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How to estimate the signs' configuration in the directed signed social networks?

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ABSTRACT

Inspired by the ensemble theory in statistical mechanics, we introduce a reshuffling approach to empirical analyze signs' configuration in the directed signed social networks of Epinions and Slashdots. In our reshuffling approach, each negative link has the reshuffling probability p_{rs} to exchange its sign with another positive link chosen randomly. Many reshuffled networks with different signs' configuration are built under different p_{rs}s. For each reshuffled network, the entropies of the self social status are calculated and the opinion formation of the majority-rule model is analyzed. We find that S_{out}s reach their own minimum values and the order parameter $|m^*|$ reaches its maximum value in the networks of Epinions and Slashdots without the reshuffling operation. Namely, individuals share the homogeneous properties of self social status and dynamic status in the real directed signed social networks. Our present work provides some interesting tools and perspective to understand the signs' configuration in signed social networks, especially in the online affiliation networks.

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1. Introduction

Recently, complex networks have undergone a remarkable development and have emerged as an invaluable tool for describing and quantifying complex systems in physics, biology and sociology. Generally, a complex network is usually described by a graph in which vertices represent the components, such as people in social network and proteins in protein–protein interaction network, and links represent the interaction among those components. In most cases, links are all considered as positive connections. For example, links in social networks indicate friendship, collaboration and sharing information [1]. However, many real social networks, especially online social networks (such as the EBay, Epinions and Slashdot), intrinsically involve negative links as well as positive ones, such as the enemy, disproval and distrust relationships. For example, users can tag directed relations to others indicating trust or distrust in the trust network of Epinions, and users can designate others as "friends" or "foes" in the social network of the technology blog Slashdot [2]. Those social networks can be represented in terms of signed social networks [3–5], where a sign of link is defined as "+1" or "−1" depending on whether it expresses a positive or negative attitude from the generator of the link to the recipient [6].

The fundamental issues are how to describe and quantify signs' configuration in real signed social networks [6] and how does the real signs' configuration affect the dynamics of and on signed social networks. For the first issue, the social balance theory, which follows the common principles that "the friend of my friend is my friend," "the enemy of my friend is also my enemy," "the friend of my enemy is my enemy," and "the enemy of my enemy is my friend" [6], was proposed to describe the signs' configuration by Heider from the aspect of social psychology [7]. Facchetti et al. computed the global level of balance of online signed social networks and found that the currently available undirected networks, such as the Epinions and Slashdot, are indeed extremely balanced [7]. Traag et al. proposed an alternative model based on the homogeneous process to explain the social balance and the evolution of cooperation [8]. Furthermore, Facchetti et al. investigated the configuration of frustration through exploring the low-energy landscape of near-optimal structural balance from the aspect of statistics mechanics [3]. However, some researches showed that many signed social networks, especially the directed online social networks, are very poorly balanced [2,9]. Then, Hsieh and his collaborators introduced a low rank modeling approach for signed networks through considering the weak balance theory and the low-rank matrix factorization approach for sign inference [10]. Leskovec et al. developed the status theory, where a positive edge (u, v) means that u regards v as having higher status than himself/herself while a negative edge (u, v) means that u regards v

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as having lower status than himself/herself, to explain the signs' configuration [6].

The second issue about the role of the real signs' configuration in the dynamics of and on signed social networks has also been studied in the last decades [11–18]. For example, Nishi and Masuda analyzed the dynamics of social balance under undirected temporal interaction. And they found that the social balance dynamics is slowed down on the temporal complete network through comparing to the corresponding static complete network [13]. Tsvetkova and his collaborators used the temporal motifs to reveal negative links, which play a role in online collaborative communities on Wikipedia [14]. Fan et al. analyzed the opinion spreading based on the SIR model in homogeneous signed networks [15]. Li et al. extended the classic voter model to signed networks and analyzed the dynamics of influence diffusion of two opposite opinions [16]. Righi and Takács studied the Prisoner's Dilemma on signed networks where the behavior of condition player is determined by link's sign [17].

Our main goal is to evaluate the real signs' configuration through calculating the information entropies of self social status and the critical order parameter of opinion formation in the directed signed social networks of Epinions and Slashdot. Each negative link has the reshuffling probability p_{rs} to exchange his/her sign with another positive link chosen randomly. Then we analyze the information entropies S_{out} and S_{in} of each reshuffled signed network. We find that individuals tend to share the homogeneous self social status in the real signed social networks. Furthermore, in order to reveal the role of the real signs' configuration in the opinion formation, the majority-rule model is realized on each reshuffled signed network. We find that the critical order parameter $|m^*|$ reaches its maximum value when $p_{rs} = 0$, which means that even more individuals share the same opinion in real signed social networks. The present signs' configuration enhances the consensus ability of the system, i.e., individuals have the tendency to share the homogeneous dynamic status in collective dynamics of opinion formation.

2. Description of signed social networks and the reshuffling approach

We consider a directed signed social network $G = (V, L, A)$, where V is the set of vertices, L denotes the set of directed links, $A = \{A_{uv}\}$ describes the signed adjacency matrix with $A_{uv} \neq 0$ if and only if $(u, v) \in L$, and A_{uv} is the sign of link (u, v). A positive sign $A_{uv}\,(=+1)$ represents that u tags v as a friend or u trusts v, while a negative sign $A_{uv}\,(=-1)$ reflects that u tags v as a foe or u distrusts v. Several real signed social networks [6], including the network of Epinions was obtained in August 12, 2003, the network of Slashdot081106 was obtained in November 6, 2008, the network of Slashdot090216 was obtained in February 16, 2009 and the network of Slashdot090221 was obtained in February 21, 2009, are considered and available at http://snap.stanford.edu. The trust network of Epinions is a product review Website with a very active user community, where users can tag their trust or distrust of the reviews of others, and the social network of the Slashdot is a technology-related network website, where a signed link means that one user likes or dislikes the comments of another user. In each network, links are inherently directed and the proportion of positive links is roughly 80% [2], see Table 1.

A given signed social network with constant macroscopic quantities (N_v, N_l, p_+) can be regarded as an isolated system, which obeys the ergodic hypothesis from the viewpoint of statistic mechanics. According to the ensemble theory in statistical mechanics, each signed social network has many configurations according to signs' configuration. As well known, to flip one or more signs will alter its signs' configuration, and we recognize that the system will experience another microscopic state. Different signs' configuration describes different microscopic state. There must exist one specific microscopic state which has the same signs' configuration as the real signed social network. In order to analyze the difference of the possible signs' configuration and the real one, we introduce a reshuffling approach to rebuild configurations of the real signed social networks of Epinions and Slashdot through the tuning reshuffling probability p_{rs}. For each p_{rs}, the reshuffled signed network is obtained and fixed after the reshuffling process finished. In the reshuffling process, each negative link has the probability p_{rs} to exchange his/her sign with another positive link chosen randomly, see Fig. 1. It is obvious that the reshuffled signed network is reduced to the real one when $p_{rs} = 0$, while all the negative signs will be reshuffled thorough randomly when $p_{rs} = 1$. Note that the reshuffling approach provides the possibility and feasibility in comparing the real signs' configuration to each possible signs' configuration. Through analyzing the social status and the opinion formation on all the reshuffled signed networks below, we can reveal the homogeneous properties of the social status and the dynamic status in the real directed signed social networks.

Table 1
Nodes and links in several signed social networks (Epinions and Slashdot) [6]. N_v is the number of the vertices, N_l is the number of the directed links and p_+ is the percent of sign "+" (i.e., the percent of the positive links).

	N_v	N_l	p_+
Epinions	131,828	841,372	85.3%
Slashdot081106	77,357	516,575	76.7%
Slashdot090216	81,871	545,671	77.4%
Slashdot090221	82,144	549,202	77.4%

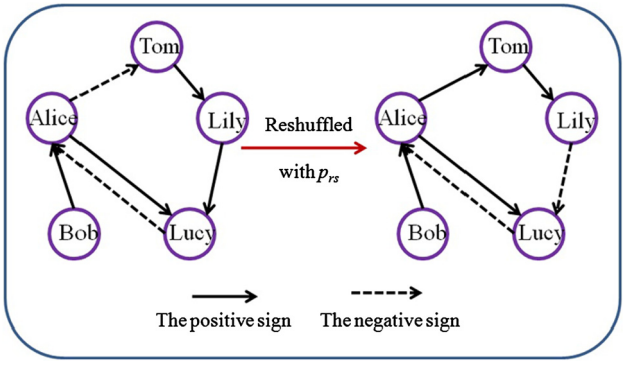

Fig. 1. (Color online.) The illustration of our reshuffling approach. The negative sign from Alice to Tom is chosen with probability p_{rs} to exchange its sign with the positive sign from Lily to Lucy chosen randomly. Note that the total number of positive signs and negative signs is fixed during our reshuffling approach.

3. The homogeneous property of self social status

Analogous to an Ising model, a positive link is mapped as one with spin "↑" while a negative link mapped as one with spin "↓". The presence of negative links introduces disorder (or frustration) in signed social network [3]. As well known, information entropy can describe the uncertainty associated with a given probability distribution. The application of entropy concept in complex networks is widely and deeply [20–24]. However, the application of entropy in the signed network is presently limited and challenged. Here, the information entropies are calculated to quantify the disorder [27] of sign "+" among out-links and in-links in signed social networks respectively.

In signed social network, sign of link describes the relationship of the corresponding connection between individuals, and then each individual can be tagged by others and tag others. In Ref. [19],

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