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Daning Hu
*University of Arizona,* hud@email.arizona.edu

J. Leon Zhao
*University of Arizona,* lzhao@eller.arizona.edu

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# A Comparison of Evaluation Networks and Collaboration Networks in Open Source Software Communities

**Daning Hu**

Department of Management Information Systems

Eller College of Management

University of Arizona, Tucson, AZ 85721

hud@email.arizona.edu

**J. Leon Zhao**

Department of Management Information Systems

Eller College of Management

University of Arizona, Tucson, AZ 85721

lzhao@eller.arizona.edu

## ABSTRACT

The open source software (OSS) development communities have experienced rapid growth in recent years. Previous social network studies on OSS communities focused on collaboration relationships. However, information about how OSS community members perceive each other is largely ignored. In this study, we report an empirical investigation of the evaluation network in an online OSS community which includes over 11,800 OSS projects and more than 94,330 developers. A collaboration network is modeled from this data set and analyzed for comparison purposes. We find the evaluation network is significantly different from collaboration network in average degree, average path length and fragmentation rate. Furthermore, we argue that the evaluation networks can be used to locate expertise - skillful developers in OSS communities and capture important social relationships among the developers missed in the collaboration network. These characteristics of the evaluation network may benefit the research of OSS development communities and expert recommendation systems.

### Keywords

Open source software, community, evaluation networks, social network analysis, expert recommendation.

## INTRODUCTION

In recent years open source software (OSS) development projects and communities experienced rapid growth in size and quality. The technical and commercial successes of many large OSS projects such as Linux, Mozila Firefox, and MySQL have demonstrated the market legitimacy of this community-based, open source model for software development (von Hippel 2001; von Hippel et al. 2003). This model differs from the traditional hierarchal software development mechanisms mainly at the equal and open relationships among OSS developers (Eric 1999). Understanding various relationships among the OSS community members such as evaluation is critical for discovering the determinants of OSS project success (Grewal et al. 2006).

Social network analysis (SNA) methods have been extensively used to study the relationships in OSS communities (Fleming et al. 2007; Grewal et al. 2006; Jin et al. 2005; Lopez-Fernandez et al. 2004; Masao et al. 2005; Oh et al. 2007; Wagstrom et al. 2005). However, all such studies focused on the collaboration relationship using project participation data and communication data such as emails (von Krogh et al. 2003; Wagstrom et al. 2005). To the best of our knowledge, the evaluation relationship in OSS communities has not been studied before, mainly due to the lack of 1) large-scale empirical evaluation data of OSS community members, and 2) the methods to model and analyze such data.

To address these two problems, we collect and analyze structural data from an online OSS community - Ohloh, including over 11,800 OSS projects involving more than 94,330 developers. With this dataset, we model an evaluation and a collaboration network using social network analysis methods. In addition, a set of network measures such as average degree, average path length, and clustering coefficient are used to compare the topologies of these two networks. We find that the evaluation network is significantly different from the collaboration network in terms of many network measures. These unique characteristics of the evaluation network may provide insights in studying OSS communities and expert recommendation systems (Hu et al. 2007).

The remainder of this paper is structured as follows. In the next section we provide a brief review of the literature relevant to this research. Then the third section describes the data source. After that, the results from our analysis are reported. At last, we conclude by discussing our findings and providing directions for future research.

## RESEARCH BACKGROUND

### Open Source Software Community

Recently many researchers have begun to study the OSS community, aiming to find out how it is related to the success of OSS software development. Such studies mainly focus on two issues. The first issue is the composition of the OSS

community. Koch et al. (2002) analyzed the logs of source code changes for an OSS project and identified a small set of core developers who are responsible for most of the source code output. Such core members are also found to have most intense communications in an OSS project (Robertsa et al. 2006). Another set of literature on OSS community composition focus on the member participation process. For example, von Krogh et al. (2003) found that new OSS community members derive benefits from specializing their initial contributions. Roberts et al. (2006) have developed a theoretical model and evaluated it using empirical data from the Apache projects, aiming to understand how participations, motivations and performance of OSS community members interrelate. The results show that people with higher status motivations are more likely to contribute. Another empirical study (Bagozzi et al. 2006) surveyed 402 active members from 191 Linux User Groups (LUG) in 23 countries and found that the participation to LUG is positively related with the person's experience level in Linux.

The second research issue is uncovering and understanding the various relationships among OSS community members. Most studies on this issue focused on the collaboration relationship. Ducheneaut (2005) observed that successful OSS developers progressively enroll into a collaboration network of human and material allies to support each other. Another descriptive study (Yutaka et al. 2000) found that the communication in OSS development collaborations heavily relies on electronic media (e.g., forum, TODO lists and mailing lists) rather than face-to-face contact. Bergquist et al. (2001) studied how giving away source codes affects OSS community members' social relations. They found OSS community members gain trust from others by actively giving out high quality source code and answering questions. However, the above research mainly focused on the relationships at a micro level. The overall effects on OSS communities caused by the accumulation of multiple relationships are largely ignored. To address this problem, a stream of literature using social network analysis methods studied the topologies of OSS collaboration networks. We introduce these studies in the following two sections.

### Social Network Analysis

Recent advances in social network analysis of various real-world networks, such as the movie actor collaboration network (Barabasi et al. 1999), the phone call network and the scientific collaboration network (Palla et al. 2007), has provided a great opportunity for modeling and analyzing the relationships in OSS communities. In SNA studies, a network is usually represented by a number of nodes (e.g., OSS developers) connected by links (e.g., evaluation relations). Three models have been employed to characterize complex networks: random graph model (Erdos et al. 1960), small-world model (Watts et al. 1998), and scale-free model (Barabasi et al. 1999). These models are then characterized by several network topological measures such as average degree, average path length, clustering coefficient and degree distribution. In random networks, each node has roughly the same number of links which equals to its average degree. A small-world network has a significantly larger clustering coefficient (Watts et al. 1998) than its random model counterpart, indicating a high tendency for nodes to form communities and groups (Watts et al. 1998). It also has a relatively small average path length (i.e., average number of steps along the shortest paths for all possible pairs of network nodes) (Watts et al. 1998). Scale-free networks (Barabasi et al. 1999), on the other hand, are characterized by the power-law degree distribution, meaning that while a big fraction of nodes in the network have just a few links, a small fraction of the nodes have a large number of links. In addition, research has shown that the functions of a complex system may be significantly affected by its network topology (Newman 2003). Therefore, network topological analysis may help researchers better understand how various relations affect the functions and behaviors of OSS communities.

### Social Network Analysis on OSS Community

Social network analysis has been extensively used to study the relationships in OSS communities, especially the collaborations among OSS developers. Madey (2002) firstly uses SNA methods to model OSS developers from SourceForge.net as a collaborative network and found it displays the scale-free network features. The small fraction of the developers with a large number of collaboration links can be explained by people's tendency to collaborate with high-profile, skillful members. A more recent empirical analysis (Jin et al. 2005) of SourceForge data has found similar scale-free features in the collaboration network. Moreover, small-world network features – large clustering coefficient and small average path length – were also found in those SourceForge networks. Crowston (2003) have studied the topology of OSS collaboration networks using data from bug reports of 122 projects. It was found that the network topologies of bigger projects are less centralized. This may be caused by the modularization process of large OSS projects. Another SNA study (Wagstrom et al. 2005) used empirical data from blog links and mailing lists to simulated OSS network evolution, aiming to develop and validate a model which can explain how developers choose which project to work on. In addition, Grewal et al. (2006) examined OSS collaboration network embeddedness and discovered it has more influence on the technical success than the commercial success of OSS projects.

### Research Gap

Although these studies have recognized social network analysis as a valid and effective analytical method to study OSS communities, they mainly have from two problems. Firstly, most of them focus on the collaboration links among OSS

members and ignore many other important relationships such as evaluations. The collaboration networks assign all OSS community members that contribute to a project a fully connected clique. This resulted in a single topology that features with many dense, fully-connected cliques. However, a big OSS project usually involves hundreds of people and many of them may not know each other at all. Therefore, such a single topology of collaboration networks may not be able to correctly represent the real-world interactions among OSS community members.

Secondly, most empirical studies on OSS communities used data involving only a handful of projects and several hundred members. As of February of 2008, SourceForge.net alone has hosted over 170,800 OSS projects and 1,800,000 registered users. A large scale analysis is needed to better understand today's OSS communities.

In this research, we use social network analysis methods to study the evaluation network in an OSS community – Ohloh. Based on the large-scale data set collected from this community, we aim to answer the following research questions: What are the topologies of the Ohloh evaluation network? How does the Ohloh evaluation network differ from the collaboration network? What unique information can be provided by the evaluation network? Through this study we hope to contribute to the research in understanding the OSS communities and to discover the potential real-world applications of evaluation network analysis such as expert recommendation systems.

## DATA COLLECTION

To reflect real-world OSS networks, we collect network structural data from a large OSS community – Ohloh, which provides information about 11,800 major OSS projects involving 94,330 people. This data source is different from other major OSS communities such as SourceForge.net mainly from two perspectives. Firstly, it provides a unique class of information about OSS community members – the "Kudo" evaluation link. Each Ohloh member can send any other member a link called "Kudo" which is a simple gesture of thanks, praise, or endorsement. A "Kudo" link is usually given to a co-developer in the same OSS project as positive evaluation for his or her contribution. Sometimes people receive "Kudo" links from others as recognition of their programming skills or appreciation for their help. Therefore, the "Kudo" evaluation links may provide more comprehensive and accurate coverage of the various social relationships among OSS community members than the usual collaboration links provided by common OSS communities such as Sourceforge.net. Moreover, Ohloh provides detail information about registered developers such as their nationalities, locations, and programming experiences while Souceforge.net does not.

Secondly, Ohloh data set covers a more compressive list of large OSS projects than Sourceforge.net because of its data sources. It retrieves OSS related data from three major software revision control repositories – Subversion, CVS and Git while SourceForge.net only has the first repository. Therefore, a lot of large OSS projects such as Mozila Firefox, Apache, MySQL and PhP that using the other two revision control repositories are only included in Ohloh rather than Sourceforge.net.

In addition, Ohloh website provides access to several other types of information about OSS projects through its API. For example, descriptive information such as the longevity of projects, software licenses were reported for each project. The project activity information keeps track of every change made in OSS projects, including what was changed, when it was changed, and who made the change. Other global statistics across all projects in Ohloh such as programming language usage are also included. Such information coupled with the results from social network analysis may provide insights about the determinants of successful OSS development.

## RESTULTS

### Basic Statistics

We then construct an evaluation network from the collected Ohloh data set. As Table 1 shows, it involves 3,451 Ohloh community members and 9,827 "Kudo" links among them. For comparison purpose, a collaboration network is also extracted with 3,185 members and 10,928 collaboration links. Each collaboration link indicates the joint participation of an OSS project. The overlap column shows how many nodes and links are shared by both networks. About 60.9% of evaluation relationships do not have corresponding collaboration relationships. This result implies that the evaluation network may provide distinct information about the social relationships among Ohloh members from the collaboration network.

|  | Evaluation Network | Collaboration Network | Overlap |
|---|---|---|---|
| Number of Nodes | 3,451 | 3,185 | 2,220 |
| Number of Links | 9,827 | 10,928 | 3,863 |

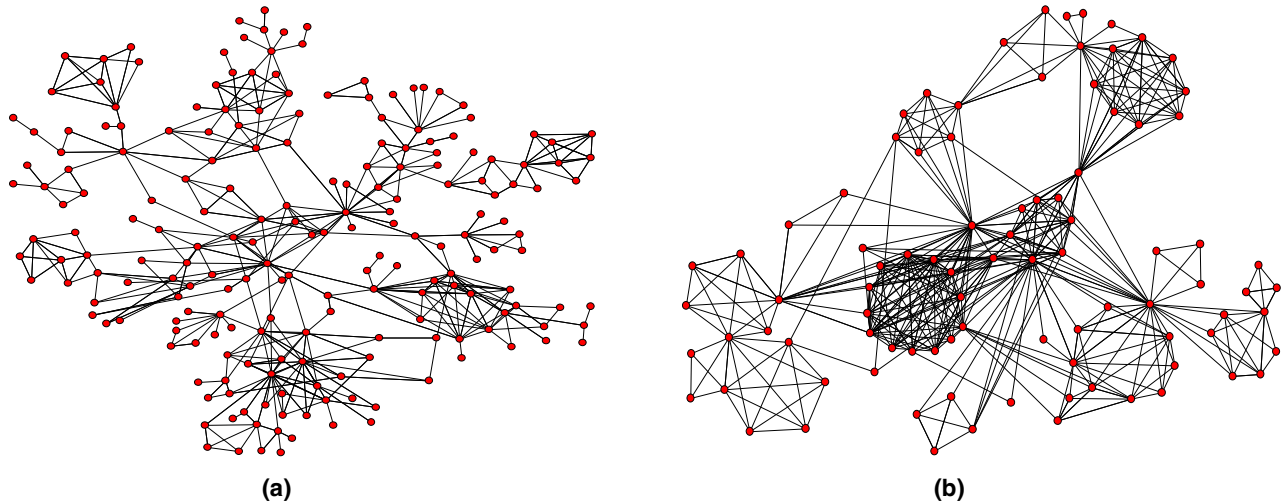**Table 1. Key statistics of Ohloh networks**

**Figure 1. (a) sample Ohloh evaluation network; (b) sample Ohloh collaboration network**

Figure 1(a) shows a part of the evaluation network in Ohloh community while a part of the collaboration network is displayed in Figure 1(b). The sample collaboration network is comprised of dense, fully connected local clusters which represent OSS projects. In contrast, for the evaluation network, it is less interconnected inside each cluster but there are more nodes and links serving as bridges among different clusters.

## SNA Centrality Measures

The first analysis we conducted was to use SNA centrality measures to describe the topology of the Ohloh evaluation network and identify its key members. Moreover, Ohloh collaboration network was analyzed in the same manner for comparison purposes. Firstly, degree measure was calculated for each community member in both networks as the number of direct links a node has (Wasserman et al. 1994). High degrees usually indicate high levels of activity and wide social influence. Therefore, the OSS community members with high degrees are likely to be the leaders of their networks. In addition, the average degree of a network was also calculated to measure how dense a network is.

Table 2 shows that the average degree of the evaluation network is smaller than the collaboration network, while the leader in evaluation network has much more links than the one in collaboration network. This contradiction may indicate the degrees of individual members in the evaluation network vary more than in the collaboration network. In another word, the positional advantages of the OSS community members are more unequally distributed in the evaluation network than the collaboration network.

|  | Evaluation Network | Collaboration Network |
|---|---|---|
| Average Degree | 4.44 | 5.68 |
| Maximum Degree | 119 | 80 |
| Minimum Degree | 1 | 1 |

**Table 2. Centrality measures of the Ohloh networks**

In addition, Table 3 lists the top 10 Ohloh members with highest degrees for both the evaluation network and the collaboration network. There is no overlap between the two sets of members. Considering these two networks share 2220 nodes, it shows the number of positive evaluations an Ohloh member received is not directly related with the number of collaborations he had with others. This result is consistent with previous finding (McDonald 2003) that expertise identified by collaboration network centrality measures does not match individuals' perceptions. Thus, the evaluation network may have more advantages than the collaboration network in terms of expert recommendation.

| Rank | Oholh username | |
|---|---|---|
|  | Evaluation Network | Collaboration Network |
| 1 | Linus Torvalds | Kjartan Maraas |
| 2 | Lennart Poettering | Henri Yandell |

| | | |
|---|---|---|
| 3 | Behdad Esfahbod | Brett Porter |
| 4 | Dave Jones | Robertburrelldonkin |
| 5 | Kay Sievers | Timeless |
| 6 | Miguel | Ruchith |
| 7 | Christopher Lenz | Deepal Jayasinghe |
| 8 | Havoc Pennington | Stephan Kulow |
| 9 | Nathan Letwory | Evenisse |
| 10 | Lukas Kahwe Smith | Davanum |

**Table 3. Top 10 Ohloh community members with highest degrees in the evaluation network and the collaboration network**

## Cluster Analysis

We also used cluster analysis to identify the connected components in a network. A cluster contains a set of nodes that can reach each other through links. Table 4 shows the results of cluster analysis for both the evaluation network and the collaboration network. The largest cluster of evaluation network in Ohloh community contains 2,864 nodes which accounts for 83% of the nodes for the whole evaluation network. The next largest cluster was of size 15, with sizes ranging down to one. The fragmentation rate is the proportion of the nodes that cannot reach each other in a network. On the other hand, the largest cluster in collaboration network only includes 1,856 nodes which account for 60% of the whole collaboration network. The fragmentation rate of the collaboration network is much higher than the evaluation network. These results show that the evaluation network is much more connected than the collaboration network in Ohloh community. This may imply that, comparing with the collaboration network, evaluation network may include more critical social relationships which bridge small local clusters to the rest of the network.

| | The Largest Cluster | |
|---|---|---|
| | Evaluation Network | Collaboration Network |
| Number of Nodes | 2,864 | 1,856 |
| Proportion | 83% | 60% |
| Fragmentation Rate | 31.1% | 64.5% |

**Table 4. Results of the cluster analysis on the Ohloh networks**

## Topological Analysis

Previous research (Jin et al. 2005; Madey 2002) found that OSS collaboration networks are scale-free networks and have small-world network properties. Since there is overlap between the two Ohloh networks, we examine if the evaluation network also has the scale-free and small-world network features. Several important network properties were examined for both networks, including the average path length, the clustering coefficient, link density, and the degree distribution. These properties then were checked against the small world and scale-free models.

Table 5 presents the small world properties of the two Ohloh networks. We focused on the largest clusters and performed topology analysis. We found that evaluation network is a small world network. Its average path length is small with respect to its size. Thus, an Ohloh member can reach any other member in the evaluation network through just 5 or 6 mediators. In addition, the evaluation network is very sparse with a very low link density of 0.0017 (Wasserman et al. 1994). These two properties have important implications for the cost of sharing codes and other resources in OSS communities. Since such cost increases as more members are involved into one project, the small average path length and link sparseness can help lower costs and enhance communication efficiency. In addition, the other small-world property, high clustering coefficient, is also found. The clustering coefficients for both Ohloh evaluation and collaboration networks are significantly higher than their random graph counterpart. The collaboration network also shows all similar small world properties.

Moreover, the evaluation network has smaller average path length than collaboration networks. Along with the higher fragmentation rate, this may imply that the evaluation network have more "shortcut" links which bridge local clusters than collaboration networks.

| | Evaluation Network | Collaboration Network | Random Network |
|---|---|---|---|
| Average Path Length | 5.643 | 6.895 | 5.110 |
| Clustering Coefficient | 0.455 | 0.783 | 0.002 |
| Link Density | 0.0017 | 0.0039 | 0.0017 |

**Table 5. Small-world and Scale-free properties for Ohloh networks**

Table 6 shows the results of linear regression of the degree distribution for both evaluation network and collaboration network. It was found that the evaluation network follows an power-law degree distribution (Newman 2001), $p(k) \sim k^{-\gamma}$, with exponent $\gamma = 1.95$. The coefficient of determination $R^2$ of the regression for evaluation network is extremely large at 0.91 (ranging from 0 to 1), indicating high fitness of the power-law degree distribution. The collaboration network also has similar results and shows scale-free features.

| | Evaluation Network | Collaboration Network |
|---|---|---|
| $R^2$ | 0.91 | 0.92 |
| $\gamma$ | 1.95 | 1.86 |

**Table 6. Results of linear regressions on degree distributions for Ohloh networks**
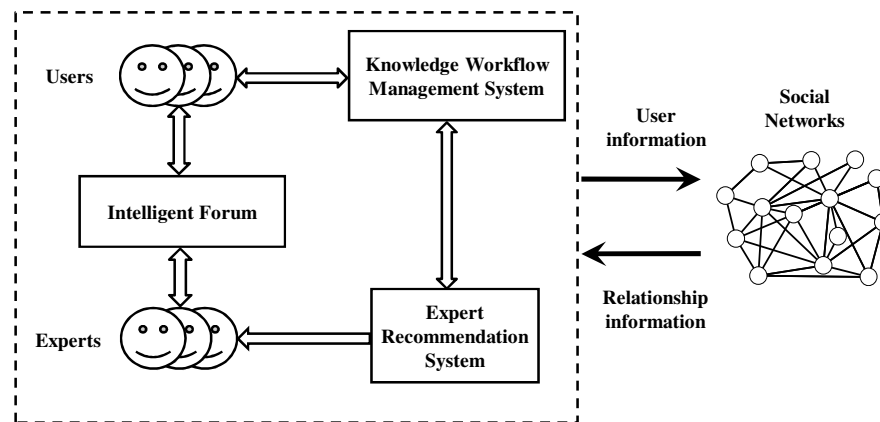
**DISCUSSIONS**



**Figure 2. An example of the use of evaluation social networks in the expert recommendations**

Our study on evaluation networks as presented in this paper was motivated by the need for an expert recommendation mechanism in OSS communities and other knowledge intensive environments. Figure 2 illustrates a knowledge transfer setting for the use of social networks in expert recommendation (Hu et al. 2007). The social networks given here capture the various social relationships among individuals. The evaluation networks studied in this paper provide an example of such social networks. Our analysis found that such evaluation networks can be useful in expert recommendation.

However, social network analysis alone is not enough for accurate expert recommendation. Semantic information is needed to uncover the meaning of the relationships. For example, in the knowledge transfer setting described in Figure 2, when a user needs some unique knowledge to help execute workflow tasks, he can submit a query to the knowledge workflow management system (KWMS) and start a discussion in the intelligent forum. KWMS will invoke the expert recommendation system (ERS) to recommend relevant experts and invite these experts to the forum discussion through emails. The ERS ranks each available expert mainly based on two types of information: 1) the evaluation relationship between the user and the expert in the evaluation social network, and 2) the semantic relevancy of the expert profile to the query. For example, if there

exists a positive evaluation relationship which is based on the joint participation of a project by an expert and a user, and more importantly, the semantic information - the description of the project matches the query keyword, then this expert is more likely to be recommended to answer the user query. This example demonstrated how the results from evaluation network analysis coupled with semantic information can be used in expert recommendation under a knowledge intensive environment.

## CONCLUSIONS

In this paper, we studied an evaluation network in the open source software development community – Ohloh. Using structure data collected from Ohloh, we performed social network analysis to uncover the topology of an evaluation network, with community members as nodes and positive evaluations as links. Moreover, we modeled and analyze the collaboration network from Ohloh data set and compared its topology with evaluation network. There are several findings from the analysis and the comparison of those two networks in Ohloh community.

- 60.9% evaluation relationships do not have corresponding collaboration relationships. The evaluation network may provide distinct information from the collaboration network.

- The degrees (i.e., numbers of links a node has) are more unequally distributed in the evaluation network than the collaboration network. This indicates there is more heterogeneity in the OSS developers' evaluation behaviors than collaborations.

- The number of positive evaluations an OSS developer receives is not directly related with the number of collaborations he has. Thus information from evaluation network is more useful than collaboration network in locating skillful OSS developers.

- The cluster analysis shows that the evaluation network is more connected than the collaboration network. This implies evaluation network may capture important social links among different clusters of OSS developers missed by collaboration networks.

- The topological analysis show that both evaluation networks and collaboration networks show features of small-world network and scale-free network, such as small average path length, high clustering coefficient and power-law degree distribution. However, the evaluation network has smaller average path length than the collaboration network. This may indicate evaluation network has more "shortcuts" links which serves as bridges among its local clusters.

In general, although evaluation network and collaboration both show scale-free and small-world network properties, they are significantly different at a series of critical network features. This is mainly because of the different nature of their links: evaluation is one-to-one personal relationship while collaboration is equally distributed relationships among a group of people. The purpose of this research is not comparing the topological differences of these two types of networks in the same context but rather demonstrating the evaluation networks in OSS community can provide distinct and value-added information from collaboration networks. Such information may be useful in the analysis of the various social relationships in OSS communities.

One limitation of this research is the lack of complete information for the developers in both Ohloh networks. Among the 94,330 developers listed in Ohloh website, only 14,075 developers registered their detail personal information and gave "Kudo" evaluation links to each other. We only include these registered developers in the two Ohloh networks. Therefore, the constructed networks in this study are the best possible approximation of the Ohloh community.

Our future work consists of several directions including (1) exploring the determinants of positive evaluation links by mining their relationships and (2) developing a ranking mechanism for use in an expert recommendation system. Our efforts will open a new venue of research in social network analysis by incorporating semantic analysis in relationship discovery and applying the relationship information in expert recommendation needed for more efficient execution of business activities.

## REFERENCES

1. Bagozzi, R.P., and Dholakia, U.M. "Open source software user communities: A study of participation in Linux user groups," *Management Science* (52:7), Jul 2006, pp 1099-1115.
2. Barabasi, A.-L., and Alert, R. "Emergence of Scaling in Random Networks," *Science* (286:5439) 1999, pp 509-512.
3. Bergquist, M., and Ljungberg, J. "The power of gifts: organizing social relationships in open source communities," *Information Systems Journal* (11:4) 2001, pp 305-320.
4. Crowston, K., and Howison, J. "The social structure of open source software development teams," *OASIS 2003 Workshop (IFIP 8.2 WG)*) 2003.

5.  Ducheneaut, N. "Socialization in an Open Source Software Community: A Socio-Technical Analysis," *Computer Supported Cooperative Work (CSCW)* (14:4) 2005, pp 323-368.

6.  Erdos, P., and Renyi, A. "On the evolution of random graphs," *Publ. Math. Inst. Hung. Acad. Sci.* (5) 1960, pp 17-61.

7.  Eric, S.R. *The Cathedral and the Bazaar* O'Reilly & Associates, Inc., 1999, p. 268.

8.  Fleming, L., and Waguespack, D.M. "Brokerage, boundary spanning, and leadership in open innovation communities," *Organization Science* (18:2), Mar-Apr 2007, pp 165-180.

9.  Grewal, R., Lilien, G.L., and Mallapragada, G. "Location, location, location: How network embeddedness affects project success in open source systems," *Management Science* (52:7), Jul 2006, pp 1043-1056.

10. Hu, D., Sarnikar, S., and Zhao, J.L. "Towards a Process-Driven Intelligent Forum System (PIFS) For Efficient Organizational Knowledge Transfer," in: *Proceedings of the 2007 international conference on Information systems*, Association for Information Systems, Montreal, Canada, 2007.

11. Jin, X., Yongqin, G., Scott, C., and Gregory, M. "A Topological Analysis of the Open Souce Software Development Community," in: *Proceedings of the Proceedings of the 38th Annual Hawaii International Conference on System Sciences (HICSS'05) - Track 7 - Volume 07*, IEEE Computer Society, 2005.

12. Koch, S., and Schneider, G. "Effort, co-operation and co-ordination in an F/OSS software project: GNOME," *Information Systems Journal* (12:1) 2002, pp 27-42.

13. Lopez-Fernandez, L., Robles, G., and Gonzalez-Barahona, J.M. "Applying social network analysis to the information in CVS repositories," *IEE Seminar Digests* (2004:917) 2004, pp 101-105.

14. Madey, G., Freeh, V., and Tynan, R. "The Open Source Software Development Phenomenon: An Analysis Based on Social Network Theory," AMCIS, Dallas, TX, 2002, pp. 1806-1813.

15. Masao, O., Tetsuya, O., Takeshi, K., Naoki, O., and Ken-ichi, M. "Supporting Knowledge Collaboration Using Social Networks in a Large-Scale Online Community of Software Development Projects," 2005, p. 835.

16. McDonald, D. "Recommending collaboration with social networks: a comparative evaluation," CHI '03: Proceedings of the SIGCHI conference on Human factors in computing systems, ACM Press, 2003, pp. 593-600.

17. Newman, M.E.J. "Scientific collaboration networks. I. Network Construction and fundamental results," *Physical Review E* (64) 2001, p 06131.

18. Newman, M.E.J. "The structure and function of complex networks," *SIAM Review* (45:2) 2003, pp 167-256.

19. Oh, W., and Jeon, S. "Membership herding and network stability in the open source community: The Ising perspective," *Management Science* (53:7), Jul 2007, pp 1086-1101.

20. Palla, G., Barabasi, A.-L., and Vicsek, T. "Quantifying social group evolution," *Nature* (446:7136) 2007, pp 664-667.

21. Roberts, J.A., Hann, I.H., and Slaughter, S.A. "Understanding the motivations, participation, and performance of open source software developers: A longitudinal study of the Apache projects," *Management Science* (52:7), Jul 2006, pp 984-999.

22. Robertsa, J., Hann, I.-H., and Slaughter, S. "Communication Networks in an Open Source Software Project," in: *Open Source Systems*, 2006, pp. 297-306.

23. von Hippel, E. "Innovation by user communities: Learning from open-source software," *Mit Sloan Management Review* (42:4), Sum 2001, pp 82-86.

24. von Hippel, E., and von Krogh, G. "Open source software and the "private-collective" innovation model: Issues for organization science," *Organization Science* (14:2), Mar-Apr 2003, pp 209-223.

25. von Krogh, G., Spaeth, S., and Lakhani, K.R. "Community, joining, and specialization in open source software innovation: a case study," *Research Policy* (32:7), Jul 2003, pp 1217-1241.

26. Wagstrom, P., Herbsleb, J., and Carley, K. "A social network approach to free/open source software simulation," First International Conference on Open Source Systems, 2005, pp. 16-23.

27. Wasserman, S., and Faust, K. *Social Network Analysis: Methods and Applications* Cambridge University Press, Cambridge, 1994.

28. Watts, D.J., and Strogatz, S.H. "Collective Dynamics of 'Small-World' Networks," *Nature* (393) 1998, pp 440-442.

29. Yutaka, Y., Makoto, Y., Takeshi, S., and Toru, I. "Collaboration with Lean Media: how open-source software succeeds," in: *Proceedings of the 2000 ACM conference on Computer supported cooperative work*, ACM, Philadelphia, Pennsylvania, United States, 2000.