Social Network Analysis to Evaluate an Interdisciplinary Research Center

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Authors' Note

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Abstract

We sought to examine the growth of an interdisciplinary center using social network analysis techniques. Specific aims were to examine the patterns of growth and interdisciplinary connectedness of the Center and to identify the social network characteristics of its productive members. The setting for this study was The Center for Interdisciplinary Research on Antimicrobial Resistance (CIRAR) at Columbia University. Periodic surveys and social network analysis comprised the study design. The data for this study included a relational survey taken by all members of the Center at three time points over one year. Respondents confirmed whether or not they had "heard of," "met," or "know the work of," or had "worked with" each of the other Center members. Data were analyzed using the social networking software program Organizational Risk Analyzer (ORA). Over time the social network increased in size, density, centralization, and complexity. The density of connections among and between different disciplines in the Center varied from Time 1 to 2 to 3; some increased, some decreased, while others stayed the same. Finally, the total degree centrality and the betweeness centrality of Center members were highly correlated to productivity. The study shows that a number of characteristics of an interdisciplinary research center can be quantified and described using social network techniques. Data from these analyses can be used to evaluate a center's progress, identify important indicators of leadership, identify areas of strength and need for improvement, and inform decisions on strategic direction.

Key Words: Interdisciplinary, Social Networking, Collaboration, Research, Growth

Introduction

Despite this nation's potential to deliver the finest health care in the world, the translational blocks from basic science to human studies and from clinical research to practice and policy clearly "impede efforts to apply science to better human health in a expeditious fashion."(Sung et al., 2003) One way to expedite the translation of research to health care delivery is through interdisciplinary research, which crosses the traditional boundaries of profession, department, or institution. Indeed, much has been written in recent years about the value of interdisciplinary collaboration, to the extent that it has become one of the academic bandwagons of the day, and the National Institutes of Health (NIH) has identified interdisciplinarity as an explicit priority in its recent Roadmap, a strategic plan for future funding priorities http://nihroadmap.nih.gov/interdisciplinary/index.asp).

In a recent survey, more than 2,000 fulltime academic researchers ranked their collaborators above salary and job security as their highest priorities for job satisfaction (Grimwade & Park, 2003). Nevertheless, academic environments generally have established incentives for an entrepreneurial, independent approach to research. It has been suggested, in fact, that the academic culture hinders collaboration and, hence, slows translational research (Pober, Neuhauser, & Pober, 2001; Sung et al., 2003). Thus, data suggest that an interdisciplinary culture must be well planned and executed before success is possible. Despite this, there is little empirical evidence of a change in the traditional departmental academic systems and networks, with many initiatives identified as interdisciplinary actually being reconfigurations of traditional modes of multidisciplinary research (Rhoten & Parker, 2004).

The ultimate purpose of interdisciplinary research is to develop new knowledge or solve a relevant human problem by combining the skills and perspectives of multiple disciplines. This requires a realistic understanding of the nature of disciplinarity. Although academic disciplines are often thought of as "bodies of teachable knowledge" (Woollcott, 1979) or as "conceptually specific structures" (Robertson, Martin, & Singer, 2003), these dehumanized descriptions do not capture the entire domain. Disciplines are also "organized social groups," "sets of social relationships" (Lattuca, 2002), and "isolated domains of human experience possessing its own community of experts" (Nissani, 1997). Many of the challenges inherent in interdisciplinary research emanate from the isolation of disciplinary experts, resulting in knowledge silos. Viewed in this way, accomplishing interdisciplinary research becomes, at least in part, an issue of social interaction and the creation of integrated social networks.

Social Network Analysis

Social network analysis involves a unique set of tools capable of revealing the patterns of human interactions. Social networking can be used to track the extent to which a network grows and also answer questions regarding how it grows: What is the disciplinary composition of the team? Is the team all connected or are there subgroups? Are there central players crucial for creating connections between people? Social network analysis can elucidate many patterns of team assembly, such as team size, membership composition, and tendency to repeat previous collaborations that can determine the performance of creative teams (Guimera, Uzzi, Spiro, & Amaral, 2005).

A "social network" is defined as a group of collaborating (or competing) entities that are related to each other (Aviv, Erlich, Ravaid, & Geva, 2003). Network methods focus on the relational linkages between entities (i.e., individuals or groups of individuals or "things," such as electronic message boards, citations, or computer stations), using techniques based on graph theoretic methods (Wasserman & Faust, 1994). A graph is a finite set of dots called nodes that are connected by edges that represent links. To create a social network graph, individuals are represented as nodes in a network and the relationships that connect them (such as "heard of" or "worked with") are represented as edges that connect the nodes. Each edge indicates an information link between two individuals. Graphs are often notated in the form of a matrix thus allowing quantitative calculation using operations from matrix and linear algebra to mathematically define characteristics of the network members and structure (Scott et al., 2005).

There is a growing body of literature on the application of network methods in the study of organizations (Borgatti & Foster, 2003; Brass, Galaskiewicz, Greve, & Tsai, 2004; Lin & Carley, 2003). Although these methods have been used in business as well as in the social and basic sciences to describe interdisciplinary interactions (Barabasi, 2005; Cott, 1997; Girvan & Newman, 2002; Newman. 2001; Singer& Kegler, 2004), there has been minimal application of social network analysis within health care research, and little is known about how an interdisciplinary research center develops after its establishment.

Specific Aims

The purpose of this project was to evaluate the growth of an interdisciplinary research center using social network analysis. Specific aims were threefold: to understand the patterns of growth over time (e.g., did members join as individuals or in subgroups?); to evaluate the extent and patterns of connectedness among center members across disciplinary and departmental boundaries and over time; and finally to determine the network characteristics of productive center members and subgroups based on work products and emerging research teams.

Methods

Sample and Setting

The Center for Interdisciplinary Research on Antimicrobial Resistance, CIRAR (P20 RR020616, National Center for Research Resources, NIH), was funded as a planning grant in 2004 to develop interdisciplinary research aimed at reducing antimicrobial resistance. The core team of researchers and staff included 15 individuals from 12 different academic departments or divisions: four nurses and four physicians as well as experts in epidemiology, microbiology, higher education, biostatistics, dentistry, health policy, informatics, economics, organizational systems, and behavioral sciences. Student liaisons from the various health professions schools were also included as full members of the team. This social network study included these core team members and others added to the team over time as they became involved in activities of the Center.

Data Collection

At the first general meeting of the Center, core team members completed a survey in which they were asked to indicate, for every other team member as well as for the external advisors and University oversight group (which provides input regarding direction and goals of the center but generally does not directly contribute to work products), four levels of relationship: whether he/she had heard of, knew the work of, had met, or had worked with each of the others. The same survey was administered at 6 and 12 months after the formation of the Center. As individuals joined and departed from the Center their names were added or removed from the survey. Individuals who left the Center were primarily students whose period of study had ended (6), or faculty members who left the University or whose interests were peripheral to the purpose of the Center (3).

Team Building and Expanding Efforts

We employed several tactics to build connections among existing members of the Center and expand the team. To facilitate interactions among members, the core team met monthly, and several smaller working groups met at regular intervals. Within the first few months of the Center's establishment, each core team member made a presentation describing his/her work during part of the monthly team meetings. The smaller working groups gave members a chance to work together; each group was responsible for carrying out one aspect of the Center's mission (e.g., identifying gaps in the field and planning educational seminars). The Center also held a team-building half-day retreat composed of short talks from core team members followed by "brain-storming" breakout groups to identify ideas for collaborative projects.

Students, postdoctoral fellows, and junior faculty were recruited by the Center through requests for applications for small pilot grants. Eight grants were awarded. We also increased our exposure through periodic seminars and guest speaking events that were extensively advertised. The Center convened two major events aimed at expanding potential collaborative partnerships: a meeting of interdisciplinary center directors across the university and a discussion forum with pharmaceutical company researchers working in the field of infectious disease. An informational pamphlet about the Center was available at all events. Any new contacts made at these events were maintained through an e-mail database that was continuously updated. Descriptions and photos of all events were posted on the Center's website http://www.cumc.columbia.edu/dept/nursing/CIRAR/), along with announcements for future events and minutes from all meetings.

Data Analysis

We selected a set of network measures to address the three specific aims for evaluating the Center. To evaluate patterns of growth over time, we examined the *size, density, complexity*, and *centralization* of the full network at the beginning and 6 and 12 months after formation of CIRAR (Times 1, 2, and 3). We also examined the average numbers of *cliques* that developed among the members in the network, and the average effective *network size*. See Table 1 for definitions of all network measures.

To evaluate cross-disciplinary collaboration, we examined the network densities of "worked with" interactions within and among three disciplinary subgroups (Medicine, Nursing, and "Other," which encompassed Public Health, Microbiology, Dentistry, Sociology, and Education). Members affiliated with more than one discipline were grouped with their primary affiliation (e.g., a nurse epidemiologist was grouped with Nursing). To reflect growth of network by discipline we examined the change in each discipline as percent of the network at Times 1, 2, and 3.

Finally, to determine characteristics of productive CIRAR members, we examined the relationship between network position and productivity. Productivity was measured in 5 categories: 1) leading a workgroup, 2) co-authoring a publication, 3) giving a presentation, 4) participating in the CIRAR retreat, and 5) participating in a grant application. Each individual received a productivity score based on activity in each of these categories.

Table 1

Definitions and Interpretation of Network Measures Used in this Study

Network Level Measures		
Measure	Definition	Interpretation
Network Density	The density of a network is equal to the total number of connections divided by the number of possible connections. The number of possible connections assumes that each person can have a link with each other person. Normalized the range is 0-1.	Represents the extent of communication within the network. Higher numbers (above .03) suggest faster information propagation and greater group cohesion.
Overall Complexity	Combined density of all relational graphs at each time period (i.e., heard of, know work, met, worked with). The ratio of the number of links versus the maximum possible links for the meta-matrix. Normalized the range is 0-1.	This measure is a predictor of network performance. As complexity increases an organization performs better up to a (unknown) point where too much complexity results in excessive coupling and the potential for error cascades.
Network Centralization, Total Degree	The centralization of the network based on the extent to which the majority of the connections are to a small set of nodes. Expresses inequality or variance in the network as a percentage of the most unequal network possible. Normalized the range is 0-1.	Indicates whether or not there is asymmetry in the distribution of connections. It indicates the degree to which communication is centralized around a single agent or small group. More centralized groups tend to be more hierarchical in nature.
Clique Count	The average number of maximally connected subgroups. A clique is defined as subgroup of people who are all directly linked to each other.	A measure of social integration and network cohesion. Members of a clique can use their strong relations to drive the process of constructing knowledge.
Effective Network Size	The average of the observed number of each individual's personal links within the network, minus redundant links (i.e., connections to the same individual through more than one person).	Indicates the average reach of the individuals: i.e., on average, for each person, how many others are likely to get information from them or to send information to them, even if that information has to go through an intermediary.
Individual Member Level Measures		
Measure	Definition	Interpretation
Centrality, Total Degree	Number of direct connections that a person has to others in the network. Normalized the range is 0-1.	Indicates the level of extroversion. Higher numbers indicate more connectivity
Centrality, Betweeness	Measures the extent to which flows of information between diverse others pass through this person. Normalized the range is 0-1.	Indicates the extent that a person is a conduit for information. People high in this measure often influence what flows in the network, and often serve as gatekeepers and brokers of information.

We then used two measures to assess network position. Total degree centrality measured the number of ties each member had to others in the network. Individuals with many ties are most likely to receive or generate whatever information is flowing through the network. Betweeness centrality measures the extent to which an individual connects those persons who may not be directly connected to each other, thus serving as a link between unconnected people (Freeman, 1979). Individuals who rank highly on this measure serve as intermediaries who are in a position to control information flow in the network (e.g., what information is received and how it is perceived). Spearman's rho was calculated to determine if individual productivity in CIRAR was associated with these measures of network prominence.

The relational data collected by survey at the three time points in the Center's development were analyzed with the software program Organizational Risk Analyzer (ORA: http://www.casos.cs.cmu.edu/projects/ora/index.html). ORA is unique among network analysis programs because it can be used to analyze multiple networks collectively. This allows calculation of measures that reflect the complexity found in organizational systems. Analysis in ORA is based on formal logic, matrix algebra, and discrete and continuous equations (Reminga& Carley, 2005). The results are index numbers that convey aspects of the distribution of relational ties within the network (Hanneman, 2001).

Results

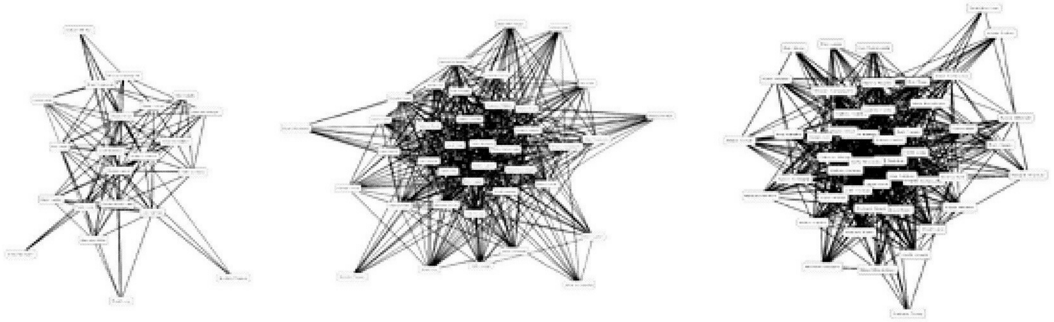
Aim 1: Patterns of Growth over Time

Network Size and Centralization

The network increased steadily in size from 22 members at Time 1, to 39 members at Time 2, and to 47 members at Time 3 -- an overall increase of approximately 113%. The "worked with" network in CIRAR showed steady increase in network centralization, from 0.21 at Time 1 to 0.41 at Time 2 and 0.50 at Time 3. Network centralization expresses inequality or variance in the network structure as the degree to which the network connections gather around a few central individuals (Scott, 2000). It can be equated with coordination in the sense of "command and control." Lower scores indicate distributed connections and higher scores suggest a more cohesive group. That is, the higher the centralization the greater the likelihood that there is one person, or a small set of people, to whom everyone is connected. Thus, over time as the CIRAR is maturing, an increasingly centralized and perhaps hierarchical organization is emerging.

These patterns are displayed in Figure 1; note the more tightly centralized core at Time 3.

Figure 1. Size and Centralization of the “Worked With” Network Over Time



Time 1, N = 22
Centralization 0.21

Time 2, N = 39
Centralization 0.41

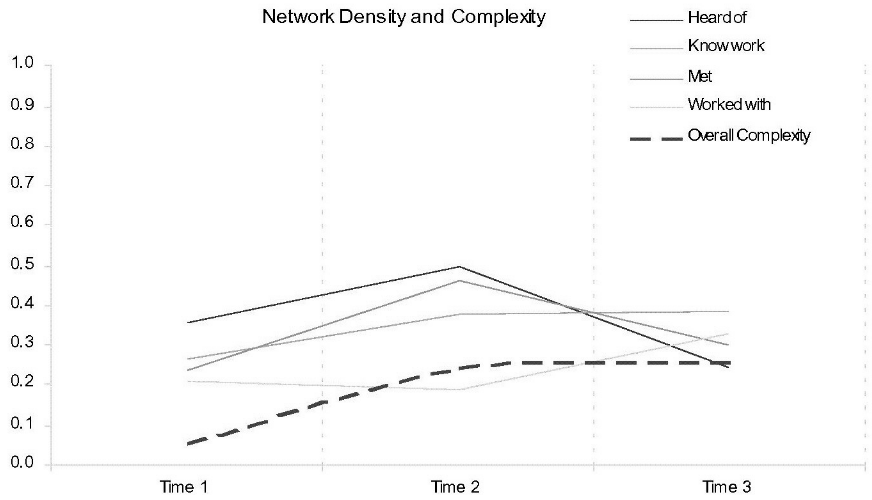
Time 3, N = 47
Centralization 0.50

Network Density and Complexity

Network density and complexity over time are compared in Figure 2. Network density describes the extent to which individuals are connected by measuring the number of connections present in relation to the number possible (i.e., as if everyone were completely connected to everyone else). Density for CIRAR’s “heard of” and “met” networks increased between Times 1 and 2 and fell between Times 2 and 3. Density in the “know work” network remained steady over time. Between Times 2 and 3 the “worked with” network showed increasing density. In other words, as the organization matured, members tended to retain a certain level of understanding of what others did (know work), even though they were less likely to have actually met these others. This suggests that the group may be moving to role-based interactions predicated on generic knowledge of what others did. At the same time, new members tended to join based on extant collaborations with current members, while current members increased collaboration, resulting in an overall increase in who “worked with whom,” despite the growth in membership.

The network complexity measure calculated all of the links recorded in the four networks we measured (heard of, know work, met, and worked with) in relation to all the links possible. The organizational complexity of CIRAR increased steadily over time, from 0.05 to 0.26, a sign of a more tightly knit organization with broadening interests and goals. The pattern of falling density and increasing complexity suggests that, on average, the typical person knew/was connected to fewer people in the overall group, but the overall group was becoming more complex as members became associated with more knowledge and activities. In general, as complexity increases, to a point, an organization will perform better due to increased connectedness (and the associated awareness of what others are doing) among sub-groups and processes (Carley, 2002) and sufficient redundancy to enable adaptivity.

Figure 2. Comparison of Network Density and Complexity Over Time



Clique Count

Cohesion in the structure of a network contributes to the creation of knowledge through shared reasoning and perspective (Burt, 2000). One indicator of cohesion is the presence of cliques – subgroups of participants within the network for which all possible links are present. In collaborative organizations cliques can drive the process of constructing knowledge by taking advantage of their strong inter-relations (Aviv et al., 2003). The average number of cliques to which a CIRAR member belonged at Time 1 was only 3. The average increased to 34 at Time 2 and fell slightly to 31 at Time 3 as research teams began to coalesce. However, there was wide variance in the clique counts, with standard deviations ranging from 0-22 at Time 1, and 0-128 at Times 2 and 3 (see Table 2). This suggests that the CIRAR was becoming more cohesive. However, whether there is a natural cap on cohesion or an optimal number of cliques (e.g., people do not have the cognitive resources to be in more than 20-40 cliques) is a point for future research.

Table 2

Measures of Network Cohesion

Measure	Time 1	Time 2	Time 3
Mean Clique Count (+/-standard deviation)	3.1 (5.48)	34.1 (41.15)	31.1 (35.60)
Minimum/Maximum	0-22	0-128	0-128
Mean Effective Size (+/-standard deviation)	1.38 (2.67)	5.14 (5.58)	6.93 (6.90)
Minimum/Maximum	0-10.2	0-18.4	0-2.6

Effective Network Size

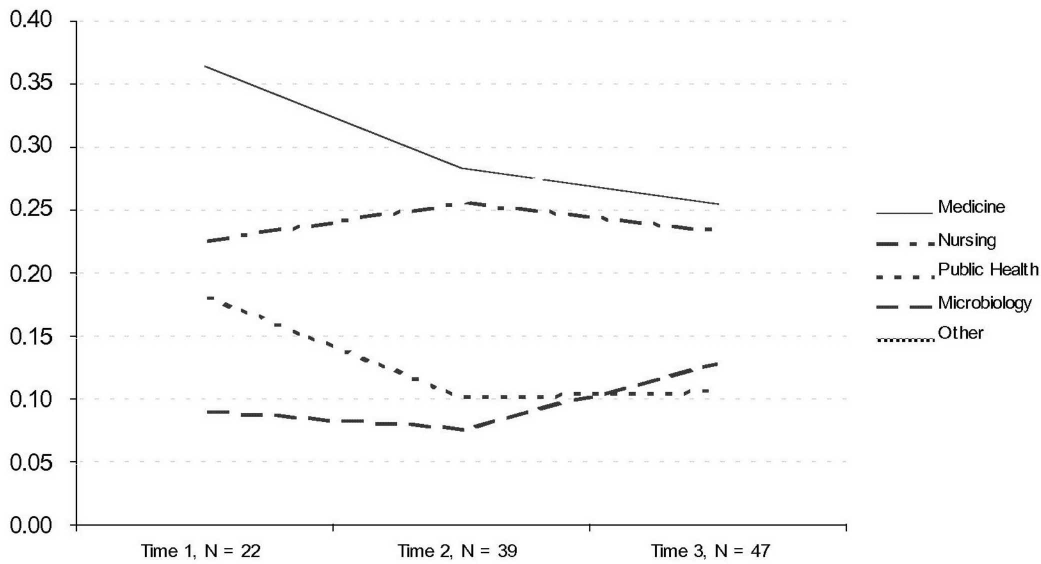
While individuals in a network may have redundant links to each other through several network members, the effective network size indicates the size of each person's network without this redundancy, and so gives a better sense of the actual number of people to which a network member is effectively linked. (Burt, 2001) On average, CIRAR's members increased the size of their personal network of connections from less than 2 at Time 1 to nearly 7 at Time 3, as displayed in Table 3. Hence, on average, over time, those who join CIRAR are likely becoming increasingly linked into CIRAR related activities by interacting with other CIRAR members.

Aim 2: Cross Disciplinary Collaboration

Disciplines as a Percent of Network

Over time, the number of members in each disciplinary group increased. At Time 1 individuals in the physician group comprised 35% of the network and were the dominant group. Nursing, public health and microbiology comprised 23%, 18%, and 9% of the network, respectively, and individuals in "other" disciplines comprised less than 15%. At Time 3, CIRAR had a more balanced membership: physicians comprised 26% of the network and no longer dominated the disciplinary makeup. Instead, individuals in the "other" disciplinary group comprised about one-third of the network. Nursing remained at 23%, public health decreased to 11%, and microbiology increased to13% (Figure 3). Essentially, over time, participation from various CIRAR sub-groups was becoming more democratic.

Figure 3. Change in Each Discipline as a Percent of the Network



Within and Between Group Densities

Over time the density of connections within the disciplinary groups in CIRAR fluctuated. Nursing started at Time 1 with a value of 1.0 (100%), indicating that all possible connections were present within the group. This fell to 78% at Time 2, and rose to 93% at Time 3. Density within the Medicine group was 29% of possible connections present at Time 1, 33% at Time 2, and 26% at Time 3. A similar pattern was found within the "Other" disciplines group, which had 17% of possible connection present at Time 1, 19% at Time 2, and 14% at Time 3. This suggests that, for most groups, members initially joined to pursue group goals, e.g., Medicine working on medicine-related matters. However, over time, as more members of their field joined; they had less in common with those in their original field.

Over time the density of connection between the disciplinary groups decreased slightly. Between "Other" disciplines and Nursing there was a decrease between Time 1 and Time 3 from 38% to 32% of possible connections present. Between Nursing and Medicine there was little change (from 30% to 29%), and there was a slight increase between the "Other" disciplines and Medicine, from 17% to 19% of possible connections present. This suggests that individuals might not be interacting across fields.

Note that we have seen three trends: 1) increased interaction overall, 2) decreases within a field or stability, and 3) possible decreases between fields. For CIRAR the number of members is likely growing faster than the connections among members. However, of those connections among members, a greater percentage appears to be between disciplines, suggesting that the group as a whole is still in a developmental stage.

Aim 3: Characteristics of Productive Members

There was a strong relationship between individuals' productivity scores and measures of network centrality. Productivity in relation to total degree centrality and betweeness centrality produced correlation coefficients of 0.75 and 0.70 respectively (two-tailed $p < 0.001$). In other words, individuals who knew more and collaborated tended to be more productive.

Discussion

As an exploratory center funded by the NIH Roadmap, the ultimate goal for CIRAR is to establish an interdisciplinary research network aimed at reducing antibiotic resistance. In this study we examined the development of CIRAR through an empirical descriptive analysis of the social network. Our results shed light on how patterns of social interactions evolved with the needs and priorities of the interdisciplinary team. The priority for the CIRAR in Time 1 through Time 2 was to expand the network and increase the familiarity among team members. During Time 3 the priority shifted to fostering emerging subgroups to work together on grant proposals. Many of the changes in network properties examined in this study reflect this basic shift in priority over time.

The period between Time1 and 2 was characterized by marked growth and increased cohesiveness. The size, density, and centralization of the network increased, suggesting that, not only did membership flourish, but members were becoming a more tightly knit group—more familiar with each other and one another's work. Growth in network density is a structural characteristic that fosters information propagation, enhances information flow, and influences how effectively individuals can act and plan future activities (Wu, Huberman, & Tyler, 2004). Growth in network centralization shows a trend toward more cohesive organizational structure. The interactions among team members were quite dispersed at Time 1, but by Time 2 and 3 had started to coalesce around focal individuals or common activities (see Figure 1). This trend is mirrored by an increase in the effective size of the average individual network. At the end of the first year, CIRAR team members on average were linked to three times as many people than at onset. These trends corroborate previously reported observations of interdisciplinary research group dynamics in which a sense of shared authority grows (Israel, Schulz, Parker, & Becker, 1998).

As the priorities of CIRAR's leadership team shifted between Time 2 and Time 3 from growth and expansion to formation of focused research teams, there were measurable changes in network dynamics. There was a steady rise in overall network complexity that reflected growth in multiple levels of associations among CIRAR team members. As the size of the network continued to increase, team members were less likely to know or have met the "new wave" of people. However, there was some increase in members working together, as demonstrated by increasing clique counts, a sign of more cohesion and potential opportunities for knowledge-generating collaborations. At the same time the variability in clique counts was great, indicating that there were many CIRAR members who were not in cliques at all, and the presence of a few quite large cliques. This pattern could be a result of all members of a clique each convincing one previous contact, who was not known by other group members, to join the center, or a few people who were already associates joining as a group. While this finding does not mitigate the positive effects of increasing clique counts over time, it does show a pattern of growth that can occur as organizations build structure, and therefore supports characterization of CIRAR as an organization still in the formative stages.

Over time CIRAR experienced changes in disciplinary make-up and cross disciplinary interactions. While at Time 1 membership was dominated by those primarily affiliated with Medicine and Nursing, by Time 3 a network emerged that was not dominated by any single disciplinary group. Also notable was the climb in team members in the "Other" disciplinary category. By Time 3 about one-third of the network fell into the "Other" category, which included those primarily affiliated with disciplines such as Dentistry, Pharmacy, Sociology, and Administration. These trends suggest that, as one might suspect, interdisciplinary centers grow in the direction of greater heterogeneity and lesser disciplinary dominance.

When we investigated the densities within and between disciplinary subgroups in the "worked with" network, the overall trend showed either slight or no meaningful difference. Due to the efforts made to forge relationships among disciplines, we expected to see little increase in density within disciplines. We did perceive that new members who joined CIRAR were working with others outside of their discipline, yet the density of connections between disciplines decreased (with the important exception of the network between Medicine and "Other"). These findings lead us to a number of insights. The absence of robust increases in connectivity within and between disciplinary sub-groups in the presence of increased density and complexity in the full "worked with" network suggests that working relationships forged within the Center may be complex and do not fall along disciplinary lines. Our findings also suggest that within- and between-group densities are of limited use for describing small sub-groups. Network density is a proportion of actual connections to all possible connections; thus, in small groups each new team member affects this ratio markedly. Finally, a study period of one year may be too short for the connections within and between disciplinary subgroups to reach their full potential.

One of our goals was to determine the network characteristics of highly productive members. We were not surprised to find that the most productive members were both highly connected themselves and well positioned to act as go-betweens to connect others. The greater the number of links an individual has translates into greater access to the flow of information. More information may translate to more insight into possibilities for cross-disciplinary interaction. Since productive individuals also served as intermediaries for others to interact and collaborate, they were in a position to participate in any work resulting from the connections they fostered. It is logical to conclude that more "connected" individuals have greater opportunities to be productive in an interdisciplinary setting. An interesting question for future research is whether the network characteristics of productive members (total degree centrality, betweeness centrality) are the result of personal traits and skills that can be taught or cultivated to improve the overall productivity of an interdisciplinary center.

Conclusions

The social network analysis of the growth of an interdisciplinary center revealed many trends that may be useful in the planning and implementation of future interdisciplinary endeavors. It also allowed us to quantify changes in size, density and cohesiveness of the Center's membership. In addition to growing in size, members also began working together more and became a more cohesive group. The Center also became more heterogeneous over time; individual disciplines decreased in percent of the total network. The most productive members of the Center were also the most connected and more likely to be those through whom others were connected to each other. We recommend the use of social networking analysis as an objective, quantitative means to assess the functioning of interdisciplinary partnerships.

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