

Social Recommendation: A Review

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Abstract Recommender systems play an important role in helping online users find relevant information by suggesting information of potential interest to them. Due to the potential value of social relations in recommender systems, social recommendation has attracted increasing attention in recent years. In this paper, we present a review of existing recommender systems and discuss some research directions. We begin by giving formal definitions of social recommendation and discuss the unique property of social recommendation and its implications compared with those of traditional recommender systems. Then, we classify existing social recommender systems into memory-based social recommender systems and model-based social recommender systems, according to the basic models adopted to build the systems, and review representative systems for each category. We also present some key findings from both positive and negative experiences in building social recommender systems, and research directions to improve social recommendation capabilities.

Keywords Social Recommendation · Social Recommender Systems · Recommender Systems · Social Network Analysis · Social Media

1 Introduction

With the development of the World Wide Web, information has increased at an unprecedented rate and the information overload problem has become increasingly severe for online users. For example, when we want to buy a computer and

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search “computer” in Amazon, it returns 11,100,260 products¹. Recommender systems, which attempt to tackle the information overload problem by suggesting information that is of potential interest to online users, have become important and popular [97, 33, 75, 58, 68]. For information customers, good recommendations allow them to quickly find relevant information buried in a large amount of irrelevant information. For information providers, recommender systems not only help determine which information to offer to individual consumers, but also improve consumer loyalty because consumers tend to return to the sites that best serve their needs [99]. Such systems are widely implemented in various domains including, product recommendation on Amazon² and movie recommendation on Netflix³.

Recommender systems became an independent research area in the mid-1990s [3] and have attracted much attention from multiple disciplines, such as mathematics, physics, psychology, and computer science [26]. For example, the winners of the Netflix prize contest, one of the most famous competitions for recommendation, consist of psychologists, computer scientists, and physicists⁴. Many techniques are used to build recommender systems, which can be generally classified into content-based methods, collaborative filtering (CF) based methods, and hybrid methods [3]. Content-based methods, rooted in information retrieval [7] and information filtering research [9], recommend items similar to the ones the user preferred in the past; CF-based methods predict user interests directly by uncovering complex and unexpected patterns from a user’s past behaviors and recommend items to a user from other users with similar interests and preferences in the past [57, 105]. Hybrid methods combine content-based and CF-based methods. We will give a brief review about techniques to build recommender systems in Section 2.

The increasing popularity of social media greatly enriches people’s social activities with their families, friends, and colleagues, which produces rich social relations such as friendships in Facebook⁵, following relations in Twitter⁶ and trust relations in Epinions⁷. Online social relations provide a different way for individuals to communicate digitally and allow online users to share ideas and opinions with their connected users. A user’s preference is similar to or influenced by their socially connected friends and the rationale behind the assumption can be explained by social correlation theories such as homophily [77] and social influence [71]. Homophily indicates that users with similar preferences are more likely to be connected, and social influence reveals that users who are connected are more likely to have similar preferences. Analogous to the fact that users in the physical world are likely to seek suggestions from their friends before making a purchase decision and users’ friends consistently provide good recommendations [103], social relations can be potentially exploited to improve the performance of online recommender systems [33, 67, 49, 68].

¹ http://www.amazon.com/s/ref=nb_sb_noss_1?url=search-alias%3Daps&field-keywords=computer

² <http://www.amazon.com/>

³ <http://www.netflix.com>

⁴ http://en.wikipedia.org/wiki/Netflix_Prize

⁵ <https://www.facebook.com/>

⁶ <https://www.twitter.com/>

⁷ <http://www.epinions.com>

In this article, we present a review of existing social recommender systems and discuss some research directions that can improve the capabilities of social recommendation. The motivation of this article is multi-fold:

- Social recommendation has been developed for several years and still there is no agreement in literature on the definition of social recommendation. These clarifications are necessary for people to gain an awareness of social recommender systems. For example, Kaifu Lee, CEO at Innovation Works, recommended a particular brand of frozen dessert maker through Chinese tweet Sina Weibo platform and a few hours later, Taobao (China’s eBay) had hundreds of sellers of the item and thousands of the machines were sold within a day. Subsequently, he wrote an article in LinkedIn entitled “The Power of Social Recommendation”, but there are many doubts about whether this kind of recommendation can be called social recommendation⁸.
- Social relations provide an independent source for recommendation; various approaches are proposed to build social recommender systems such as trust ensemble [70], trust propagation [49], and social regularization [68]. A classification of existing social recommender systems can help users gain a quick understanding of many social recommender systems. A review of existing social recommender systems will let users familiarize themselves with the state-of-the-art social recommender systems.
- On the one hand, there is recent work reporting significant recommendation performance improvement for social recommender systems [33, 67, 49, 68, 52]. On the other hand, there are also unsuccessful attempts at applying social recommendation [15, 30, 92, 48]. For example, IBM’s Black Friday report says Twitter delivered 0 percent of referral traffic and Facebook sent just 0.68 percent [48]. It is important to discuss key findings from both positive and negative experiences to seek a deeper understanding and further development of social recommender systems.
- Social recommendation is still in the early stages of development, and there are many challenging issues needing further investigation. It is necessary to discuss some research directions that can improve social recommendation capabilities and make social recommendation applicable to an even broader range of applications.

Our major contributions are summarized below:

- We give narrow and broad definitions of social recommendation to cover most existing definitions of social recommendation in the literature and discuss the unique property of social recommender systems and its implications compared with traditional recommender systems;
- We present a classification of social recommender systems according to the basic models to build social recommender systems, and review representative systems for each category in detail;
- We summarize key findings from some positive and negative experiences in applying social recommender systems;
- We discuss some research directions to improve recommendation capabilities including exploiting the heterogeneity of social networks and weak dependence

⁸ <http://www.linkedin.com/today/post/article/20121203134252-416648-the-power-of-social-recommendation>

connections, segmenting users and items, considering the temporal information of rating and social information, understanding the role of negative relations, and integrating cross-media social networks.

The rest of this article is organized as follows. We review existing recommender systems including content-based methods, collaborative filtering based methods and hybrid methods in Section 2. In Section 3, we formally define social recommendation, discuss the unique property of social recommendation, classify and review existing social recommender systems, and discuss some key findings from both positive and negative experiences in applying social recommender systems. In Section 4, we discuss possible research directions for improvement of social recommendation. The article is summarized in Section 5.

2 Traditional Recommender Systems

In a typical recommender system, there is a set of users and a set of items. Let $\mathbf{u} = \{u_1, u_2, \dots, u_n\}$ and $\mathbf{v} = \{v_1, v_2, \dots, v_m\}$ be the sets of users and items respectively, where n is the number of users and m is the number of items. A user u_i rates a subset of items with some scores. We use $\mathbf{R} \in \mathbb{R}^{n \times m}$ to denote the rating matrix where \mathbf{R}_{ij} is the rating score if u_i gives a rating to v_j , otherwise we employ the symbol “?” to denote the unknown rating. Usually the rating matrix is very sparse, suggesting that there are lots of unknown ratings in \mathbf{R} . For example, the density of the rating matrix in commercial recommender systems is often less than 1% [97]. If item v_j has attributes, we use $\mathbf{x}_j \in \mathbb{R}^\ell$ to represent v_j where ℓ is the number of attributes. The task of recommender systems is to predict the rating for user u_i on a non-rated item v_j or to recommend some items for given users, i.e., to predict missing values in \mathbf{R} based on known ratings.

Since recommender systems first became an independent research area in the mid-1990s, there have been many recommender systems proposed, which can be generally grouped into content based, collaborative filtering (CF) based and hybrid recommender systems [95, 51]. In the following subsection, we will briefly review each category with its representative systems.

2.1 Content Based Recommender Systems

Content based recommender systems have their roots in information retrieval [7] and information filtering research [9]. They recommend items similar to the ones that the user has preferred in the past. Most existing content based recommender systems focus on recommending items with textual information such as news, books and documents. The content in these systems is usually described with keywords [8, 90] and the informativeness of a keyword to a document is often measured by TFIDF weight [121]. TF weight of a keyword to a document denotes the frequency of the keyword in the document, while IDF weight of a keyword is defined as the inverse document frequency of the keyword.

Let x_{jk} be the TFIDF weight of the k -th keyword in v_j and the content of v_j can be represented as $\mathbf{x}_j = (x_{j1}, x_{j2}, \dots, x_{j\ell})$. With these representations, content based recommender systems recommend items to a user which are similar to items the user liked in the past [90]. In particular, various candidate items are

compared with items previously rated by the user. A similarity measure such as a cosine similarity measure is adopted to score these candidate items. Besides the traditional heuristics based information retrieval methods, there are also content based recommender systems that use other techniques such as various classification and clustering algorithms [90, 82].

As noticed in [8, 3], content based recommender systems have several limitations: (1) *limited content analysis* - these systems are difficult to apply to domains which have an inherent problem with automatic feature extraction such as multimedia data; (2) *over-specialization* - items recommended to a user are limited to those similar to items the user already rated; (3) *new user problem* - to let content based recommender systems understand a user's preference, the user has to rate a sufficient number of items, hence, content based recommender systems fail to recommend items for users with few or no ratings.

2.2 Collaborative Filtering Based Recommender Systems

Collaborative filtering is one of the most popular techniques to build recommender systems [97, 57, 105]. It can predict user interests directly by uncovering complex and unexpected patterns from a user's past behaviors such as product ratings without any domain knowledge [57, 105]. The underlying assumption of collaborative filtering based recommender systems is that if users have agreed with each other in the past, they are more likely to agree with each other in the future than to agree with randomly chosen users. Existing collaborative filtering methods can be categorized into memory-based methods and model-based methods [36, 10, 105].

2.2.1 Memory based Collaborative Filtering

Memory based methods use either the whole user-item matrix or a sample to generate a prediction [105], which can be further divided into user-oriented methods [44, 10] and item-oriented methods [97, 53]. User-oriented methods predict an unknown rating from a user on an item as the weighted average of all the ratings from her similar users on the item, while item-oriented methods predict the rating from a user on an item based on the average ratings of similar items by the same user. The key problems a memory-based CF method has to solve are computing similarity and aggregating ratings. User-oriented methods and item-oriented methods can leverage similar techniques to address these two problems; thus, we use user-oriented methods as examples to illustrate representative methods for computing similarity and aggregating ratings.

Computing similarity for user-oriented methods : Computing user-user similarity is a critical step for user-oriented methods. There are many techniques proposed to tackle this problem such as Pearson Correlation Coefficient [94], Cosine similarity [17], and probability-based similarity [53, 22], among which Pearson Correlation Coefficient and Cosine similarity are the most widely used ones.

- *Pearson Correlation Coefficient* : Each user is presented as a vector of ratings. For example, the i -th user will be denoted as \mathbf{R}_i . Pearson Correlation Coefficient measures the extent to which two variables linearly relate with each

other [94]. Pearson Correlation Coefficient between u_i and u_j can be calculated as

$$\mathbf{S}_{ij} = \frac{\sum_{k \in I} (R_{ik} - \bar{R}_i) \cdot (R_{jk} - \bar{R}_j)}{\sqrt{\sum_{k \in I} (R_{ik} - \bar{R}_i)^2} \sqrt{\sum_{k \in I} (R_{jk} - \bar{R}_j)^2}}, \quad (1)$$

where I denotes the set of items rated by both u_i and u_j and $\mathbf{S} \in \mathbb{R}^{n \times n}$ represents the user-user similarity matrix. \bar{R}_i denotes the average rate of u_i .

- *Cosine similarity* : Cosine similarity computes the cosine of the angle formed by the rating vectors [17]. For example, the cosine similarity between u_i and u_j can be calculated as,

$$\mathbf{S}_{ij} = \frac{\sum_{k \in I} R_{ik} \cdot R_{jk}}{\sqrt{\sum_{k \in I} R_{ik}^2} \sqrt{\sum_{k \in I} R_{jk}^2}}, \quad (2)$$

Aggregating ratings for user-oriented methods : After obtaining a user-user similarity matrix, user-oriented methods will predict a missing rating for a given user by aggregating the ratings of users similar to her. Various aggregating strategies have been proposed [94, 97, 53] and the most widely used strategy is weighted average rating as

$$\hat{\mathbf{R}}_{ij} = \bar{\mathbf{R}}_i + \frac{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} (\mathbf{R}_{kj} - \bar{\mathbf{R}}_k)}{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik}}, \quad (3)$$

where \mathcal{N}_i is the set of users who have rated the j -th item v_j .

2.2.2 Model based Collaborative Filtering

Model-based methods assume a model to generate the ratings and apply data mining and machine learning techniques to find patterns from training data [124, 105], which can be used to make predictions for unknown ratings. Compared to memory based CF, Model-based CF has a more holistic goal to uncover latent factors that explain observed ratings [124]. Well-known model-based methods include Bayesian belief net CF models [10, 81], clustering CF models [115, 11], random walk based methods [124, 47] and factorization based CF models [37, 45, 89, 57, 96]. Factorization based CF methods [57, 96] are very competitive if not the best and are widely adopted to build recommender systems [12].

Factorization based CF models assume that a few latent patterns influence user rating behaviors and perform a low-rank matrix factorization on the user-item rating matrix. Let $\mathbf{u}_i \in \mathbb{R}^K$ and $\mathbf{v}_j \in \mathbb{R}^K$ be the user preference vector for u_i and item characteristic vector for v_j respectively, where K is the number of latent factors. Factorization based collaborative filtering models solve the following problem

$$\min_{\mathbf{U}, \mathbf{V}} \sum_{i=1}^n \sum_{j=1}^m \mathbf{W}_{ij} (\mathbf{R}_{ij} - \mathbf{U}_i \mathbf{V}_j^\top)^2 + \alpha (\|\mathbf{U}\|_F^2 + \|\mathbf{V}\|_F^2), \quad (4)$$

where $\mathbf{U} = [\mathbf{U}_1^\top, \mathbf{U}_2^\top, \dots, \mathbf{U}_n^\top]^\top \in \mathbb{R}^{n \times K}$ and $\mathbf{V} = [\mathbf{V}_1^\top, \mathbf{V}_2^\top, \dots, \mathbf{V}_m^\top]^\top \in \mathbb{R}^{m \times K}$. K is the number of latent factors (patterns),

which is usually determined via cross-validation. The term $\alpha(\|\mathbf{U}\|_F^2 + \|\mathbf{V}\|_F^2)$ is introduced to avoid over-fitting, controlled by the parameter α . $\mathbf{W} \in \mathbb{R}^{n \times m}$ is a weight matrix where \mathbf{W}_{ij} is the weight for the rating for u_i to v_j . A common way to set \mathbf{W} is $\mathbf{W}_{ij} = 1$ if $\mathbf{R}_{ij} \neq 0$. The weight matrix \mathbf{W} can also be used to handle the implicit feedback and encode side information such as user click behaviors [28], similarity between users and items [88, 62], quality of reviews [93] and user reputation [112].

Collaborative filtering based recommender systems can overcome some of the shortcomings of content based recommender systems. For example, CF based systems use rating information; hence, they are domain-independent and can recommend any items. However, CF based systems have their own limitations such as the cold-start problem (new items or new users) and the data sparsity problem [3, 105].

2.3 Hybrid Recommender Systems

To avoid certain limitations of content and collaborative filtering systems, hybrid approaches combine content and CF based methods. Various strategies are proposed to combine content and CF based methods, which can be roughly classified into three categories [3]. We will briefly review each category with representative systems.

Combining different recommenders: under this strategy, content and CF based methods are implemented separately and then their predictions are combined to obtain the final recommendation. Various ways are proposed, such as a voting scheme [91] and a linear combination of ratings [18], to combine predictions from content and CF based methods.

Adding content based characteristics to CF models: systems with this strategy use content based profiles and uncommonly rated items to calculate user-user similarities. These systems can overcome some sparsity-related problems of CF methods and recommend items directly when item scores highly against the user's profiles [91, 38].

Adding CF based characteristics to content based models: the most popular approach under this strategy is to use a dimensionality reduction technique on the content profile matrix. For example, in [104] latent semantic indexing is used to create a collaborative view of a set of user profiles, which improves recommendation performance compared to pure content based approaches.

3 Social Recommendation

One of the earliest social recommender systems appeared in 1997 [54]. Myriads of social media services such as Facebook and Twitter have emerged in recent years to allow people to easily communicate and express themselves conveniently. The pervasive use of social media generates social information at an unprecedented rate. For example, Facebook, the largest social networking site produces 35,000,000,000 online friendships [41] and the most popular user on Twitter, the largest microblogging site, has 37,974,138 followers⁹. The rapid development of social media has

⁹ <http://twitaholic.com/>

greatly accelerated the development of social recommender systems [55,41]. In this section, we will first give the definitions of social recommendation, discuss the opportunities for social recommendation systems compared to traditional recommender systems, classify and review existing social recommender systems, and finally summarize some key findings from positive and negative experiences in applying social recommender systems.

3.1 Definitions of Social Recommendation

Social recommendation has been studied since 1997 [54] and has attracted increasing attention with the growing popularity of social media [55,41], however, it has no commonly accepted definition. In this subsection, we give narrow and broad definitions of social recommendation based on existing definitions in the literature.

A narrow definition of social recommendation is any recommendation with online social relations as an additional input, i.e., augmenting an existing recommendation engine with additional social signals. Social relations can be trust relations, friendships, memberships or following relations. A tutorial with the title “Introduction to Social Recommendation” at the 19th international world wide web conference (WWW2010) followed this narrow definition [55]. In this definition, social recommender systems assume that users are correlated when they establish social relations [72,75,67]. For example, users’ preferences are likely to be similar to or influenced by their connected friends. Under this assumption, social recommendation leverages user correlations implied by social relations to improve the performance of recommendation. Representative systems under this definition include TidalTrust [34], MoleTrust [75,118], SoRec [70], SocialMF [49], SoReg [68] and LOCALBAL [112].

Another tutorial titled “Social Recommender Systems” at the 20th international world wide web conference (WWW2011) adopted a broad definition of social recommendation where social recommender systems are defined as any recommender systems that target social media domains [41]. The definition covers recommender systems recommending any objects in social media domains such as items (the focus of recommender systems under the narrow definition), tags [102], people [13,5], and communities [14]. The sources they use are not limited to online social relations but include all kinds of available social media data such as social tagging [69], user interactions [52] and user click behaviors [78].

With narrow and broad definitions, let us go back to examine the example of Kaifu Lee’s recommendation. Since the recommendation happens in social media domains, Kaifu Lee’s recommendation is a sort of social recommendation under the broad definition. However, the sources mentioned in this recommendation are not limited to social networks, and this recommendation does not satisfy the narrow definition.

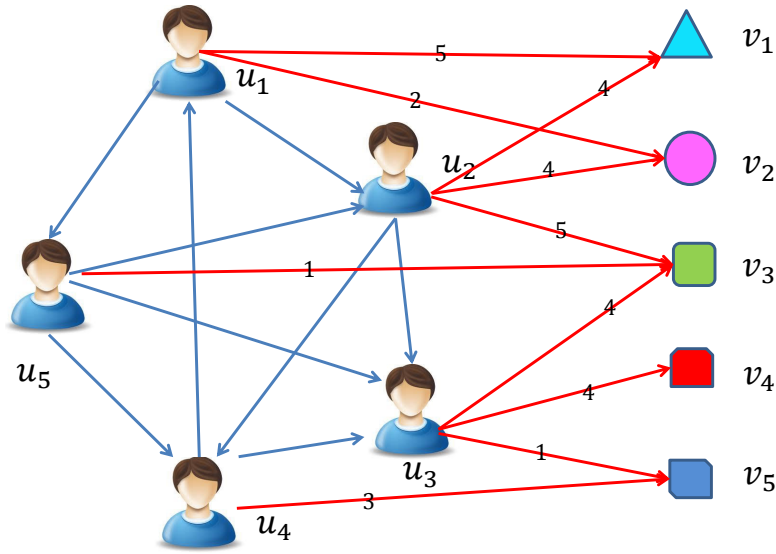
In this article, we focus on social recommender systems under the narrow definition. The reason is two fold. First, similar techniques can be applied to implementing social recommender systems under both definitions. Second, the narrow definition is straightforward and helps readers gain a deeper understanding of state-of-the-art social recommender systems.

3.2 A Unique Feature of Social Recommendation and Its Implications

The increasing popularity of social media allows online users to participate in online activities which produce rich social relations. In social recommender systems, in addition to the rating information \mathbf{R} , users can connect to each other. Let $\mathbf{T} \in \mathbb{R}^{n \times n}$ denote user-user social relations where $\mathbf{T}_{ij} = 1$ if u_j connects to u_i and zero otherwise. The availability of social relations \mathbf{T} provides an independent source for recommendation and this unique property of social recommendation brings about new opportunities.

First, traditional recommender systems assume that users are independent and identically distributed (known as the *i.i.d.* assumption). However, online users are inherently connected via various types of relations such as friendships and trust relations. Figure 1 shows a simple example of connected users in social media, and Figures 1(b) and 1(c) demonstrate its two data representations for traditional recommender systems and social recommender systems, respectively. In addition to the rating matrix in traditional recommender systems, users in social recommender systems are connected, providing social information. Since they are connected, users are correlated rather than independent and identically distributed. For example, [120] finds that users with following relations are more likely to share similar interests in topics than two randomly chosen users, and [109] shows that users with trust relations are more likely to have similar preferences in item ratings. This phenomenon is observed in most online social networks and can be explained by social correlation theories such as homophily [77] and social influence [71]. Note that one user is more likely to have similar interests with her connected users than those randomly chosen users, which does not indicate that her connected users are equivalent to her most similar users w.r.t. rating information. Assume that u_i connects to d users. We use C_i and S_i with the size d to denote sets of the connected users and the top- d similar users of u_i , respectively. In [108], the authors show that the overlap between C_i and S_i is less than 10%, which is consistent with the observation in [19]. If we change our perspective and consider connections as similarity measurements, social information provides similarity evidence and C_i is the list of the similar users w.r.t. social information [43]. Then the above observation can be explained by the key finding in [42] - lists of similar users obtained by different sources are found to be highly different from each other. It also suggests that an aggregation of rating and social information may be valuable. In addition to similarity evidence, social information also provides another unique evidence, i.e., familiarity evidence, which is very importance in recommendation since in the physical world, we usually ask suggestions from our friends who are familiar with our tastes [43,42]. Both similarity and familiarity evidence from social information indicate that social networks contain complementary information to rating information and provide an independent source of information about online users. Exploiting social relations can potentially improve recommendation performance.

Second, besides recommender systems, social recommendation involves the independent research field of social network analysis [119, 100, 101, 20]. Social network analysis (SNA) is the methodical analysis of social networks and has emerged as a key technique in modern sociology. It has gained a significant following in various disciplines such as communication studies, economics, geography, and computer science; consumer tools for it are now commonly available [101]. Social recommender systems can take advantage of research results from social network anal-



(a) Connected Users

	v_1	v_2	v_3	v_4	v_5
u_1	5	?	2	?	?
u_2	4	4	5	?	?
u_3	?	?	4	4	1
u_4	?	?	?	?	3
u_5	?	?	1	?	?

(b) Traditional Recommender Systems

	v_1	v_2	v_3	v_4	v_5		u_1	u_2	u_3	u_4	u_5
u_1	5	?	2	?	?	u_1	0	1	0	0	1
u_2	4	4	5	?	?	u_2	0	0	1	1	0
u_3	?	?	4	4	1	u_3	0	0	0	0	0
u_4	?	?	?	?	3	u_4	1	0	1	0	0
u_5	?	?	1	?	?	u_5	0	1	1	1	0

(c) Social Recommender Systems

Fig. 1 A Simple Example of Connected Users

ysis such as social correlation theories [77, 71], status analysis [87, 56], community detection [60, 114], online trust [72, 110] and heterogeneous networks [106] for recommendation. Research achievements from social network analysis pave ways to exploit social relations and can be applied to building social recommender systems.

3.3 Existing Social Recommender Systems

As mentioned earlier, collaborative filtering is widely adopted to build recommender systems, and most existing social recommender systems are based on CF techniques. Therefore, our discussion in this article is focused on CF based social recommender systems. Social recommendation has two inputs, i.e., rating information and social information, as shown in Figure 1(c). Most existing social recommender systems choose CF models as their basic models to build systems and propose approaches to capture social information based on results from social network analysis. Therefore, a general CF based social recommendation framework contains two parts: (1) a basic CF model and (2) a social information model, which can be formally stated as

$$\begin{aligned} \text{a social recommendation CF model} = \\ \text{a basic CF model} + \text{a social information model} \end{aligned} \quad (5)$$

The basic CF model in a social recommendation CF model creates a way to classify social recommender systems. Following the classification of CF based recommender systems, we classify social recommender systems into two major categories according to their basic CF models: memory based social recommender systems and model based social recommender systems.

3.3.1 Memory based Social Recommender Systems

Memory based social recommender systems use memory based CF models, especially user-oriented methods as their basic models. A missing rating for a given user is aggregated from the ratings of users correlated to her, denoted as N^+ . For a given user, traditional user-oriented methods use similar users N , while memory based social recommender systems use correlated users N^+ obtained from both rating information and social information. Social recommender systems in this category usually follow two steps. First, they obtain the correlated users $N^+(i)$ for a given user u_i , and second is the classical last step of memory based CF methods - aggregating ratings from the correlated users obtained by the first step for missing ratings. Different social recommender systems in this category use different approaches to obtain correlated users N^+ in the first step; next, we will present details about some representative approaches.

Social based Weight Mean [117, 118]: For a given u_i , this strategy simply considers a u_i 's directly connected users $\mathcal{F}(i)$ as the set of her correlated users $N^+(i)$,

$$N^+(i) = \{u_j | \mathbf{T}(i, j) = 1\} \quad (6)$$

TidalTrust [34]: Users in this system are connected via trust relations. The authors design a metric TidalTrust to estimate trust values among users based

on the following two observations: (1) shorter propagation paths produce more accurate trust estimates; (2) paths with higher trust values create better results. To estimate trust values among users, TidalTrust performs the following steps,

- searching a shortest path from the source user to raters and setting the shortest path length as the path depth of the algorithm;
- computing trust value from the source user to a rater at the given depth. For a pair of users u_i and u_k who are not directly connected, a trust value is aggregated from the trust value from u_i 's direct neighbors to u_j , weighted by the direct trust values from u_i to her direct neighbors as

$$\mathbf{S}_{ij} = \frac{\sum_{u_k \in \mathcal{F}(i)} \mathbf{S}_{ik} \mathbf{S}_{kj}}{\sum_{u_k \in \mathcal{F}(i)} \mathbf{S}_{ik}} \quad (7)$$

- after trust values \mathbf{S} are calculated, $N^+(i)$ is defined as the set of users whose trust values with u_i exceeds a given threshold τ ,

$$N^+(i) = \{u_j | \mathbf{S}_{ij} \geq \tau\} \quad (8)$$

MoleTrust [73–75]: A new trust metric, MoleTrust, is proposed and consists of two major steps. First, cycles in trust networks are removed. To obtain trust values, a large number of trust propagations have to be executed. Therefore, removing trust cycles beforehand from trust networks can significantly speed up the proposed algorithm because every user only needs to be visited once to infer trust values. With this operation, the original trust network is transformed into a directed acyclic graph. Second, trust values are calculated based on the obtained directed acyclic graph by performing a simple graph random walk: first the trust of the users at 1-hop away is computed, then the trust of the users at 2-hop away, etc. After trust values are computed, MoleTrust defines users within *maximum-depth* and have rated the target item as correlated users N^+ , where *maximum-depth* is a predefined parameter.

Although MoleTrust has similar operations to TidalTrust, they are very different in two aspects. First, the definitions of correlated users in these two systems are different. TidalTrust adds a user u_k to $N^+(i)$ only if she is on a shortest path from u_i with respect to a target item, while MoleTrust considers all users who have rated the target item and that can be reached through a direct or propagated trust relation within *maximum-depth* as $N^+(i)$. Second, MoleTrust needs a predefined trust threshold to determine users who will be considered in the rating aggregating process, while TidalTrust determines the trust threshold automatically, which denotes the path strength (the minimum trust rating on a path).

TrustWalker [49]: The intuition of this system is from two key observations. First, a user's social network has little overlap with users similar to her [19], suggesting that social information provides an independent source of information. Second, ratings from strongly trusted friends on similar items are more reliable than ratings from weakly trusted neighbors on the same target item. The first observation indicates the importance of trust-based approaches while the second observation suggests the capability of item-oriented approaches. To take advantage of both approaches, TrustWalker proposes a random walk model to combine trust based and user oriented approaches into a coherent framework. It queries a user's direct and indirect friends' ratings for the target item as well as similar items by performing random walk in online social networks. For example, to obtain a rating

for u_i to v_j . Suppose that we are at a certain node u_k . Then TrustWalker works as follows at each step of a random walk: if u_k rated v_j , then it stops the random walk and returns \mathbf{R}_{kj} as the result of random walk; otherwise, it has two choices - (1) it also stops random walk and randomly selects one of the items v_k similar to v_j rated by u_i and returns \mathbf{R}_{ik} , or (2) it continues random walk and walks to author user u_k in u_i 's trust networks.

TrustWalker employs the Pearson Correlation Coefficient of ratings expressed for items to calculate item-item similarity. Since values of Pearson Correlation Coefficient are in the range of $[-1, 1]$, only items with positive correlation with the target item are considered. The similarity between v_i and v_j is then computed as,

$$\text{sim}(i, j) = \frac{1}{1 + e^{-\frac{N_{ij}}{2}}} \times PCC(i, j) \quad (9)$$

where N_{ij} is the number of users who rated both v_i and v_j , and $PCC(i, j)$ is Pearson Correlation Coefficient of v_i and v_j .

3.3.2 Model based Social Recommender Systems

Model-based social recommender systems choose model-based CF methods as their basic models. Matrix factorization techniques are widely used in model based CF methods. There are several nice properties of these matrix factorization techniques [25, 79]: (1) many optimization methods such as gradient based methods can be applied to find a well-worked optimal solution, scaled to thousands of users with millions of trust relations; (2) matrix factorization has a nice probabilistic interpretation with Gaussian noise; (3) it is very flexible and allows us to include prior knowledge. Most existing social recommender systems in this category are based on matrix factorization [67, 65, 126, 50, 116, 68, 6, 123, 107, 110, 111, 86, 46, 109]. The common rationale behind these methods is that users' preferences are similar to or influenced by users whom they are socially connected to. However, the low cost of social relation formation can lead to social relations with heterogeneous strengths (e.g., weak ties and strong ties mixed together) [122]. Since users with strong ties are more likely to share similar tastes than those with weak ties, treating all social relations equally is likely to lead to degradation in recommendation performance. Therefore for each social relation, these methods associate a strength, which is usually calculated by rating similarity in existing social recommender systems. For example, when we choose cosine similarity, if u_i and u_k are connected, \mathbf{S}_{ik} is calculated as the cosine similarity between the rating vectors of u_i and u_k , otherwise we set \mathbf{S}_{ik} to 0. Therefore, the strength between u_i and u_k \mathbf{S}_{ik} can be formally defined as

$$\mathbf{S}_{ik} = \begin{cases} \frac{\sum_j \mathbf{R}_{ij} \cdot \mathbf{R}_{kj}}{\sqrt{\sum_j \mathbf{R}_{ij}^2} \sqrt{\sum_j \mathbf{R}_{kj}^2}} & \text{when } u_i \text{ and } u_k \text{ are connected,} \\ 0 & \text{otherwise.} \end{cases} \quad (10)$$

Unlike traditional matrix factorization based recommender systems, social recommender systems in this category can take advantage of social information, and a unified framework can be stated as,

$$\min_{\mathbf{U}, \mathbf{V}, \Omega} \|\mathbf{W} \odot (\mathbf{R} - \mathbf{U}^\top \mathbf{V})\|_F^2 + \alpha \text{Social}(\mathbf{T}, \mathbf{S}, \Omega) + \lambda(\|\mathbf{U}\|_F^2 + \|\mathbf{V}\|_F^2 + \|\Omega\|_F^2), \quad (11)$$

where $\text{Social}(\mathbf{T}, \mathbf{S}, \Omega)$ is the term introduced to capture social information based on social network analysis and Ω is the set of parameters learned from social information. α is employed to control the contributions from social information. \mathbf{W} controls the weights of known ratings in the learning process. According to different definitions of $\text{Social}(\mathbf{T}, \mathbf{S}, \Omega)$, we further divide social recommender systems in this category into three groups: co-factorization methods, ensemble methods, and regularization methods. Next, we will review some representative systems in detail for each group.

Co-factorization methods [67, 109]: The underlying assumption of systems in this group is that the i -th user u_i should share the same user preference vector \mathbf{u}_i in the rating space (rating information) and the social space (social information). Social recommender systems in this group perform a co-factorization in the user-item matrix and the user-user social relation matrix by sharing the same user preference latent factor. SoRec [67] and LOCABAL [109] are two representative systems in this group.

SoRec [67]: SoRec defines $\text{Social}(\mathbf{T}, \mathbf{S}, \Omega)$ as

$$\min \sum_{i=1}^n \sum_{u_k \in \mathcal{N}_i} (\mathbf{S}_{ik} - \mathbf{u}_i^\top \mathbf{z}_k)^2, \quad (12)$$

where \mathcal{N}_i is the set of users directly connected to u_i and $\mathbf{Z} = \{\mathbf{z}_1, \mathbf{z}_2, \dots, \mathbf{z}_n\} \in \mathbb{R}^{K \times n}$ is the factor-specific latent feature matrix. With this term, the user preference matrix \mathbf{U} is learned from both rating information and social information by solving the following optimization problem:

$$\min_{\mathbf{U}, \mathbf{V}, \mathbf{Z}} \|\mathbf{W} \odot (\mathbf{R} - \mathbf{U}^\top \mathbf{V})\|_F^2 + \alpha \sum_{i=1}^n \sum_{u_k \in \mathcal{N}_i} (\mathbf{S}_{ik} - \mathbf{u}_i^\top \mathbf{z}_k)^2 + \lambda(\|\mathbf{U}\|_F^2 + \|\mathbf{V}\|_F^2 + \|\mathbf{Z}\|_F^2) \quad (13)$$

LOCABAL [109]: LOCABAL defines $\text{Social}(\mathbf{T}, \mathbf{S}, \Omega)$ as

$$\min \sum_{i=1}^n \sum_{u_k \in \mathcal{N}_i} (\mathbf{S}_{ik} - \mathbf{u}_i^\top \mathbf{H} \mathbf{u}_k)^2. \quad (14)$$

LOCABAL is different from SoRec and it is based on social correlation theories where the user preferences of two socially connected users are correlated via the correlation matrix \mathbf{H} . In Eq. (14), for two socially connected users u_i and u_k , their preference vectors \mathbf{u}_i and \mathbf{u}_k are correlated through \mathbf{H} , which is controlled by their social strength \mathbf{S}_{ik} where $\mathbf{H} \in \mathbb{R}^{K \times K}$ is the matrix to capture the user preference correlation. A large value of \mathbf{S}_{ik} , i.e., u_i and u_k with a strong connection, indicates that their preferences \mathbf{u}_i and \mathbf{u}_k should be tightly correlated via \mathbf{H} , while a small value of \mathbf{S}_{ik} indicates that \mathbf{u}_i and \mathbf{u}_k should be loosely correlated. $\text{Social}(\mathbf{T}, \mathbf{S}, \Omega)$ can be applied to both directed and undirected social networks via the correlation

matrix \mathbf{H} . For a directed social network, the learned matrix \mathbf{H} is asymmetric, while for an undirected social network, the learned matrix \mathbf{H} is symmetric.

With the definition of $Social(\mathbf{T}, \mathbf{S}, \Omega)$, LOCABAL solves the following optimization problem,

$$\begin{aligned} \min_{\mathbf{U}, \mathbf{V}, \mathbf{Z}} \quad & \|\mathbf{W} \odot (\mathbf{R} - \mathbf{U}^\top \mathbf{V})\|_F^2 + \alpha \sum_{i=1}^n \sum_{u_k \in \mathcal{N}_i} (\mathbf{S}_{ik} - \mathbf{u}_i^\top \mathbf{H} \mathbf{u}_k)^2 \\ & + \lambda (\|\mathbf{U}\|_F^2 + \|\mathbf{V}\|_F^2 + \|\mathbf{H}\|_F^2) \end{aligned} \quad (15)$$

Note that LOCABAL and SeRoc have the same form by further factorizing \mathbf{z}_k into $\mathbf{H} \mathbf{u}_k$. After obtaining factorized factors of the matrix \mathbf{S} , we can use the factors to reconstruct \mathbf{S} . For example, for LOCABAL, after learning \mathbf{U} and \mathbf{H} , we can reconstruct \mathbf{S} as $\hat{\mathbf{S}} = \mathbf{U}^\top \mathbf{H} \mathbf{U}$. The reconstructed matrix $\hat{\mathbf{S}}$ can be used to perform social relation prediction [80, 109]. Therefore, one advantage of approaches in this group is that they jointly perform recommendation and social relation prediction.

Ensemble methods [65, 110]: The basic idea of ensemble methods is that users and their social networks should have similar ratings on items, and a missing rating for a given user is predicted as a linear combination of ratings from the user and her social network. We give details about two representative systems below.

STE [65]: The rating from the i -th user u_i to the j -th item v_j will be estimated by STE as

$$\hat{\mathbf{R}}_{ij} = \mathbf{u}_i^\top \mathbf{v}_j + \beta \sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{u}_k^\top \mathbf{v}_j, \quad (16)$$

where $\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{u}_k^\top \mathbf{v}_j$ is a weighted sum of the predicted ratings for v_j from u_i 's social network, and β controls the influence from social information. It is easy to verify that Eq. (16) is equivalent to the following matrix form:

$$\hat{\mathbf{R}} = (\mathbf{I} + \beta \mathbf{S}) \mathbf{U}^\top \mathbf{V}. \quad (17)$$

STE is to minimize the following term,

$$\begin{aligned} & \|\mathbf{W} \odot ((\mathbf{R} - \mathbf{U}^\top \mathbf{V}) - \beta \mathbf{S} \mathbf{U}^\top \mathbf{V})\|_F^2 \\ & = \|\mathbf{W} \odot (\mathbf{R} - \mathbf{U}^\top \mathbf{V})\|_F^2 + \alpha Social(\mathbf{T}, \mathbf{S}, \Omega) \end{aligned} \quad (18)$$

where $Social(\mathbf{T}, \mathbf{S}, \Omega)$ is defined as,

$$\begin{aligned} & \|\mathbf{W} \odot (\mathbf{R} - \beta \mathbf{S} \mathbf{U}^\top \mathbf{V})\|_F^2 \\ & - 2Tr(\mathbf{W} \odot ((\mathbf{R} - \mathbf{U}^\top \mathbf{V})(\beta \mathbf{S} \mathbf{U}^\top \mathbf{V}))) \end{aligned} \quad (19)$$

mTrust [110]: a variant of mTrust will predict the rating from u_i to v_j as,

$$\hat{\mathbf{R}}_{ij} = \mathbf{u}_i^\top \mathbf{v}_j + \beta \frac{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{R}_{kj}}{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik}}, \quad (20)$$

where $\frac{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{R}_{kj}}{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik}}$ is a weighted mean of the ratings for v_j from u_i 's social network. mTrust solves the following optimization problem,

$$\min_{\mathbf{U}, \mathbf{V}, \mathbf{S}} \sum_i \sum_j (\mathbf{R}_{ij} - \mathbf{u}_i^\top \mathbf{v}_j - \beta \frac{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{R}_{kj}}{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik}})^2 \quad (21)$$

Similar to STE, we can also find a standard form of Eq. (11) from Eq. (21) for mTrust where $Social(\mathbf{T}, \mathbf{S}, \Omega)$ is defined as,

$$\begin{aligned} & \sum_i \sum_j \mathbf{W}_{ij} \left((\mathbf{R}_{ij} - \beta \frac{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{R}_{kj}}{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik}})^2 \right. \\ & \quad \left. - 2(\mathbf{R}_{ij} - \mathbf{u}_i^\top \mathbf{v}_j) \left(\beta \frac{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{R}_{kj}}{\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik}} \right) \right) \end{aligned} \quad (22)$$

Note that there are two major differences between STE and mTrust. First, \mathbf{S}_{ik} denotes the influence from u_k to u_i for mTrust and will be learned from the data automatically, while \mathbf{S}_{ik} in STE is the predefined similarity between u_i and u_k . Second, STE incorporates a weighted sum of the predicted ratings from social networks, while mTrust incorporates a weighted mean of the existing ratings from social networks.

Regularization methods [50, 68]: Regularization methods focus on a user's preference and assume that a user's preference should be similar to that of her social network. For a given user u_i , regularization methods force her preference \mathbf{u}_i to be closer to that of users in u_i 's social network \mathcal{N}_i . SocialMF [50] and Social Regularization [68] are two representative systems in this group.

SocialMF [50]: SocialMF forces the preference of a user to be closer to the average preference of the user's social network and defines $Social(\mathbf{T}, \mathbf{S}, \Omega)$ as,

$$\min \sum_{i=1}^n (\mathbf{u}_i - \sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{u}_k)^2, \quad (23)$$

where $\sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{u}_k$ is the weighted average preference of users in u_i 's social network \mathcal{N}_i and SocialMF requires each row of \mathbf{S} to be normalized to 1. The authors demonstrated that SocialMF addresses the transitivity of trust in trust networks because a user's latent feature vector is dependent on the direct neighbors' latent feature vectors, which can propagate through the network and make a user's latent feature vector dependent on possibly all users in the network.

With the term to capture social information, SocialMF solves the following optimization problem,

$$\begin{aligned} & \min_{\mathbf{U}, \mathbf{V}} \|\mathbf{W} \odot (\mathbf{R} - \mathbf{U}^\top \mathbf{V})\|_F^2 + \alpha \sum_{i=1}^n (\mathbf{u}_i - \sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} \mathbf{u}_k)^2 \\ & \quad + \lambda (\|\mathbf{U}\|_F^2 + \|\mathbf{V}\|_F^2) \end{aligned} \quad (24)$$

Social Regularization [68]: For a given user, users in her social network may have diverse tastes. With this intuition, social regularization proposes a pair-wise regularization as,

$$\min \sum_{i=1}^n \sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} (\mathbf{u}_i - \mathbf{u}_k)^2, \quad (25)$$

where the preference closeness of two connected users is controlled by their similarity based on their previous ratings. Similarity can be calculated by Pearson Correlation Coefficient or Cosine similarity of commonly rated items by two connected users. A small value of \mathbf{S}_{ik} indicates that the distance between latent feature

vectors \mathbf{u}_i and \mathbf{u}_k should be larger, while a large value indicates that the distance between the latent feature vectors should be smaller. Eq. (25) can be rewritten into its matrix form as,

$$\begin{aligned}
& \frac{1}{2} \sum_{i=1}^n \sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} (\mathbf{u}_i - \mathbf{u}_k)^2 \\
&= \sum_{i=1}^n \sum_{k=1}^n \mathbf{S}_{ik} (\mathbf{u}_i - \mathbf{u}_k)^2 \\
&= \frac{1}{2} \sum_{i=1}^n \sum_{k=1}^n \sum_{j=1}^K \mathbf{S}_{ik} (\mathbf{U}_{ij} - \mathbf{U}_{kj})^2 \\
&= \sum_{i=1}^n \sum_{k=1}^n \sum_{j=1}^K \mathbf{S}_{ik} \mathbf{U}_{ij}^2 \\
&\quad - \sum_{i=1}^n \sum_{k=1}^n \sum_{j=1}^K \mathbf{S}_{ik} \mathbf{U}_{ij} \mathbf{U}_{kj} \\
&= \text{Tr}(\mathbf{U}^\top \mathcal{L} \mathbf{U}), \tag{26}
\end{aligned}$$

where $\mathcal{L} = \mathbf{D} - \mathbf{S}$ is the Laplacian matrix and \mathbf{D} is a diagonal matrix with the i -th diagonal element $\mathbf{D}(i, i) = \sum_{j=1}^n \mathbf{S}(j, i)$.

Recommender systems with social regularization solve the following problem,

$$\begin{aligned}
& \min_{\mathbf{U}, \mathbf{V}} \|\mathbf{W} \odot (\mathbf{R} - \mathbf{U}^\top \mathbf{V})\|_F^2 + \alpha \sum_{i=1}^n \sum_{u_k \in \mathcal{N}_i} \mathbf{S}_{ik} (\mathbf{u}_i - \mathbf{u}_k)^2 \\
& \quad + \lambda (\|\mathbf{U}\|_F^2 + \|\mathbf{V}\|_F^2) \tag{27}
\end{aligned}$$

One advantage of approaches in this category is that they indirectly model the propagation of tastes in social networks, which can be used to reduce cold-start users and increase the coverage of items for recommendation.

3.4 Discussion

Social recommendation can potentially solve some challenging problems of traditional recommender systems such as the data sparsity problem and the cold-start problem, and has attracted broad attention from both academia and industry. On the one hand, social recommendation has been studied for many years in literature. Many successful systems have been proposed and recommendation performance improvement is reported. On the other hand, successful systems in industry are rare and there is a lot of work reporting unsuccessful experiences in applying social recommender systems in academia. In this subsection, we present some key findings from both positive and negative experiences in applying social recommender systems to seek deeper understanding and further development of social recommendation.

3.4.1 Positive Experiences in Social Recommendation

In the physical world, users often seek recommendations from their friends; we have similar observations in the online worlds. For example, 66% of people on social sites have asked friends or followers to help them make a decision and 88% of links that 14-24 year olds clicked were sent to them by a friend and 78% of consumers trust peer recommendations over ads and Google SERPs¹⁰. The intuition of social recommendation makes sense and that is why people believe social recommendation can potentially improve recommendation performance. There have been many successful social recommender systems proposed in recent years in academia as reviewed in the above subsections, and we summarize some key findings from these successful experiences below.

First, online users are inherently correlated [69]. They rarely make decisions independently and usually seek advice from their friends before making purchase decisions. A user's preference is more likely to be similar to that of her social network than to those of randomly chosen users. This phenomenon is widely observed in many online social networks such as following relations in Twitter [120] and trust relations in Epinions [109]. This phenomenon can be explained by well-studied social theories such as homophily and social influence, which supports the utility of social recommendation. Furthermore, there is little overlap between a user's social network and her similar users [19]. Connected users provide different information from similar users for recommendation, which can be exploited to improve the quality of recommendations [49].

Second, to create good quality recommendations, traditional recommender systems need enough historical ratings from each user. Since the rating matrix is usually very sparse due to most users rating few of the millions of items, two users don't have enough of the number of items rated in common required by user similarity metrics to compute similarity. Therefore, the system is forced to choose neighbors in the small portion of comparable users and is probably going to miss other non-comparable but relevant users [75]. Most of these systems are not able to generate accurate recommendations for users with few or no ratings. Social recommendation can make recommendations as long as the user is connected to a large enough component of the social network [50], hence social recommendation can significantly reduce cold-start users. For example, in [75], traditional recommender systems totally fail for new users, however, by considering ratings of trusted users, social recommendation achieves a very small error and is able to produce a recommendation for almost 17% of the users.

Finally, on a very sparse dataset that contains a large portion of cold start users and of items rated by just one user, coverage becomes an important issue since many of the ratings become hardly predictable [64]. Coverage refers to the fraction of ratings for which, after being hidden, the recommender systems are able to produce a predicted rating. By propagating trust, it is possible to reach more users; hence, to compute a predicted trust score among them and to count them as neighbors, social recommendation can improve the coverage of recommendation especially for new items. For example, in [31], traditional recommender systems cannot be applied to new locations; however, social recommendation can achieve

¹⁰ <http://www.firebellymarketing.com/2009/12/social-search-statistics-fromses-chicago.html>

more than 20% recommendation accuracy for new locations when exploiting social relations.

In summary, the key findings from successful experiences are - (1) social information contains complementary information and results from social network analysis provide the necessary technical support for social recommendation; (2) users' opinions and tastes can be propagated via social networks, which can reduce the size of cold-start users; (3) social recommendation can significantly improve the coverage of recommendation.

3.4.2 Negative Experiences in Social Recommendation

Due to the potential value of social information in recommender systems, social recommendation is aggressively pursued in industry. However, a recent report shows that the startup ideas of social recommendations consistently fail [92]. IBM's Black Friday report says Twitter delivered 0 percent of referral traffic and Facebook sent just 0.68 percent [48]. Even in academia, unsuccessful attempts at social recommender systems are also reported [59, 15, 30]. In this subsection, we summarize some key points from negative experiences in applying social recommender systems.

First, the low cost of formation of connections allows one to have an inordinate number of friends in the online world. For example, a Facebook user has 130 friends on average, and an average Twitter user has 126 followers. Research by Robin Dunbar indicates that 100 to 150 is the approximate natural group size in which everyone can really know each other because our minds are not designed to allow us to have more than a very limited number of people in our social world. The emotional and psychological investments that a close relationship requires are considerable, and the emotional capital we have available is limited [24]. Since the social network comprises of valuable friends, casual friends and event friends, users are not necessarily all that similar and social relations mixed with useful and noise connections may introduce negative information into recommender systems [92]. For example, social recommender systems simply using all available relations perform worse than traditional recommender systems [6, 110].

Second, the available social relations are extremely sparse, and the distribution of the number of social relations follows a power-law-like distribution [84], suggesting that a small number of users specify many social relations while a large proportion of users specify a few relations. Users with many social relations are likely to be active users [4] and they are likely to have many ratings, while users with fewer ratings are likely to also have fewer connections [109]. For users with enough ratings, traditional recommender systems already perform well, while for users with fewer ratings, they are likely to also have fewer social relations and social recommender systems cannot help much. For example, social recommender systems in [59, 15, 30] gain a little or even no improvement compared to traditional recommender systems.

Finally, most existing successful social recommender systems use trust relations and recommend items to a user from her trusted users. Trust plays a central role in exchanging relationships involving unknown risk [32], which provides information about with whom we should share information and from whom we should accept information [35]. The role of trust is especially critical in some online communities such as e-commerce sites and product review sites, which has been described as

the “wild wild west” of the 21st century [76]. These successful social recommender systems assume that trust relations are formed when users have similar opinions to similar products. With this assumption, users are likely to seek recommendations from their trusted friends and social recommender systems are likely to be successful. However, trust is a complex concept and has different interpretations in different contexts [21, 27, 2]. A user in the context of product review sites such as Epinions will trust the users if she agrees with their opinions about products, while a user in the context of P2P networks will trust others because of their reliability. Different interpretations of trust may result in different solutions for social recommendation, which suggests that more nuanced approaches are needed to exploit trust relations for recommendation. Trust relations are not necessarily equivalent to other types of social relations. For example, following a user in Twitter does not indicate one’s trust in the user. The success of exploiting trust relations for recommendation may not be applied to other relations, and different types of social relations may have very different impacts on social recommender systems [125].

In summary, key findings from negative experiences in applying social recommender systems include - (1) social relations are too noisy and may have a negative impact on recommender systems; (2) cold-start users are likely to also have few or no social relations and it is difficult for social recommender systems to improve recommendation performance for these users; and (3) different types of social relations have different effects on social recommender systems, and successful experiences in exploiting trust relations may not be applicable to other types of relations.

3.5 Evaluation

In this subsection, we discuss the evaluation of social recommender systems, focusing on available datasets and evaluation metrics for social recommendation.

3.5.1 Datasets

There are benchmark datasets to evaluate traditional recommender systems such as Netflix data ¹¹ and MovieLens data ¹². Compared to traditional recommendation, social recommendation has recently emerged with the development of social media, and there are no agreed benchmark datasets. However, there are datasets publicly available for the purpose of research; here is a list of several representative ones.

Epinions03 ¹³: This dataset was collected by Paolo Massa in a 5-week crawl (November/December 2003) from the Epinions.com [73]. In Epinions, people can write reviews for various products with ratings, and also they can add members to their trust networks or “Circle of Trust”. This dataset provides user-item rating information and user-user trust networks. Note that the trust network here is directed.

¹¹ http://en.wikipedia.org/wiki/Netflix_Prize

¹² <http://www.grouplens.org/node/73>

¹³ http://www.trustlet.org/wiki/Downloaded_Epinions_dataset

*Flixster*¹⁴: This dataset was crawled from the Flixster website [50], which is a social networking service. In Flixster, users can rate movies and can also add some users to their friend list, establishing social networks. Flixster provides user-item rating information and user-user friendship networks. Note that social relations in Flixster are undirected.

*Ciao*¹⁵: This dataset was collected by authors in [110,111]. Ciao is a product review website where users can rate and write reviews for various products, and they can also establish social relations with others. In addition to rating and social information, Ciao provides extra contextual information including temporal information about when ratings are provided, the category information of products, and information about the reviews such as the content and helpfulness votes.

*Epinions11*¹⁶: This dataset was collected during 2011 and is also from Epinions [110,111]. In addition to information in Epinion03, this dataset includes richer information for social recommendation, including temporal information for both rating and social information, categories of products, information about reviews, and distrust information, which allows advanced research about social recommendation. For example, the temporal information about when users establish trust relations can be used to study the evolution of social relations in social recommendation.

Note that some social recommendation papers use other datasets such as Epinions02 [128], FilmTrust [34], and Douban [68]. We do not give details to them because these datasets are publicly unavailable or similar to datasets listed above.

3.5.2 Evaluation Metrics

Although the inputs of traditional recommendation and social recommendation are different, their outputs are the same, i.e., the predicted values for unknown ratings. Therefore, metrics that evaluate traditional recommender systems can also be applied to evaluate social recommender systems.

To evaluate recommender systems, the data is usually divided into two parts—the training set \mathcal{K} (known ratings) and the testing set \mathcal{U} (unknown ratings). Recommender systems will be trained based on \mathcal{K} , and the quality of recommendation will be evaluated in \mathcal{U} . Different evaluation metrics are proposed to evaluate the quality of recommendation from different perspectives, such as prediction accuracy, ranking accuracy, diversity and novelty, and coverage. Prediction accuracy and ranking accuracy are two widely adopted metrics.

Prediction Accuracy: Prediction accuracy measures the closeness of predicted ratings to the true ratings. Two widely used metrics in this category are Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE).

The metric RMSE is defined as

$$RMSE = \sqrt{\frac{\sum_{(u_i, v_j) \in \mathcal{U}} (\mathbf{R}_{ij} - \hat{\mathbf{R}}_{ij})^2}{|\mathcal{U}|}}, \quad (28)$$

where $|\mathcal{U}|$ is the size of \mathcal{U} and $\hat{\mathbf{R}}_{ij}$ is the predicted rating from u_i to v_j .

¹⁴ <http://www.cs.ubc.ca/~jamalim/datasets/>

¹⁵ <http://www.public.asu.edu/~jtang20/datasetcode/truststudy.htm>

¹⁶ <http://www.public.asu.edu/~jtang20/datasetcode/truststudy.htm>

The metric MAE is defined as

$$MAE = \frac{1}{|\mathcal{U}|} \sum_{(u_i, v_j) \in \mathcal{U}} |\mathbf{R}_{ij} - \hat{\mathbf{R}}_{ij}|. \quad (29)$$

A smaller RMSE or MAE value means better performance, and due to their simplicity, RMSE and MAE are widely used in the evaluation of recommender systems. Note that previous work demonstrated that *small improvement in RMSE or MAE terms can have a significant impact on the quality of the top-few recommendation* [57].

Ranking Accuracy: Ranking accuracy evaluates how many recommended items are purchased by the user. Precision and recall are two popular metrics in this category. Recall captures how many of the acquired items are recommended, while precision captures how many recommended items are acquired, for example, Prec@N is used to indicate how many top-N recommended items are acquired. Long recommendation lists typically improve recall, while reducing precision. Therefore F-score is a metric combining them, and it is less dependent on the length of the recommendation list.

Another popular metric is Discount Cumulative Gain (DCG), which is defined as

$$DCG = \frac{1}{|\mathbf{u}|} \sum_{u_i \in \mathbf{u}} \sum_{j=1}^{|\mathcal{L}|} \frac{\hat{\mathbf{R}}_{ij}}{\max(1, \log_b j)} \quad (30)$$

where \mathcal{L} is the ranked list of recommended items.

In this survey, we do not give a general comparison of existing social recommender systems and the reasons are three-fold. First, although some datasets are publicly available, there are still no agreed benchmark datasets for social recommendation. Second, social recommendation is a complex problem and different algorithms are designed to capture its different aspects. For example, algorithms in [117, 118] are for controversial items, while MoleTrust is for cold-start users. Third, some algorithms may require additional sources to capture social information more effectively, for example, mTrust needs the category information of items [110], therefore, it is difficult to seek a fair comparison for all systems. However, there are some common questions to answer when accessing a recommender system including (1) which datasets we are going to adopt; (2) which metrics we will use; (3) what kinds of items we want to recommend; and (4) which kinds of users we want to recommend to. To help readers further understand the assessment process, we summarize evaluations of representative social recommender systems w.r.t. these questions in Figure 2.

4 Research Directions of Social Recommendation

Since the performance boost varies from domain to domain, social recommendation is still in the early stages of development and an active area of exploration. In this subsection, we discuss several research directions that can potentially improve the capabilities of social recommender systems and make social recommendation applicable to an even broader range of applications.

Algorithms	Datasets							Metrics					Items		Users	
	D ₁	D ₂	D ₃	D ₄	D ₅	D ₆	D ₇	M ₁	M ₂	M ₃	M ₄	M ₅	I ₁	I ₂	U ₁	U ₂
SBWM[117,118]	✓							✓	✓	✓			✓			✓
TidalTrust[34]						✓						✓		✓		✓
MoleTrust[73-75]	✓								✓	✓				✓	✓	✓
TrustWalker[49]					✓			✓		✓	✓			✓	✓	✓
SoRec[67]	✓								✓					✓	✓	✓
LOCABAL[109]			✓	✓				✓	✓					✓		✓
STE[65]	✓							✓	✓					✓	✓	✓
mTrust[110]			✓	✓												
SocialMF[50]		✓			✓			✓						✓		✓
SoReg[68]	✓						✓	✓	✓					✓		✓

Fig. 2 Summarization of Evaluations of Representative Social Recommender Systems. Note that the meanings of symbols in the table are stated as $\{D_1(\text{Epinions03}), D_2(\text{Flixster}), D_3(\text{Ciao}), D_4(\text{Epinions11}), D_5(\text{Epinions02}), D_6(\text{FilmTrust}), D_7(\text{Douban})\}$, $\{M_1(\text{RMSE}), M_2(\text{MAE}), M_3(\text{Coverage}), M_4(\text{F-Measure}), M_5(\text{Others})\}$, $\{I_1(\text{Controversial Items}), I_2(\text{Other Items})\}$, and $\{U_1(\text{Cold-start Users}), U_2(\text{Other Users})\}$.

4.1 The Heterogeneity of Social Networks

Most existing social recommender systems treat a user's connections homogeneously. However, connections in online social networks are intrinsically heterogeneous and are a composite of various types of relations [113,106,110]. Figure 3 illustrates an example of u_1 's social relations with $\{u_2, u_3, \dots, u_9\}$. The user u_1 may treat her social relations differently in different domains. For example, u_1 may seek suggestions about "Sports" from $\{u_2, u_3\}$, but ask for recommendation about "Electronics" from $\{u_4, u_5\}$. In [110], the authors found that people place trust differently to users in different domains. For example, u_i might trust u_j in "Sports" but not trust u_j in "Electronics" at all. For different sets of items, exploiting different types of social relations can potentially benefit existing social recommender systems [110].

4.2 Weak Dependence Connections

Most existing model-based social recommender systems solely make use of a user's strong dependence connections, i.e., direct connections, which underestimates the diversity of users' opinions and tastes [92]. If users in the physical world only had strong dependence connections, then life would be pretty boring since strong dependence connections indicate strong similarities. Actually, users can establish weak dependence connections with others in social networks when they are not directly connected. Weak dependency connections can provide important context

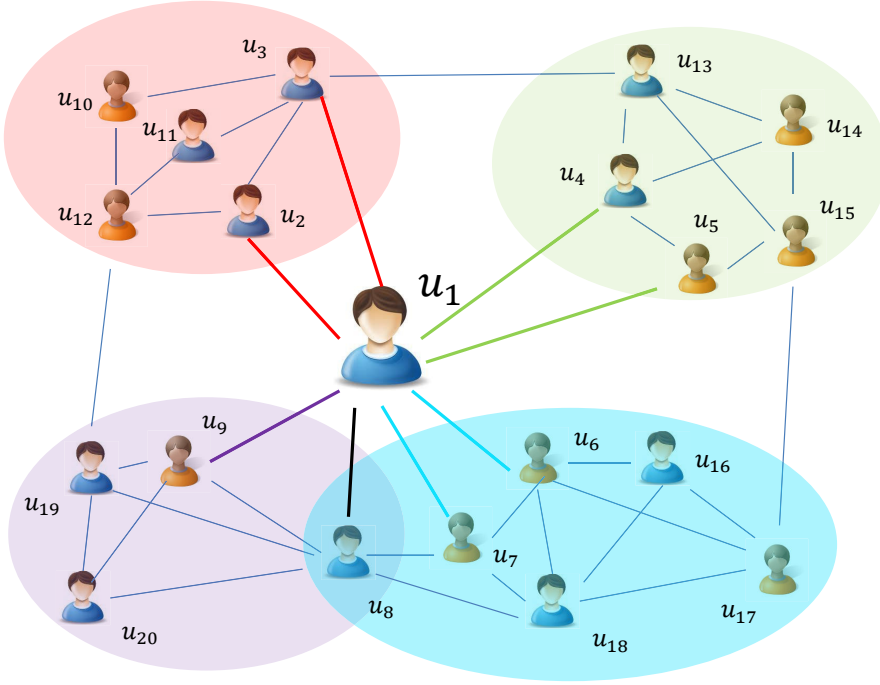


Fig. 3 An illustration of u_1 's social connections

information about users' interests, and are proven to be useful in job hunting [39], the diffusion of ideas [40], knowledge transfer [61] and relational learning [113], while rarely used in recommendation.

Identifying weak dependence connections for recommendation is an interesting direction to investigate. One possible way to find weak dependence connections is to exploit users' geo-locations. For example, [98] notices that users geographically close are likely to share similar interests, and that users geographically close are likely to visit similar locations [31]. Another possible way is to detect groups in social networks. Connected users in online social networks form groups where there are more connections among users within groups than among those between groups [85, 29]. For example, in Figure 3, $\{u_1, u_2, u_3, u_{10}, u_{11}, u_{12}\}$ form a group while $\{u_1, u_3, u_5, u_{13}, u_{14}, u_{15}\}$ form another group. According to social correlation theories, similar users interact at higher rates than dissimilar ones; thus, users in the same group are likely to share similar preferences, establishing weak dependency connections when they are not directly connected [113].

4.3 User Segmentation

In traditional recommender systems, for a given user, ratings of users most similar to her are aggregated to predict a missing rating. When involved in social information, besides being similar, users are socially connected. A user's most similar

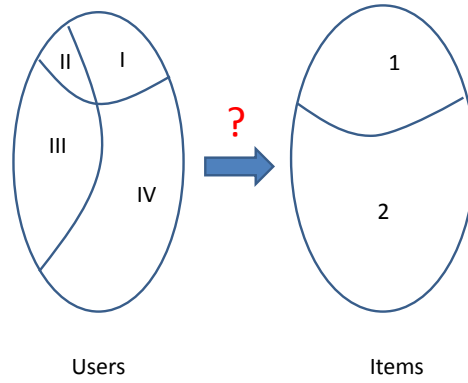


Fig. 4 User segmentation for social recommendation, where “I”, “II”, “III” and “IV” denote connected and non-similar users, connected and similar users, non-connected and similar users, and non-connected and non-similar users respectively, while “1” and “2” denote cold-start items and normal items, respectively.

users usually have little overlap with her connected users [19]. Therefore, users can be segmented into four groups as illustrated in Figure 4 - I: connected and non-similar users; II: connected and similar users; III: non-connected and similar users; and IV: non-connected and non-similar users. According to the number of attracted ratings, items can be segmented into cold-start items and normal items. Different types of users may contribute differently for different types of items. For example, connected users can improve the recommendation accuracy of cold-start locations [31], while similar users are important to recommend normal items [73]. Therefore, microcosmic investigations of users and items may give us a deeper understanding of the role of social networks and can potentially improve recommendation performance.

4.4 Temporal Information

Customer preferences for products drift over time. For example, people interested in “Electronics” at time t may shift their preferences to “Sports” at time $t + 1$. Temporal information is an important factor in recommender systems and there are traditional recommender systems that consider temporal information [23, 58]. Temporal dynamics in data can have a more significant impact on accuracy than designing more complex learning algorithms [58]. Exploiting temporal information for recommender systems is still challenging due to the complexity of users’ temporal patterns [58].

Social relations also change over time. For example, new social relations are added, while existing social relations become inactive or are deleted. The changes of both ratings and social relations further exacerbate the difficulty of exploiting temporal information for social recommendation. A preliminary study of the impact of the changes in both ratings and trust relations on recommender systems demonstrates that temporal information can benefit social recommendation [111].

4.5 Negative Relations

Currently most existing social recommender systems use positive relations such as friendships and trust relations. However, in social media, users also specify negative relations such as distrust and dislike. Authors in [1] found that negative relations are even more important than positive relations, revealing the importance of negative relations for social recommendation. There are several works exploiting distrust [66, 117] in social recommender systems. They treat trust and distrust separately, and simply use distrust in an opposite way to trust such as filtering distrusted users or considering distrust relations as negative weights. However, trust and distrust are shaped by different dimensions of trustworthiness, and trust affects behavior intentions differently from distrust [16]. Furthermore, distrust relations are not independent of trust relations [118]. A deeper understanding of negative relations and the correlations to positive relations can help us develop efficient social recommender systems by exploiting both positive and negative social relations.

4.6 Cross Media Data

A user generally has multiple accounts in social media. For example, a user who has an account in Epinions might also have an account in eBay. A new user on one website might have existed on another website for a long time. For example, a user has already specified her interests in Epinions and has also written many reviews about items. When the user registers at eBay for the first time as a cold-start user, data about the user in Epinions can help eBay solve the cold-start problem and accurately recommend items to the user. Integrating networks from multiple websites can bring about a huge impact on social recommender systems and provide an efficient and effective way to solve the cold-start problem. The first difficulty of integrating data is connecting corresponding users across websites and there is recent work proposed to tackle this mapping problem [83, 127, 63]. The study of the mapping problem makes integration of cross-media data for social recommendation possible and brings about new opportunities for social recommender systems.

5 Conclusion

Social recommendation has attracted broad attention from both academia and industry, and many social recommender systems have been proposed in recent years. In this paper, we first give a narrow definition and a broad definition of social recommendation to cover most existing definitions of social recommendation in literature, and discuss the unique feature of social recommender systems as well as its implications. We classify current social recommender systems into memory-based social recommender systems and model-based social recommender systems according to the basic models chosen to build the systems, and then present a review of representative systems for each category. We also discuss some key findings from positive and negative experiences in applying social recommender systems. Social recommendation is still in the early stages of development and needs further

improvement. Finally we present research directions that can potentially improve performance of social recommender systems including exploiting the heterogeneity of social networks and weak dependence connections, microcosmic investigation of users and items, considering temporal information in rating and social information, understanding the role of negative relations, and integrating cross-media data.

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