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Optimizing dynamical changes of structural balance in signed network based on memetic algorithm

Shanfeng Wang[a], Maoguo Gong[a,*], Haifeng Du[b], Lijia Ma[a], Qiguang Miao[c], Wei Du[b]

[a] Key Laboratory of Intelligent Perception and Image Understanding of Ministry of Education, Xidian University, Xi'an, Shaanxi Province 710071, China
[b] Center for Administration and Complexity Science, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, China
[c] School of Computer, Xidian University, Xi'an, Shaanxi Province 710071, China

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ABSTRACT

In dynamical evolution of structural balance, unbalanced signed networks evolve to structurally balanced ones. In this paper, we compute the least number of sign changes in the evolution of structural balance. It is suggested that there be a certain bias towards flipping positive or flipping negative signs. The number of flipped signs is quantified by an objective function. Moreover, a memetic algorithm is proposed to optimize the objective function. Experiments show that our algorithm is efficient and effective to optimize dynamical evolution of structural balance.

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1. Introduction

Many real-world systems can be modeled as networks (Newman, 2001, 2011; Watts and Strogatz, 1998). In these networks, individuals are represented by the nodes and relationships between individuals are represented by the edges. To study relationships between nodes, such as friendship, collaboration, or membership in a community, interactions in the social system are characterized by the signed edges in signed networks. Social signed networks consist of a group of interacting individuals, where a positive/negative edge represents the friendly/hostile relationship between individuals (Everett and Borgatti, 2014; Doreian and Mrvar, 2009; Srinivasan, 2011; Szell et al., 2010; Bonacich and Lloyd, 2004).

Structural balance is an important notion in the analysis of signed network structure. Balance theory has been applied in many fields, such as social psychology, international relationships (Antal et al., 2006). Leskovec et al. (2010) and Szell et al. (2010) examined the validity of structural balance in online multimedia websites. Structural balance theory was proposed from social psychology research by Heider (1946). This theory begins with notions with tension. Heider's theory was generalized to the language of networks by Cartwright and Harary (1956). Cartwright has proved many fundamental theorems about the structure of balanced networks. In Xiaolong and Zeng (2014), a comprehensive review of these existing studies about structural balance was given.

Real world signed networks are rarely balanced. Many methods are proposed to compute the unbalance of signed networks, i.e., how unbalanced a signed network is. Marvel et al. (2009) introduced an quantity to denote the potential function of signed networks. In Marvel et al. (2009), the sum of all the negative product of triangles is divided by the total number of triangles. In Terzi and Winkler (2011), the fraction of unbalanced triads in the networks is associated with the eigenvalues of the network's adjacency matrix. An efficient spectral algorithm is proposed to compute the fraction of unbalanced triangles, in which the top-n eigenvalues rather than all the eigenvalues are used. In Anchuri and Magdon-Ismail (2012), the unbalance of the networks is measured by the frustration in signed networks. The frustration is the sum of the number of negative edges between nodes in the same community and the number of positive edges between nodes in different communities. These methods gave the overall amount of frustration of the network, but they could not provide any information on which relationships remain unbalanced. Facchetti et al. (2011) proposed an energy function to compute global balance in signed networks. The minimum of energy function is equivalent to the minimum number of edges which make signed network unbalanced. A network is structurally balanced when its energy function is zero. In Iacono et al. (2010), an efficient heuristic method was introduced to optimize this energy function. In this method, the so-called apparent disorder from the network is eliminated in the process of transformation, and the number of negative edges decreases. Sun et al. (2014) proposed an memetic algorithm to compute the global balance by optimizing the energy function above.

* Corresponding author at: Xidian University, No. 2, South TaiBai Road, Xi'an 710071, China. Tel.: +86 029 8820 2661; fax: +86 29 88201023.
E-mail address: gongieee@gmail.com (M. Gong).

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In dynamical evolution of signed networks, an initial structurally unbalanced network achieves balance. In the evolution process of signed networks, the sign of existing edges can be changed or deleted and new edges can be formed. Dynamics models following various balance-theoretic update rules have been studied over the past few years. Antal et al. (2005) proposed two discrete models for dynamics of structural balance: one is called local triad dynamics (LTD) and the other is constrained triad dynamics (CTD). In these models, signs on certain edges are shifted if the total number of imbalanced triads decreases. These models usually arrives at one balanced state or the state named "jammed states", in which these models are trapped into an unbalanced local minimum (Marvel et al., 2009; Antal et al., 2005). Marvel et al. (2009) modeled a fully-connected signed social networks. These models paid attention to the sequential sign change process on a fixed network. Deng and Abell (2010) studied local sign change adjustment of signed networks by following different rules. In Deng et al. (2012), sign adjustment in weighted signed networks under five kinds of balancing rules was studied. Van de Rijt (2011) employed a best-response dynamics model of sentiment change. Marvel et al. (2011), Srinivasan (2011), Traag et al. (2013) and Summers and Shames (2013) proposed continuous-time models to analyze the underlying evolution mechanisms of signed networks. More details about evolution of balance can be found in Xiaolong and Zeng (2014).

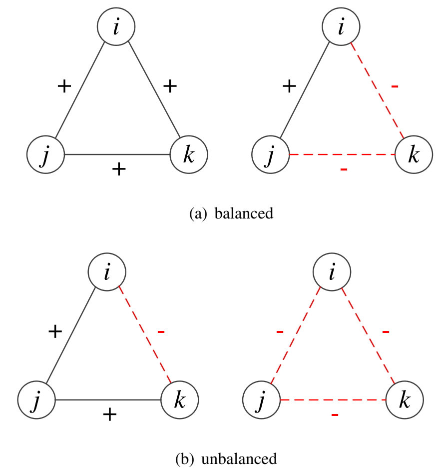
In this paper, we study special cases of dynamical evolutions, in which a network evolves from its current state to global balance with the least number of sign changes. That is, we want to minimize the number of edge signs that need to be flipped in the evolution of structural balance. We do not focus on the triad-based update rules of balance and we study the least number of sign changes in dynamics evolution of balance, that is, in our evolution processes, we assume that none of edges is deleted and none of new edges is formed. An objective function about the number of sign changes is proposed to quantify this problem. Our main contributions in this paper are as follows. We formulate the problem optimizing dynamics of structural balance as an optimization problem. In our problem, instead of using a total number of flipped signs, there is a certain bias towards flipping positive or flipping negative signs in our model, and the bias varies with a parameter. We propose a memetic algorithm with local search procedure to optimize the objective function above. Comparative experiments on four signed networks demonstrate that the proposed algorithm can effectively optimize dynamics of structural balance. Our algorithm can give the information about which edges resulting in the unbalance of signed networks.

The rest of the paper is organized as follows: In Section 2, the related background, including the definition of structural balance, energy function, our objective function and memetic algorithm are given. The proposed algorithm is described in detail in Section 3. In Section 4, the proposed algorithm is validated on four real signed network. The conclusion is summarized in the last section.

2. Related background

2.1. Structural balance

According to Heider theory of structural balance, for a signed network with only three nodes, there are four configurations, as shown in Fig. 1. In Fig. 1(a), a triangle with three positive edges or one positive edge and two negative edges is balanced, since both of them satisfy the adages that "a friend of my friend is my friend" and "an enemy of my friend is my enemy". In Fig. 1(b), triangles with two positive edges and one negative edge or three negative edges are unbalanced, for they do not satisfy the logic of friendship above. There are odd number of negative edges in balanced triangles and even number of negative edges in unbalanced triangles. Triangle is structurally balanced, when the product of edge signs is positive and triangle is structurally unbalanced, when the product of edge signs is negative.



(a) balanced

(b) unbalanced

Fig. 1. Four configurations of signed triangles. The solid lines represent the positive edges and the dashed lines represent the negative edges.

From Heider theory of balance, a signed network is balanced if all the triangles in the network are balanced. A more general definition of structural balance is that a network contains no cycle with negative product. Cartwright and Harary (1956) indicated that the triangle based and cycle based definitions of structural balance are equivalent on complete graph. Abell (1968) provided that an incomplete, affective, symmetric structure with k-subgraphs is balanced if and only if there are 2^{k-1} ways to partition the node set of this signed network such that: all intra-subgraph edges are positive or unconnected and all inter-subgraph edges are negative or unconnected.

2.2. Energy function

In Facchetti et al. (2011), an energy function is proposed to compute global balance in signed networks. Computing global balance means assigning a +1 and a −1 to all the nodes to achieve the minimum of energy function:

$$H(s) = \sum\nolimits_{(i,j)} \frac{(1 - J_{ij} s_i s_j)}{2} \tag{1}$$

where the summation runs over all adjacent pairs of nodes; $J_{ij} \in \{\pm 1\} = \mathbb{B}_2$ is entry of the adjacent matrix of signed network representing the edge between node s_i and node s_j; $\mathbf{s} = [s_1, \ldots, s_n]^T \in \mathbb{B}_2^n$, i.e., $s_i \in \{\pm 1\}$, $i = 1, \ldots, n$ indicate the variables associated to the nodes of the network.

When node signs s_i and s_j are same, each term in (1) gives a zero distribution if J_{ij} represents friendship or a +1 distribution if J_{ij} represents hostility, whereas when node signs s_i and s_j are different, the summand is zero if J_{ij} represents hostility, otherwise +1. When the energy function (1) of a signed network is zero, the network is structurally balanced.

2.3. Quantifying dynamical evolution of structural balance

We want to compute the minimum number of sign changes in dynamical evolution of signed networks, and then a criterion is needed to test whether signed networks evolve to balanced ones. As described above, when energy function (1) of a signed network is zero, the network is balanced, so that Eq. (1) is adopted as the criterion.

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