after receiving a message, or even send one more to someone else; however, without receiving any messages, this person may not send any messages in a long time. That is, most of the time people's social behavior is activated by others'. Whereas, it is conceivable maybe the interactions make individual passive, for instance, an ongoing topic between interacting individuals terminates, or one party is reluctant to keep on interacting and so on. Hence we consider that social interactions would make an individual more active, or more inactive. An activated individual might keep reticent or contact to more than one neighbor. On the other hand, an individual might act at will without environmental stimulations. Incorporating all these considerations, the schemes of our model are as follows:

N nodes (individuals) are arranged on a network. At beginning, a random activity a_i equally distributed between 0 and 1, is assigned to node i. At each processing step t, the system is updated by:

(i) with probability p, the node with the highest activity is chosen to send messages to its n neighbors; or with probability $1-p$, an arbitrary node is chosen to be the sender, denoted as S_t. Here n is the number of messages sent in one processing step and is not larger than the degree of the sender;
(ii) If the sender S_t has received messages in previous time steps, with probability q, the sender sends one of the n messages back to the node which sent the last message to the sender, or with probability $1-q$, it sends a message to a randomly selected neighbor of S_t. And other $n-1$ messages are sent to other neighbors randomly.
(iii) The sender and all the nodes received message (receivers) at the current time step update their activity values to be new random numbers between 0 and 1.
(iv) Go into the next time step $t+1$ and repeat the above procedures.

With regard to messages spreading, we define a series of message sendings that are activated by a common source node as a "burst". At the beginning of a burst, all nodes in the network are unaffected by this burst, denoted by status U. At each time step, the nodes involved in the burst, i.e. the sender and the receivers are denoted by status A. Senders in a burst are relevant; therefore a sender in status U signifies the ending of the current burst and will start a new burst, thus all nodes turn to U status. At the ending of a burst, the number of nodes in status A is defined as the range of the burst, denoted by N_b, and the total number of time steps in the burst period is defined as the burst duration time t_b.

This model has three free parameters for a given network: n, p and q. When messages are sent ($n \geq 1$) by the most active individual ($p = 1$) and all the individuals involved in the action mutate their activities, interactions come about and lead to coupled system. If the network is regular (for example, a Ring) and n equals the degree of nodes, this simple model is same as Bak–Sneppen model [35,36]. When $p < 1$, it incorporates Poisson initiations of messages. If $n = 0$, the direct interactions between individuals are ignored completely, this case is equivalent to Barabási queueing model. Thus we give an association between priority-queue models and criticality phenomena.

3. Simulation results

3.1. Simulations on Ring

In the first instance, we concentrate on the dynamics on a Ring that every individual has two neighbors. There are several modes for the sending of messages. The first one is that the sender sends no message to its neighbor, namely, $n = 0$, thus the interactions between individuals are eliminated. This case is equivalent to Barabási queueing model, in which the node with