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SISL and SIRL: Two knowledge dissemination models with leader nodes on cooperative learning networks

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HIGHLIGHTS

- Cooperative learning network is a uniform network with small-world characteristics.
- The dynamic transmission mechanism of knowledge on CLN is revealed.
- The spreading threshold on CLN has been analyzed.
- Leader nodes play important role in the knowledge spreading process on CLN.

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ABSTRACT

Cooperative learning is one of the most effective teaching methods, which has been widely used. Students' mutual contact forms a cooperative learning network in this process. Our previous research demonstrated that the cooperative learning network has complex characteristics. This study aims to investigating the dynamic spreading process of the knowledge in the cooperative learning network and the inspiration of leaders in this process. To this end, complex network transmission dynamics theory is utilized to construct the knowledge dissemination model of a cooperative learning network. Based on the existing epidemic models, we propose a new susceptible–infected–susceptible-leader (SISL) model that considers both students' forgetting and leaders' inspiration, and a susceptible–infected–removed-leader (SIRL) model that considers students' interest in spreading and leaders' inspiration. The spreading threshold $\lambda_c$and its impact factors are analyzed. Then, numerical simulation and analysis are delivered to reveal the dynamic transmission mechanism of knowledge and leaders' role. This work is of great significance to cooperative learning theory and teaching practice. It also enriches the theory of complex network transmission dynamics.

1. Introduction

Cooperative Learning has proven to be effective. Presently it is utilized in schools and universities in all over the world with students covering all ages [1,2]. In 1974, David and Roger Johnson identified that cooperative learning promoted mutual liking, better communication, high acceptance, and support, as well as demonstrated an increase in a variety of thinking

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strategies among individuals in the group [3]. There are five basic essential elements of cooperative learning, including face-to-face promotive interaction [4]. In mutual contact activities, students help, assist, support and encourage each other to fulfill the task. In the work of [5], Gillies explained the importance of interaction in cooperative learning groups. In cooperative learning, students are in different groups, and the mutual contact between the students forms a cooperative learning network (CLN). According to the literature reviews, researchers have already reached a consensus that interaction is important in cooperative learning.

Learning is a complex and interactive process which takes place at all times and the dissemination of knowledge is in the process of interaction. The authors of Ref. [6] discussed the mechanisms. However, knowledge dissemination on CLN has its own characteristic and the model has not been effectively portrayed. Therefore, it is full of great significance to study on the knowledge dissemination mechanism on CLN. The knowledge dissemination on CLN is similar to the disease spreading in the crowd. A node can spread the information to multiple nodes, and also be eliminated. Knowledge transfer through direct contact among individuals [7]. The study of epidemic spreading models in the crowd is one of the main contents of spreading dynamics on complex networks. Among those models, the susceptible–infected–susceptible (SIS) model and the susceptible–infected–removed (SIR) model are most commonly used.

In our previous study, SNA was used to analyze the relationship of students of one class, then CLN was built and topological properties were calculated. In this paper, we do some further research and focus on the knowledge dissemination mechanism on CLN. Referring to the existing epidemic models, we propose two models. One is the susceptible–infected–susceptible-leader (SISL) model that considers both students' forgetting and leaders' inspiration, another is the susceptible–infected–removed-leader (SIRL) model that considers students' interest in spreading contents and leaders' inspiration. Leaders in this paper are not group chiefs but excellent students who are highly active in knowledge dissemination. Model analysis and numerical simulation are provided to explain the transmission mechanism of knowledge on CLN.

The rest of this paper is organized as follows. In Section 2, the related background is described. The SISL model, the SIRL model, and parameters are provided in Section 3. Section 4 provides some numerical simulations and explanation. Some concluding remarks are entered in Section 5.

2. Background

2.1. Knowledge dissemination model

Knowledge management is full of significant to a firm. Knowledge dissemination, as an important part of knowledge management, has been studied for so many years [8]. Lin researched on knowledge sharing and interpersonal relationships by compared of family firms and non-family firms, which emphasized the incentive reward systems [9]. Zhu et al. focused on tacit knowledge and proposed two knowledge dissemination models, one considered of intention mechanism and the other considered of employee mobility [10,11]. Alves outlined a framework for knowledge sharing in horizontal networks to understand the way knowledge sharing happens and its similarities between different networks [12].

At present, there are a few researches using complex network theory in knowledge dissemination. Most of them paid attention to the influence of network connection and structure on knowledge dissemination. Cowan et al. found that the knowledge dissemination in small world network was faster than others [13]. A method of community detection in large networks was concerned, and the implication of social structures on knowledge creation and diffusion was discussed in Ref. [14]. C. de Kerchove et al. focused on the information propagation influenced by the network topology [15]. The authors of Ref. [16] conducted the research into the law of how the community degree and clustering coefficient influence the knowledge dissemination efficiency in complex networks. Lin found that the organizational structure characteristics influenced the knowledge sharing among organizational units and the interaction among units had a significant influence on knowledge sharing [17]. Wanly found that knowledge propagation was closely related to the spreading speed of knowledge in organization and other factors [18]. Knowledge dissemination also influenced by other factors, such as individual attributes, the spreading content, the knowledge subjects and the relationship with the spreading target [19–21].

2.2. Spreading dynamics on complex networks

Spreading dynamics on complex networks focused on the propagation mechanism, dynamical behaviors and the control method for these behaviors efficiently and feasibly in complex network both in nature and human society [22]. The susceptible–infected–susceptible (SIS) model and the susceptible–infected–removed (SIR) model are two common epidemic spreading models. Based on the original model, Zhou T, Yang R et al. proposed new models with identical infectivity [23,24]. Some researchers did further study and put forward improved models with infective vectors [25–27]. The study [28] proposed a new SIS model with the feedback mechanism on networks. Xia et al. [29,30] proposed a SIR model including the factor of the infection medium, and another SIR model containing time delay and the medium simultaneously. SIS and SIR models are also used to describe the process of rumor diffusion in social networks. In Ref. [31], the authors added the participation of independent spreaders. Qian et al. presented a new SIR rumor model with independent spreaders [32]. In Ref. [33], a susceptible–exposed–infected–removed (SEIR) model with hesitating mechanism was proposed. Centola et al.

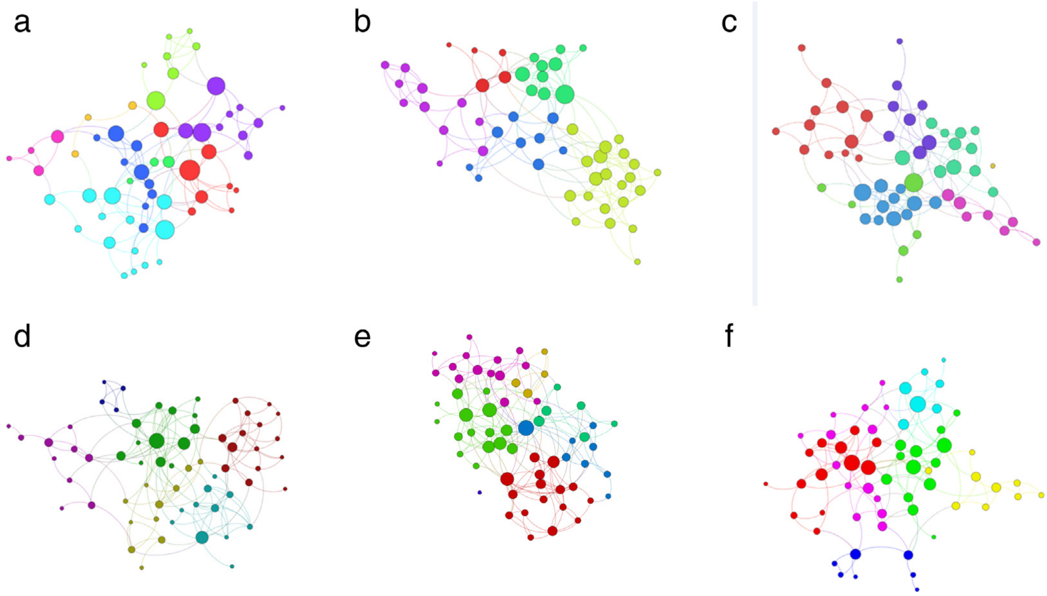

Fig. 1. The cooperative learning networks of six classes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

recommended caution in the generalization of simple diffusive models for information spreading in society [34], although the dynamics of knowledge spreading was similar to epidemiology [14,35]. Nevertheless, all these studies inspired our work on the knowledge dissemination model in CLN.

2.3. Cooperative learning network

Social Network Analysis (SNA) is a method for visualizing the structures of people and connection, which has been applied in many fields. As an effective method, SNA has been used to analyze the phenomenon of cooperative learning. Mansur & Yusof discussed the clustering in cooperative learning [36]. Chen et al. studied the optimization of cooperative learning groups based on genetic algorithm [37,38]. Zhang et al. proposed a novel grouping scheme considering the multidimensional feature clustering [39]. Chen et al. studied cooperative learning with appropriate learning partners in a problem-based learning environment and in a web-based cooperative learning environment using SNA [40,41].

Our previous study used SNA to analyze the relationship of students of one class and got the CLN. In Ref. [42], our group defined CLN as follow: students in a certain range, contact, influence and sharing knowledge which constitute a network system. Each student is regarded as a node, and the connection between the students as the edge. Based on this, we can get a CLN without the weight and direction. In this work, we set the range of students within a class to form a CLN.

We recruited 18 classes in two junior high schools and one primary school at Xi'an in the investigation. Every student was asked to write down the names of students who did he gave or get from knowledge in learning. Questionnaires were sent in the classroom to obtain the data of informal cooperative learning using SNA. The network analysis software Gephi (8.0 beta) was used for data processing and analyzing.

Fig. 1 shows the cooperative learning networks of six classes. From this study, we have found that the average degree of the CLN is 5 ($\langle K \rangle \approx 5$), the degree distribution is exponential, average path length $L = 3$, average cluster coefficient $C = 0.3638$, which is far greater than the same size of a random network. Results have indicated that CLN is a uniform network with small-world characteristics. Communication among students establishes a dynamic connection, and the influence of two connected nodes can indirectly affect other nodes, so as to affect the whole CLN knowledge dissemination, and affect the knowledge acquirement of each individual on CLN.

As shown in Fig. 1, the nodes represent the students. The larger the node is, the greater the degree is. The degree refers to the individuals the student has connected with. The smaller the node is, the smaller the degree is. In one community, nodes share the same color, and are closely internally contacted.

3. Dissemination model on cooperative learning network

Basic epidemic models on complex networks, such as SIS model and SIR model, consider the mutual contact between individuals. The knowledge dissemination on CLN is similar to the spreading of the epidemic and the spreading of the rumor in the crowd. In the process of learning, students are the subject, with a variety of characteristics. Meanwhile, the spreading process can be effected by a lot of factors, such as forgetting, interest in the knowledge, leaders' inspiration, etc.

In this paper, we focus on the knowledge dissemination on CLN, considering students' forgetting and the inspiration from leaders among students or students' interest in dissemination the learning contents and the leader's inspiration. Referring to the SIS model and SIR model structures proposed in [26,29], two knowledge dissemination models on CLN are established. Then, the dynamic spreading mechanism of knowledge dissemination is discussed. In the models, leaders are in the state of infected, but they are more active than ordinary nodes.

3.1. SISL model

Referring to the SIS model, the susceptible–infected–susceptible-leader (SISL) model is defined as follows. In this model, students' forgetting and leaders' inspiration are taken into account.

There are two discrete states in this model, that is, susceptible (i.e. unknown state or forget state), infected (i.e. known state). The ordinary student nodes are in one of them. The leaders want to make the knowledge spread as far as possible on CLN, so they are in leading state, which belong to infected state.

The knowledge transmission of SISL model is described in the following way: At each step, a susceptible individual acquires knowledge with probability α if it is connected to an ordinary infected individuals, then, infected individuals forget it and become susceptible again with probability β ($\beta \ll \alpha$). In addition, susceptible individuals may also become infected state with probability γ because of leaders' inspiration. In this model, the ordinary student nodes run through the cycle susceptible $\rightarrow$ infected $\rightarrow$ susceptible, namely, the unknown student become known due to the cooperative learning among students or leaders' inspiration, then, return to the unknown state due to forgetting. Since the duty of the leaders is to facilitate the dissemination of knowledge, they are in the known state all the time. When there is no leaders' inspiration ($\gamma = 0$), the model will return to the original SIS model.

CLN is a small-world network with a uniform topology. In a homogeneous network, generally, we assume that each individual has roughly the same number of links, so $k \approx \langle k \rangle$. $N(I)$ is the number of individuals in the infected state, including leaders nodes. $N(S)$ is the susceptible individual number, and N is the total number. Then, $N = N_{(\mathrm{I})} + N_{(\mathrm{S})}$. $\rho(t)$ and $s(t)$ respectively denotes the density of infected and susceptible individuals at time t, and $s(t) + \rho(t) = 1$. The density of L nodes is $\phi(t)$. Considering students' forgetting and leaders' inspiration, the CLN knowledge dissemination dynamic equation can be described as

$$\frac{\mathrm{d}\rho\,(t)}{dt} = -\rho(t) + \lambda \langle k \rangle \rho(t)\,(1 - \rho(t)) + \gamma \phi(t)\,(1 - \rho(t)) \tag{1}$$

where, λ ($\lambda = \alpha/\beta$, set $\beta = 1$, then $\lambda = \alpha$) is the knowledge dissemination rate, γ is the probability of unknown individuals turn to known state due to leaders' inspiration, β_2 is the density of L node in infected nodes. Let $\phi(t) = \beta_2 \rho(t)$, where $0 \le \lambda$, γ, $\beta_2 \le 1$ then

$$-\rho(t) + \lambda \langle k \rangle \rho(t)\,(1 - \rho(t)) + \gamma \beta_2 \rho(t)\,(1 - \rho(t)) = \rho(t)\,[(\lambda \langle k \rangle + \gamma \beta_2)\,(1 - \rho(t)) - 1] = 0.$$

One has

$$\lambda_c = \frac{1 - \beta_2 \gamma}{\langle k \rangle}. \tag{2}$$

On CLN, λ_c is the knowledge dissemination threshold. The value relates to the average degree distribution $\langle k \rangle$ of CLN, β_2 and γ. When there are no L nodes, $\lambda_c = 1/\langle k \rangle$ is the spreading threshold of the SIS model in a homogeneous network.

3.2. SIRL model

In the process of learning, the students have a definite tendency for the dissemination of knowledge. When one student thinks that he is the sole owner of the knowledge which others do not know, he is willing to share it to his neighbors as soon as possible. When most of the neighbors around him know the knowledge, he would think that this knowledge is no longer fresh and has no communication value, thus he will stop spreading it. The propagation is similar to the SIR model. Referring to the existing model, L nodes are added to study the susceptible–infected–removed-leader model on CLN, which considers the students' spreading interest and the leaders' inspiration simultaneously. In this model, knowledge forgetting would not be taken into account any more. The SIRL model can be depicted in Fig. 3.

There are three states in this model, susceptible (i.e. unknown state), infected (i.e. known and spread state), and removed (i.e. known but will not spread state). The ordinary student nodes are in one of the three discrete states at a time. L nodes are in the state of infected, but they are more active than ordinary nodes. When the density of infected students is high, L nodes will no longer spread this knowledge in large scale, and turn into the removed state.

The SIRL knowledge transmission model is described in the following way: at each step, a susceptible individual acquires knowledge with probability α if it is connected to an infected individual, and becomes infected state. Meanwhile, some excellent students absorb knowledge efficiently and become leaders, which are infected state and are the most active nodes in the CLN. L nodes may return to ordinary nodes with probability γ because of their own factors. When the density of neighbors in the infected state is high enough, the node would not have spreading interest. Then this node becomes known but not spread state with probability β. This node will no longer have a contribution to the dissemination of knowledge on CLN, and be in the removed state. At the same time, nodes in the infected state become removed state due to leaders' inspiration with probability β_1. In this model, student nodes run through the cycle susceptible → infected → removed. When there are no L nodes in the CLN knowledge dissemination process (i.e. $\gamma = 0, \beta_1 = 0$), the model is proposed to the standard SIR model.

Similar to the SISL model, $s(t), i(t), r(t)$ respectively represents the density of individuals in the susceptible state, infected state and removed state at time t. Normalize the condition, one gets $s(t) + i(t) + r(t) = 1$. $\phi(t)$ is the density of L nodes, and set $\phi(t)$ equals $\beta_2 i(t)$. Based on the mean field theory, the CLN knowledge dissemination dynamic equation considering students' interest in spreading contents and leaders' inspiration can be described as

$$\begin{cases} \dfrac{ds(t)}{dt} = -\alpha\langle k\rangle s(t)i(t) - \gamma\phi(t) \\ \dfrac{di(t)}{dt} = \alpha\langle k\rangle s(t)i(t) - \beta i(t) + \gamma\phi(t) - \beta_1 i(t)\phi(t) \\ \dfrac{dr(t)}{dt} = \beta i(t) + \beta_1 i(t)\phi(t). \end{cases} \tag{3}$$

Here $\beta = 1, \phi(t) = \beta_2 i(t)$ and $s(t) + i(t) + r(t) = 1$, so

$$s(0) \approx 1, \quad i(0) \approx 0, \quad r(0) \approx 0, \quad s(0) \approx 1, \quad i(0) \approx 0, \quad r(0) \approx 0$$

where,

$$\frac{df\,(r(\infty))}{dr(\infty)}_{\|r(\infty)=o} = \frac{d\,(1 - s(\infty))}{dr(\infty)}_{\|r(\infty)=o} = -\frac{ds(\infty)}{dr(\infty)}_{\|r(\infty)=o} > 1.$$

Then,

$$\lambda > \frac{1 - \gamma\beta_2}{\langle k\rangle}.$$

Thus

$$\lambda_c = \frac{1 - \beta_2\gamma}{\langle k\rangle}. \tag{4}$$

When $\lambda \le \lambda_c$, $i(t) = 0$, and when $\lambda \ge \lambda_c$, $i(t)$ is the stable non-negative equilibrium point.

In the SIRL model, spreading threshold λ_c is associated with the density of L nodes in infected individuals β_2, the probability γ which is the probability of leader nodes turn to ordinary infected students nodes, and the CLN average degree distribution $\langle k\rangle$. When T nodes do not exist, $\lambda_c = 1/\langle k\rangle$ is the spreading threshold of the SIR model in a homogeneous network.

4. Numerical simulations and discussion

In Ref. [42], our group has analyzed the topological properties and characteristics of CLN. Based on this, through numerical simulation, we analyze the transmission mechanism and characteristics on CLN of the SISL and SIRL model in this section.

4.1. SISL model numerical simulation and discussion

We implement numerical simulations to explore the dynamical process of SISL model as shown in Fig. 2. Based on data of one class, we set $\rho(0) = 0.1$, the average degree $\langle k\rangle = 5$, parameters $\gamma = 0.6$, $\beta_2 = 0.05$. In this case, the spreading threshold $\lambda_c = 0.194$ The results are shown in Fig. 4.

Fig. 4 shows the density of infected individuals changing with different knowledge dissemination rate λ over time. With the spread of knowledge, the density of infected nodes becomes stable, and the system tends to a steady state eventually. λ_c is the spreading threshold of SISL model. When knowledge dissemination rate $\lambda > \lambda_c$, the density of susceptible individuals increases gradually beginning with initial value $\rho(0) = 0.1$ and reaches a steady state in the end. With the increase of λ, the density of infected individual increases faster, and the shorter time to achieve steady state, meanwhile, the stable value is greater. However, when $\lambda < \lambda_c$, knowledge cannot spread out on CLN, and the density of infected individuals declines beginning with initial value.

Fig. 5 shows the density of infected individuals changing on stability with different knowledge dissemination λ. If $\lambda > \lambda_c$ knowledge can be spread on CLN, ultimately, the system reaches equilibrium state. Knowledge dissemination rate λ larger, the system reaches the stable state more quickly, and the density of infected nodes greater, which eventually stabilizes at about 0.8. After the system is stable, there are still susceptible nodes. No matter how larger the knowledge dissemination rate is, there will not be only infected nodes exist in the end. However, if $\lambda < \lambda_c$, knowledge cannot spread, and the density of infected nodes eventually stabilized at 0 points.

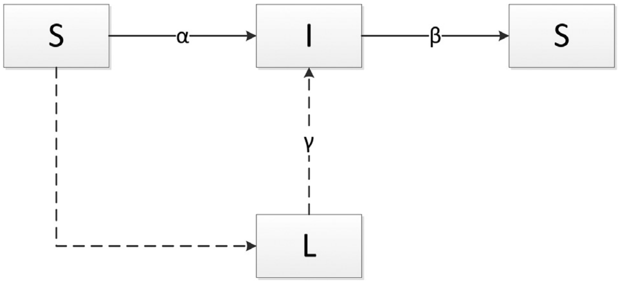

Fig. 2. The SISL model.

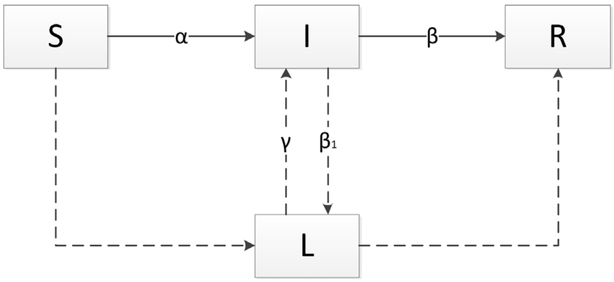

Fig. 3. The SIRL model.

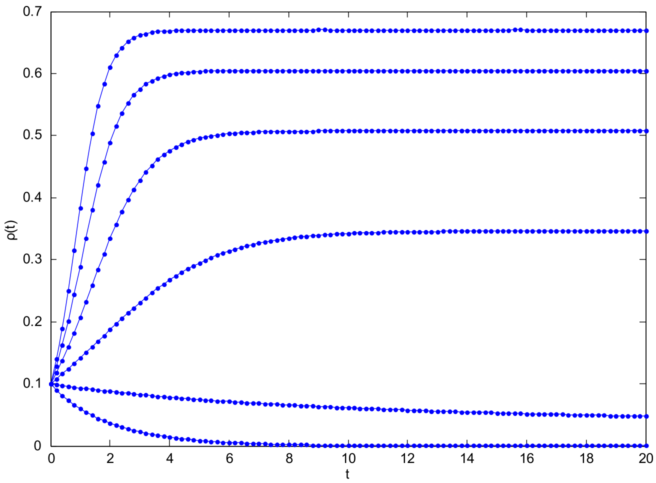

Fig. 4. The influence of knowledge dissemination rate λ on the density of infected individuals. Spreading rate $\lambda = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6$ (bottom to top).

The numerical simulation results coincide with the practice. When knowledge is very intractable, which is beyond the students' ability, at this time knowledge dissemination λ is smaller, so the spreading process on CLN is relatively difficult. Even if there are quite a few students mastered it, knowledge will slip from their memory because of none timely review and forgotten. Then, the knowledge would extinction in the network. When knowledge is simple, most students will be able to access it. The less difficulty, the easier to spread. With students' explanation and the leaders' inspiration, knowledge will quickly spread in the network, ultimately majority of students will grasp. Finally, owing to learning disabilities of other factors, some students may not fully grasp the knowledge.

4.2. SIRL model numerical simulation and discussion

The numerical simulation results of SIRL model are presented in Figs. 6 and 7. Similar to SISL model, we set $\rho(0) = 0.1$, the average degree $\langle k \rangle = 5$, parameters $\gamma = 0.3$, $\beta_1 = 0.6$. In Fig. 6, $\beta_2 = 0.05$.

Figs. 6a and 6b illustrate the impact of knowledge dissemination rate λ on the stable density of nodes in three separately states. The number of susceptible nodes gradually reduces while the number of removed nodes gradually increases. The

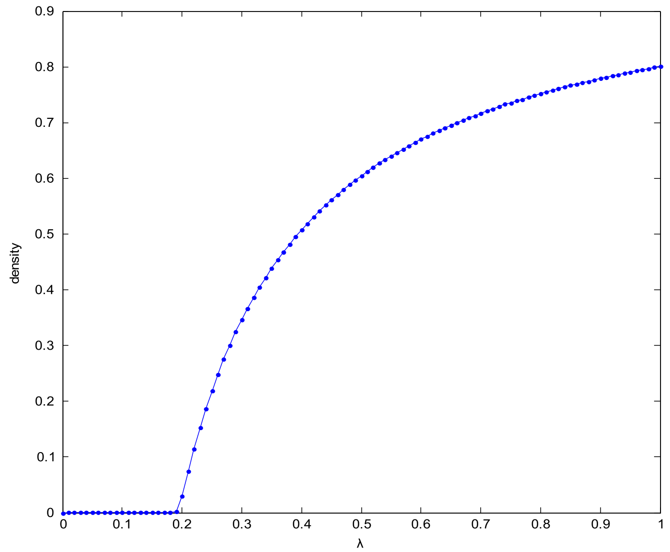

Fig. 5. The influence of knowledge dissemination rate λ on the stable density of infected individuals.

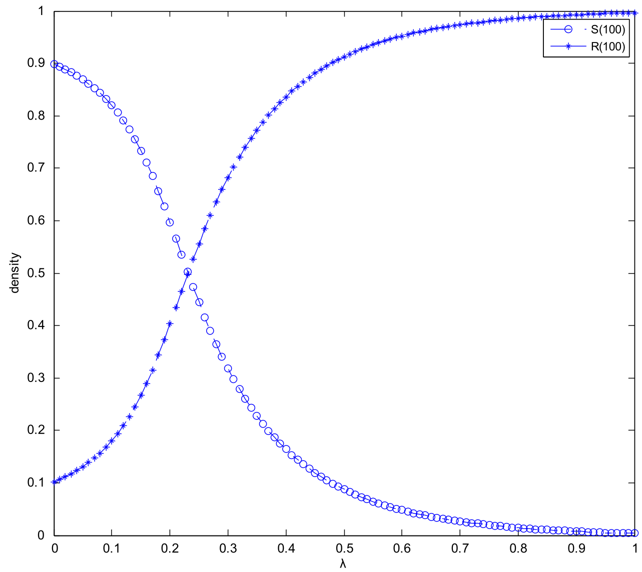

Fig. 6a. The influence of λ on the stable density of susceptible individuals and removed individuals.

variation trends of susceptible nodes and removed nodes are increasing firstly and then decreasing. While, the ultimate stable density of infected node is shocking in a small range, due to the changing density of the other nodes. Either in the process of knowledge dissemination, or at the final point, nodes are in a variety of states. Eventually, the system reaches steady state.

Fig. 7 illustrates the densities of three kinds of nodes changing over time. In SIRL model, the density of susceptible nodes decreases rapidly from the initial 0.9, then stabilizes gradually. The density of infected nodes increases firstly then decreases, finally tends to a stable value about 0 points. The density of removed nodes gradually increases to a steady state. After reaching steady state, there are not only removed nodes, but also a fewer infected nodes and a certain amount of susceptible nodes. From Fig. 7, one can find that with the increasing of β_2, the stable density of susceptible nodes decreases, and that of removed nodes increases. That means, L nodes play an important role on CLN, and the more L nodes is, the better the spreading effect will be.

In cooperative learning, initially, only a few students know the knowledge, so they are under higher interest in spreading, due to the communication among students and leaders' inspiration, the knowledge spreads rapidly. Then, more and more students participate in the spreading. In this case, the density of infected nodes increases and the number of susceptible nodes reduces rapidly. When most students obtain the knowledge, students' spreading interest would reduce, and the

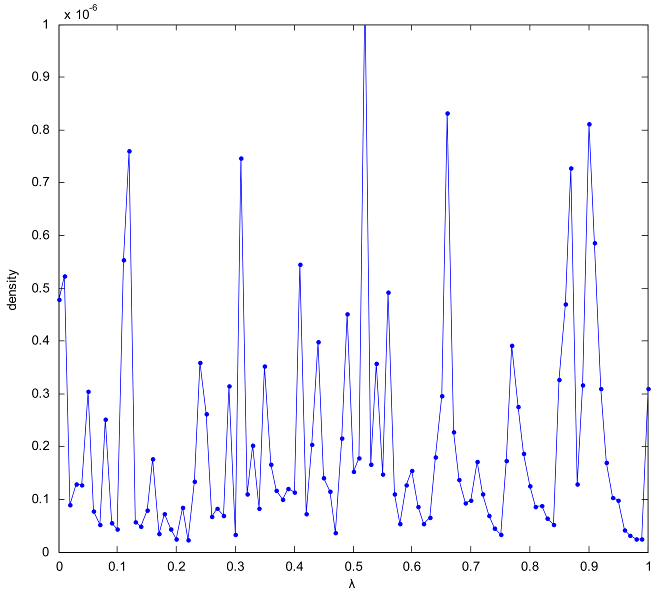

Fig. 6b. The influence of λ on the stable density of infected individuals.

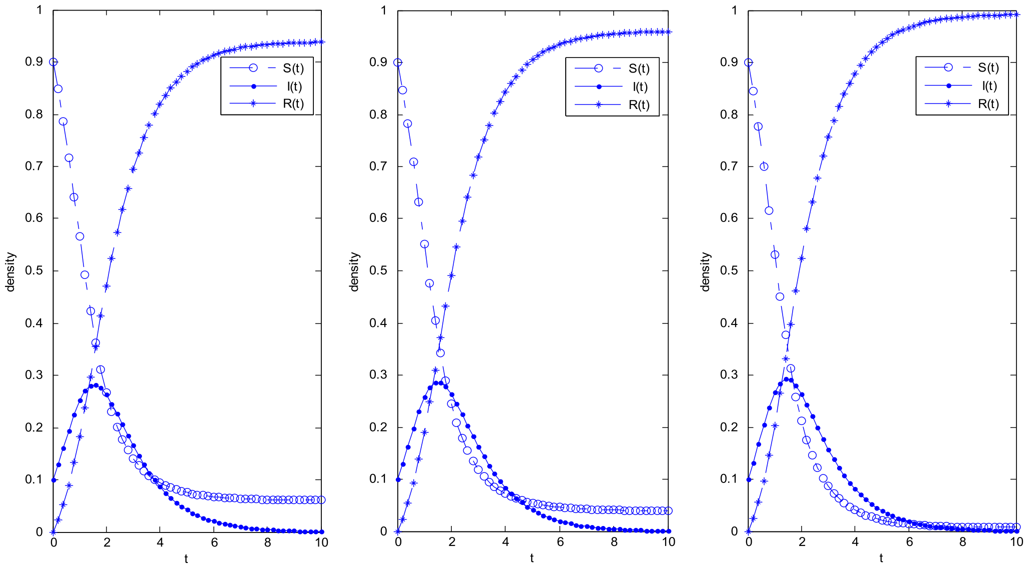

Fig. 7. The densities of different individuals changing over time. $\beta_2 = 0.3, 0.5, 0.8$ (left to right).

communication decrease, so as to more individuals transform from infected state to removed state. With the stopping of spread, three types of nodes will be stable. In the end, most individuals in the state of removed, only a minority in susceptible state, and almost nobody in infected state.

5. Conclusions

In this paper, we do some research on knowledge dissemination model on CLN. Based on our previous study on cooperative learning network, referring to the SIS and SIR model, we introduce two knowledge dissemination models. One is SISL model considering students' forgetting and leaders' inspiration, and the other is SIRL model considering students' interest in contents and the leaders' inspiration. Different from other studies on cooperative learning, we study on the knowledge dissemination dynamic mechanism of CLN. Using complex network transmission dynamics theory, the threshold of knowledge dissemination of cooperative learning network is analyzed. Finally, we discuss the two models by numerical simulation.

Research and numerical simulation results show that the SISL model and the SIRL model can effectively explain the dynamic behavior of knowledge dissemination on CLN. At the same time, it provides theoretical guidance for the development of cooperative learning. In cooperative learning, it is important to ensure that knowledge dissemination rate is larger than the threshold. The students' zone of proximal development and existing cognitive should be ascertained to confirm the difficulty value of the cooperative learning content. Leaders should stimulate partners' interest in communicating and studying, inspire them timely to make sure knowledge can be transmitted in a large scale. As for teachers, the organizer, should change the teaching strategy, decompose teaching content, reduce the knowledge difficulty to improve knowledge dissemination rate λ on CLN, in order to make the cooperative learning efficiency. And also, the significant influence of leaders among students should pay sufficient attention to.

This study also makes contributions to the development of complex network transmission dynamics. The models present in this paper also pave the ground for the study of rumor diffusion and disease spreading on complex networks. In the future, we will study the influence of special nodes on knowledge dissemination on CLN and other related issues.

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