Evaluating Interdisciplinarity with Social Network Analysis

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Abstract
The Santa Fe Institute sponsors an annual Complex Systems Summer School, a four week intensive course in complex systems funded by the National Science Foundation. In each school, a group of scholars from diverse backgrounds is asked to spontaneously organize into interdisciplinary groups and execute a project within four weeks' time. This event comprises a natural experiment in which the operation of homophily, the tendency to select other team members on the basis of shared characteristics, can be observed. Using network analysis methods, this study examined evidence of homophily in the formation of project collaborations by measuring the extent of group sorting according to gender, discipline, international region, American vs. non-American nationality, and professional role. The extent of group sorting also clearly measures the interdisciplinarity of project collaborations formed by participants in CSSS 2007, and serves as a novel method for evaluating an interdisciplinary program.

Introduction
The Santa Fe Institute, a non-profit research institute sponsors an annual four week intensive summer course in complex systems, Complex Systems Summer School (CSSS). Participants are selected in a competitive admissions process, and represent diverse disciplines such as physics, ecology, computer science, healthcare, humanities, biology, and linguistics. The participants are mixed in gender and hail from many different nations. Most participants are PhD students, postdoctoral students, and recent PhD graduates. However, there are also several corporate participants.

Participants are strongly encouraged to purposefully interact and engage in discussion with participants from other disciplines. Additionally, participants are directed to incept and execute interdisciplinary group projects for presentation on the final day. The nature of these projects, and the formation of project teams, is left to the participants. It is notable that the participants are largely strangers to each other, having never previously met.

Homophily, the tendency to select other team members on the basis of similar characteristics, has been argued by many to be a fundamental and often decisive factor in the formation of social networks and organizations, and in the adoption of cultural and behavioral preferences by individuals. [1] [2] [3] Scholars have argued that as a salient factor in the formation of social affiliations, homophily serves as an agent of inequality through its perpetuation and intensification of existing patterns of access to resources.

The Complex Systems Summer School is a fairly unique scenario, each year gathering a variety of researchers from diverse backgrounds who have not previously collaborated, and directing them to collaborate. Given the active encouragement of participants to engage in interdisciplinary or multidisciplinary projects, it constitutes a natural experiment in which one can observe the extent to which the homophily principle operates. So, the primary purpose of this study was to assess the diversity of formed project collaborations in terms of the following characteristics: gender, discipline, global region of origin, American vs. non-American nationality, and professional role. This study also sought to describe and characterize the overall network structure representing the formed project collaborations, including reciprocity, hubs, and emergent subgroups.

Methods
Sample
All participants in the Santa Fe Institute's 2007 Complex Systems Summer School were studied in this social network analysis. Information describing the identity of the participants and project group composition is publicly available. The participants were PhD students, postdoctoral fellows, recent PhD graduates, and employees of Santa Fe Institute corporate partners, from various nations and disciplines. The participants, almost all of whom were previously unknown to each other, were encouraged to spontaneously form collaborative teams and execute a project for presentation on the final day. More specifically, participants were directed to select a project and team (if applicable) by the end of week two.

Data collection
Data describing project collaborations were collected via electronic survey during week three of CSSS 2007. By week three, participants were expected to have begun at least one interdisciplinary project. (Many participants engaged in more than one project). The survey included a checklist of all participants, and respondents were asked to check off

the names of all participants with whom they were currently collaborating on a project. Respondents were also asked to indicate discipline and gender. Participants were invited to complete the survey via e-mail. Participants who did not respond to initial e-mail requests were approached in person. Some participants were provided paper versions of the survey to ease participation, and responses were later entered by the investigators. Completion of the survey was encouraged by the summer school director and there was substantial peer encouragement to complete the survey, as participants were interested to see the results.

Network Analysis

At the end of the week, responses were downloaded into a spreadsheet and prepared for analysis using Excel. Additional information indicating country of origin was extracted from program materials and entered by investigators. With this data, we constructed an undirected graph representing project collaborations. This graph was the basis of all analyses. Data were analyzed using UCINet [4], Pajek [5],NetDraw [6], and Matlab [7]. The network graph was visualized using UCINet. Non-respondents and a respondent without collaborative project involvement were excluded from some analyses. When inclusion was feasible based on public information, gender was inferred and discipline designated "not reported".

Results

The survey response rate was 84.38% (54/64 rostered participants). Gender and discipline of survey completers is described in tables 1 and 2. Survey completers reported collaborations with persons who did not complete the survey, and in doing so, provided data describing those individuals, so the network graph included sixty-three vertices, representing nearly all participants.

Table 1. *Characteristics of survey respondents.*

Gender	
Male	39 (72.22%)
Female	15 (27.78%)
Total	*54 (100%)*
Discipline	
Social Sciences/ Humanities	20 (37.04%)
Physics	10 (18.52%)
Biology	7 (12.96%)
Ecology	4 (7.41%)
Healthcare	4 (7.41%)
Informatics	9 (16.67%)
Total	*54 (100%)*

Table 2. *CSSS participant characteristics inferred from program materials.*

American Nationality	
American	23 (42.59%)
Not American	31 (57.41%)
Total	54
Region	
Asia	9 (16.67%)
Europe	15 (27.78%)
Australia	5 (9.26%)
North America	23 (42.59%)
South America	2 (3.70%)
Total	54
Professional Role	
Student	40 (74.07%)
Post-doctoral Fellow	6 (11.11%)
Professor	4 (7.41%)
Industry	4 (7.41%)
Total	54

The reported project collaborations were represented by an undirected graph with n=63 vertices and m=328 edges (see figure 1). Its general characteristics are described in table 3. Assortative mixing coefficients were calculated for the previously described characteristics. The results are presented in table 4. Reciprocity, subgroups, and hubs were visualized (figures 2-4).

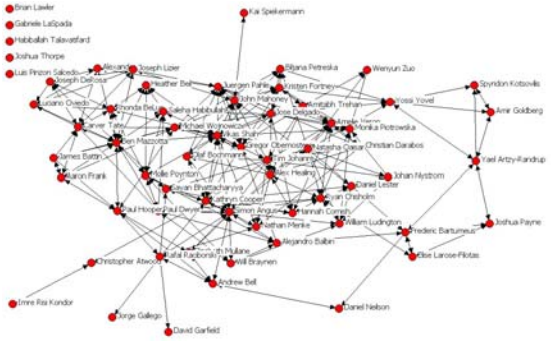


Figure 1. Project collaboration network.

Table 3. *Network graph characteristics.*

Vertices (n) = 63
Edges (m) = 328
Mean degree (z) = 6.83
Mean vertex-vertex distance (l) = 3
Diameter = 8
40 unreachable pairs
Clustering coefficient (C) = 0.4143

Table 4. *Assortative mixing coefficients (rank ordered).*		
	Coefficient for Assortative Mixing (Q)	
	All Edges	Reciprocal Edges
1. Discipline	0.1819	0.1948
2. American*	0.1656	0.1587
3. Region**	0.1191	0.1291
4. Professional Role***	0.0292	0.0254
5. Gender	0.0155	0.0137

* *American: American or not American*

** *Region: Asia, Europe, Australia, North America, South America*

*** *Professional Role: Student, Post-doc, Professor, Industry*

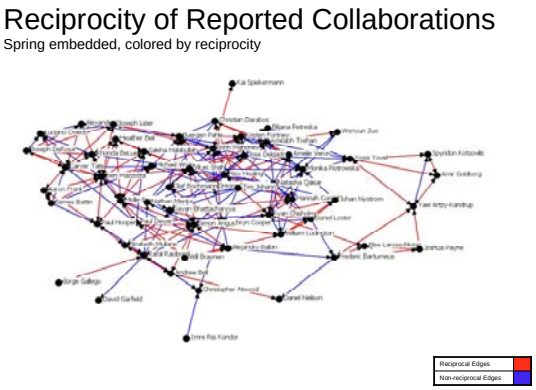
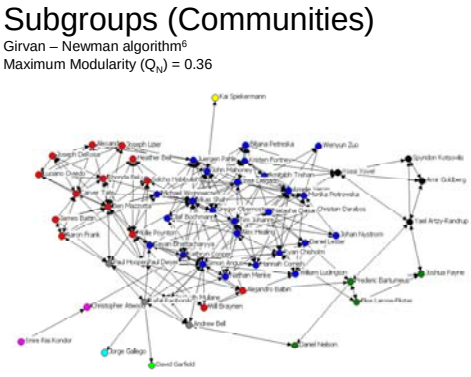


Figure 2. Reciprocity or reported collaborative relationships.



*Girvan M. and Newman M. E. J., Proc. Natl. Acad. Sci. USA **99**, 7821-7826 (2002)

Figure 3. Subgroups

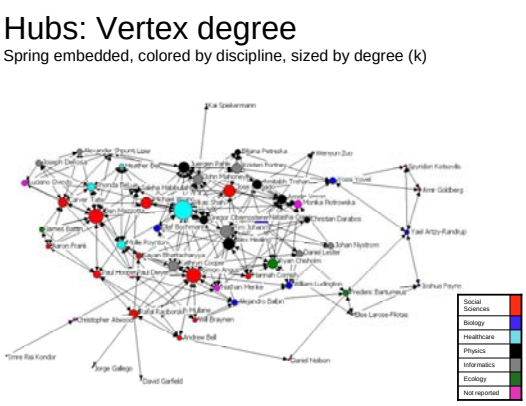


Figure 4. Hubs

Discussion

The network graph, pictured in figure 1, appears tightly clustered and highly connected, indicating there was substantial collaboration among participants in the 2007 CSSS. Project collaborations were very diverse, in terms of discipline, gender, American vs. non-American nationality, global region of origin, and professional role. While all assortative mixing coefficients were low, discipline appears to have exerted some effect on project collaborations and discipline was the highest value assortative mixing coefficient.

The probability distribution p(k) was right skewed, with several highly connected individuals, but most individuals were connected to a median six others. Many edges were not reciprocal, and this may have reflected confusion over group membership during week three (see figure 2). Multiple subgroups formed, as seen in figure 3.

Conclusions

Social network analysis of project collaborations at CSSS 2007 revealed substantial collaboration among participants. Participants were highly connected with each other, reflecting overall group cohesiveness, with some subgroup formation. Homophily, as measured by assortative mixing according to participant characteristics, exerted minimal effect. While all assortative mixing was low, the most influential sorting characteristic in collaborative team formation was discipline.

These findings seem intuitive to the investigators, both participants in CSSS 2007. In the CSSS environment, there was no urgency to satisfy discipline-specific tenure requirements or to secure funding. Almost all participants stayed together in group housing for the duration of the school, and participants attended lectures, tutorials, tea/coffee

breaks, meals, and after hour social activities together. It is possible that participants in CSSS were able to form highly interdisciplinary teams because they did not face institutional barriers to interdisciplinary work, such as the satisfaction of tenure requirements, physically separate working spaces, and availability of funding sources. Moreover, they were placed in an environment of substantial social interaction.

More surprising, however, are the extremely low levels of assortative mixing according to other, non-academic characteristics. These findings seem to contradict the expectation, which has been empirically validated in previous studies, that people tend to associate according to preexisting shared characteristics. We hypothesize that the low levels of assortative mixing at CSSS can be mainly attributed to participants' predispositions, but also to the academic setting that proactively encourages interdisciplinarity. The organizers' emphasis on breaking down academic barriers may have also contributed to participants' willingness to transcend other non-academic barriers. Given the nature of the data at hand, we have no means to further investigate this assumption. But if found to be true, it might have implications on policies aimed at discouraging socio-cultural exclusive behaviors. As such, it warrants further investigation.

Research institutions increasingly engage in initiatives and programs designed to foster interdisciplinarity. Interdisciplinary research and education is an important goal of many institutions that recognize the importance of diverse perspectives in scientific innovation. While methods and metrics exist for the studying the interdisciplinarity of individual studies and publications, evaluation techniques that measure interdisciplinarity of programs are not evident in the literature.

Typical programmatic evaluation of interdisciplinarity is limited to the number and variety of disciplines, or at the other extreme, the interdisciplinarity of individual projects. In this study, social network analysis of interdisciplinarity yielded substantial insight into the overall interdisciplinarity of collaborations within a group of scientists attending the Santa Fe Institute's Complex Systems Summer School. The social network analysis methods and metrics used in this study could be applied in any university or research group to measure interdisciplinarity. Adequate measurement of interdisciplinarity is essential for evaluating the effectiveness of programs and initiatives designed to promote interdisciplinary collaboration.

Acknowledgements
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