FINAL REPORT

A MULTI-METHOD ANALYSIS OF THE SOCIAL AND TECHNICAL CONDITIONS FOR INTERDISCIPLINARY COLLABORATION

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OVERVIEW OF RESULTS

At the 1999 Annual Meeting of the History of Science Society, Sheila Jasanoff, professor of science and public policy at Harvard University and then president of the Society for Social Studies of Science, made the following remarks:

> Both historical and contemporary studies have done much in recent years to bring greater transparency to the inner workings of science and technology. Making the process of science more accessible by illuminating the normally invisible backstages of laboratories and other scientific spaces, … much wisdom can be gained from looking at science and technology as social institutions in which people collaborate and compete, struggle for credibility, seek to make livings, and yearn for success or glory … [However,] science's specialness derives from the objects of its quest, not from the strategies by which scientists try to achieve it (Jasanoff, 2000: 621).

While we agree with Jasanoff that there is value in examining the internal workings of scientific institutions, we agree with this sentiment precisely because of the importance we attribute to the process, as well as the products, of science.

This project has concerned itself with the strategies of collaboration, and specifically with those strategies as implemented in and emerging from interdisciplinary research centers. In recent years, interdisciplinarity has become synonymous with all things modern, creative and progressive about scientific research. The interdisciplinary imperative has arisen not from a simple philosophic belief in "interdisciplinarity" or "heterogeneity" but from the character of problems currently under study, many of which require the combined efforts of scholars trained in different disciplines. Thus, just as industry has used flexible, cross-disciplinary teams to spark innovation, many academics now seek new kinds of intellectual alliances to address complex social and scientific problems. As a result, interdisciplinary research centers have sprung up at universities around the country, hosting agendas, affiliates, and activities that span traditional epistemological as well as organizational boundaries.

At the same time that interdisciplinary research centers have become increasingly important at universities in the United States, we have learned little about how they originate and operate. There is a vast body of theoretical literature in the sociology of science about how interdisciplinary research *should be* organized, how scientists *might* behave in interdisciplinary collaboration, and how such activities *could be* facilitated through better management. However, to date, there is a lack of empirical work dedicated to understanding how centers *are* organized, how researchers *do* behave, and how their activities *are* facilitated. Thus, while there is a general acceptance of interdisciplinary collaboration as both a worthy and authentic component of "new" science and scientific research in theory, the idea remains largely misunderstood, misconstrued, and mismeasured in practice.

We believe that before funding agencies, university leaders, and individual scholars promote and pursue these centers further, the academic, science and policy communities should have a better understanding of the factors that influence their formation and functionality. Thus, we challenge Jasanoff's conclusion, arguing that the emergence of new interdisciplinary research centers begs investigators from the various communities of science studies to find new ways of talking about the objects of science at the same time that it also demands scholars of organizational studies to develop new ways of framing and assessing the strategies that scientists employ in their quests for these objects.

Summary of Study Objectives

Our goal with this one-year pilot project – entitled "A Multi-Method Analysis of the Social and Technical Conditions for Interdisciplinary Collaboration" – was to study the networks of a sample of six interdisciplinary research centers and the factors that condition them. Although the centers in our sample differ in organizational size, age, location, structure and type, each center has been assembled for the express purpose of conducting interdisciplinary research and research training.

Using techniques of social network analysis and ethnographic methods, the specific objectives of the pilot study were three-fold:

1. To model the structure, relations, and positions of the research networks in each of the different centers of our sample;
2. To assess the relationship between the attributes of the individuals engaged in these networks, the conditions of the organizations that host them, and the nature of the interactions that populate them; and,
3. To identify "hotspots" of interdisciplinary academic collaboration within these networks.[1]

This study was not designed to evaluate the research outcomes produced by these centers, but rather to explore the research practices and processes, as well as the researcher positions and relations, within these organizations. We were particularly eager to understand, for example, if, when, and which researchers of different disciplines interact; in what activities they engage; and, how they learn about each other's approaches, borrow each other's tools, and create new techniques while working in interdisciplinary research environments.

The formative theory guiding this study is itself interdisciplinary, and was generated from pre-existing findings in the literature on the sociology of knowledge, the sociology of science and innovation, organizational learning and development, and organizational social psychology. Moreover, like Rousseau (1985), we believe that any theory about organizational processes must explicitly address the level of analysis with which studies addressing organizational phenomena are concerned. Thus, the framework bracing this study took a multi-level approach, meaning that we considered variables at the individual, relational, and organizational levels of analysis. Specifically, we tested for the effects of the following four variables on researcher inter/actions: (1) disciplinary affiliation, (2) professional background, (3) interdisciplinary exposure, and (4) institutional context (e.g., organizational size, organizational age, organizational structure).

By addressing the three objectives, the results of this study accomplish three things:

1. Inform the current debates in science, research, and policy about what interdisciplinary research "should be" with heretofore unavailable evidence of what interdisciplinary research "is and can be."
2. Offer valuable theoretical, methodological, and empirical insights that advance the literature in sociology of science, science and technology studies, research policy and management, higher education, and social network analysis.
3. Provide the participating centers as well as other interested parties with observations and recommendations that will be directly useful to them in their ongoing efforts to develop and catalyze interdisciplinary research and research training.

[1] It is only in the next phase of the study that we will be able to focus in greater detail on what is actually being produced and/or innovated at the interactional "hotspots" identified in objective 3.

These combined results are key to informing current conjectural notions that underlie ideas about the practices and processes of interdisciplinary research centers today and will be critical to clarifying future methods and metrics that can better support such centers tomorrow.

Summary of Study Findings

On the one hand, our cross-center analyses of survey responses regarding research practices and processes suggest that a transformation toward interdisciplinary research has in fact begun *in* the centers as well as *due to* the centers we examined. On the other hand, like other recent studies, our individual center-by-center analyses of research positions and relations imply that the transformation toward interdisciplinary research in these centers may be more subjective than objective and more individualized than generalized.

First, we found that, on average, 60% of researchers believe that the research he/she does inside the center qualifies as multidisciplinary or interdisciplinary. This compares to a mean of only 51% who describe the work they do outside the center as multidisciplinary or interdisciplinary, which suggests that the research centers have increased the multi/interdisciplinary research opportunities of their affiliates by almost 20%. Moreover, our research implies that, in addition to expanding the interdisciplinary research actions of center affiliates, the centers in our sample are also contributing to the initiation and facilitation of interdisciplinary research interactions between center affiliates. From our data, it appears that, on average, 84% of the current connections between researchers within a center were initiated after the founding of the center. And, a comparison of the research relations that have predated the centers with the research relations that currently occupy the centers reveals an increase in the diversification of represented disciplines.

Second, it also seems that center affiliates tend to interact with about 10 other researchers from their center at least weekly and with about 14 researchers monthly or less, with some evidence of cross-disciplinary exchange particularly at the level of monthly interactions. Thus, and as our interview data support, the interdisciplinary research opportunities emerging from these centers are both collaborative and independent in nature. It is also worth noting that the most popular – if not preferred – method of collaboration and particularly interdisciplinary collaboration is via informal face-to-face interactions as opposed to either technologically-mediated or formal venues of collaboration. We find this particularly important in light of current interest in “cyber-structures.” While we do not disagree with the benefits that technology can offer collaborative science at a distance, we warn that it alone is not an alternative to the interpersonal exchanges that are the foundation of working research partnerships.

Third, in addition to increasing, initiating and facilitating opportunities for interdisciplinary research inter/actions within the centers, our research suggests that the centers in our sample are also influencing the research agendas and career trajectories of center members outside the centers. On average, 83% of researchers believe that their participation in the center has positively influenced their own research agenda and 74% believe that this participation has positively influenced their career trajectories. Thus, even though a significant majority of the researchers report positive influences on both dimensions of their academic development, it does appear that, at least in the current structure of academia, the intellectual benefits of interdisciplinary collaboration outweigh the professional rewards to some degree.

Moreover, in this analysis, we found there to be a clear and negative correlation between the number of graduate students in the center and the percentage of affiliates who feel the center has had a positive influence on career development. While our sample is too small to confirm

this correlation as causation, our ethnographic data corroborated the idea that graduate students perceive and/or experience fewer positive effects, and in some cases even more negative effects, of interdisciplinary research center affiliation on their careers than other center members. Nevertheless, while most concerned about the professional repercussions at an individual level, the graduate students in our sample were often the most enthusiastic about the epistemological need for, and were engaged in the scholarly practices of, interdisciplinary research.

Fourth, the stakes of the professional cost-benefit calculation that researchers must make around participating in interdisciplinary research centers become even higher when one considers the investment side of the equation. We found that, on average, researchers commit approximately 50% of their total work time to center-related inter/activities. We consider this to be a substantial allocation given that in many cases – if not most – interdisciplinary and center-based research is often not recognized favorably or reviewed equally when compared to disciplinary and department-based research at the time of student and faculty evaluations. Not only does this finding in combination with the above raise implications for faculty reward systems, but these results also raise questions about the impact of these centers on the nature of faculty identities and loyalties and about whether and how the university structure can accommodate faculties with multiple affiliations versus single institution, department, and discipline associations.

While the aggregated survey responses regarding research practices and processes do not allow us to distinguish between the multidisciplinary versus interdisciplinary nature of their research inter/actions and inter/activities, our analysis of the individual center research relations provide more detail in this area. What this aspect of our research first suggests, generally speaking, is that the networks in each center actually appear to be more multidisciplinary than interdisciplinary in the end. In other words, the centers and the networks that occupy them tend to demonstrate more of an inclusion, rather than an integration, of different disciplines.

In fact, the networks in all centers even reveal specific instances, albeit to varying degrees, in which there are clear divisions between represented disciplines and distinct clusters of monodisciplinary relations. This is particularly true where the “functional distance” between disciplines represented by researchers is greater and at the level of knowledge creating versus information sharing. This is not a critique of the centers but rather a commentary on their stage of development. It is not uncommon for collaborative organizations and programs to stall at a point of parallel multidisciplinarity on the way toward fully integrated interdisciplinarity.

Second, as part of our network analyses, we considered the relations of participating researchers both in terms of what they report as close – “knowledge creating” – collaborations and as collegial – “information sharing” – collaborations.[2] It appears from the networks we produced that, on average, center researchers tend to have 14 connections overall – eight information sharing connections and six knowledge creating connections – with other researchers in their respective centers. We also know that, when controlling for researchers’

[2] We asked survey respondents to qualify their relationships to other researchers as close, collegial, familiar, or distant. A “close” relation refers to someone “you count among your closest professional and/or intellectual collaborators … with whom you share notes, data, findings, etc; with whom you develop projects, ideas, and concepts as well as prepare papers, documents, presentations; with whom you engage intellectually and/or from whom you seek research direction and advice.” A “collegial” relation refers to “someone with whom you talk and share information, data but you don’t count him/her among your closest collaborators.” you count among your closest professional and/or intellectual We did not analyze relationships considered familiar or distant as these were defined as having no professional or intellectual nature.

disciplines and considering only their interdisciplinary connections between researchers, both the average number of information sharing connections and the average number of knowledge creating connections held by a researcher decrease to five and three, respectively. This compares to an average of three information sharing and three knowledge creating connections to researchers of the same discipline.

While the total number of possible interdisciplinary versus disciplinary connections at either level varies by the distribution of disciplines represented in a center, the fact that fact that there are more information sharing connections than knowledge creating connections between researchers overall and between researchers of different disciplines suggests to us that collegial rather than close relations may dominate the work of the centers in our sample. This finding is neither unanticipated nor inauspicious. The most recent organizational theories on the process of cross-functional teams in industry suggest that too high degrees of closeness among team members may actually suppress innovation. The theory is that highly close groups focus more on maintaining relationships and thus tend to seek concurrence rather than difference regarding ideas. Given that much of the motivation behind interdisciplinary research centers is the desire for intellectual innovation while the reality of academia is the need for scholarly publication, this finding raises questions about how interdisciplinary information sharing connections – which might be critically creative but not immediately productive – can be adequately enabled by interdisciplinary centers and also properly acknowledged by the larger university structures and cultures.

Third, moving from researcher relations to researcher positions, our data indicate that center directors consistently occupy the most central positions – the "hubs" – in the research networks, meaning they tend to be the most connected to all other researchers in the center. Beyond the center directors, there is no other significant correlation between an individual's position as network "hub" and his/her professional rank, and the professional rank of those who play this role ranges from graduate student to full professor. However, apart from center directors in this specific "hub" position and in contrast to our original hypothesis, as a population senior faculty do not consistently represent the most central group of researchers in the centers' networks. Instead, it appears that graduate students are often more centrally integrated in the networks than are senior faculty – particularly at the level of knowledge creating activities.

Fourth, in contrast to "hubs," who have the most overall connections to other researchers in the center, "bridges" refer to researchers who have the most cross-disciplinary connections to other researchers in the center. As we hypothesized, researchers from "hybrid" disciplines or researchers with higher rates of previous interdisciplinary exposure tend to hold this position in the centers. And, more importantly, we found that with the exception of some overlap by some of the center directors, those who occupy the "hub" positions in a network are *not* the same individuals who serve as the interdisciplinary "bridges" in a network. Whereas the former are often content experts in their respective fields (regardless of rank), the latter are most often graduate students and/or frequently methodologists or technicians.

The most interesting take-away from these two findings related to position is the centrality of graduate students to the overall network and to the interdisciplinary network in particular. This is especially interesting given our earlier finding of a negative correlation between the proportion of graduate students in a center and the percentage of center affiliates who report positive influences of the center on career development. As we stated above, we know from our interview data that, despite the real or perceived professional risks, many of these graduate students are motivated to seek or to accept assignments in interdisciplinary centers because of

their intellectual interests and epistemological values which attach importance to interdisciplinarity.

Thus, we believe that for these centers to be effective and productive over the long term, universities must recognize these intellectual and epistemological factors as being the primary motivations for center affiliation and to respond to these factors not just by creating more centers but also changing broader university structures and cultures to respect and reward these interests and values. We think it is telling that there are very few assistant professors in our sample of centers and warn against the possibility of attrition from these centers as current students become future faculty in today's departmental and disciplinary-oriented university.

Finally, in addition to thinking about the effect of individual attributes on researcher relations and positions, we were also interested in determining the influence of a center's immediate institutional context on its research networks. Although the analysis of our ethnographic data is not yet complete and thus our results in this arena are not fully developed, a few critical points regarding context have already emerged. First, in terms of organizational size, we found that increases in center size from small (less than 20) to medium (21-50) may increase the number of information sharing ties but not knowledge creating ties, and that increases from medium to large (more than 51) do not appear to increase either of the two.

Moreover, in fact, the data suggest that increases in center size from medium to large could actually *decrease* the number of interdisciplinary knowledge creating activities without improving interdisciplinary information sharing activities. These findings lead us to believe that despite current trends toward large centers, smaller and medium size centers may be more conducive and productive to interdisciplinary inter/activities. Specifically, for interdisciplinary centers in which the intent is to have both knowledge creating and information sharing activities, we recommend an organizational structure which houses several small close collaborations of between 10 and 15 researchers but allows for more informal, less intense interaction between 40 and 50 researchers total.

Second, we found that the average duration of researcher connections and the frequency of researcher interactions are more significant in determining the nature of research relations than the age of the center itself. Within that, our findings suggest that the density of and enthusiasm around knowledge creating collaborations seem to peak between two and four years, whereas information sharing collaborations can often be beneficial initially and immediately. And, in fact, our interview data lead us to believe that while longer organizational life cycles give centers the time needed to perfect research practices and processes to support of the center's research and researchers, individual long-term and full-time affiliations for researchers can actually limit rather than accentuate researcher interaction and innovation.

On the one hand, we found that history between center members can lead to positive interpersonal relations and thereby to a sense of commitment to the other people with whom they are working. However, on the other hand, we found that too much history in one center over long periods of time tends to lead to stronger feelings of ambivalence toward rather than commitment to the center and its other members. Researchers tend to develop negative feelings about a center the longer they are locked in, whereas researchers who feel freer to enter and exit collaborative relationships and to balance them with other aspects of their professional lives expressed more satisfaction with the process and the outcomes of the interdisciplinary center.

Third, we found that, generally speaking, all the centers in our sample lack a unified and unifying theme, problem, or product around which to organize their work. Moreover, in most

cases, the centers in our sample have adhered to researcher affiliation practices that have resulted in the implementation of research networks looking for tangible points of intersection rather than in the designation of research problems finding networked solutions.

This lack of organizing principle may explain to some extent why there are more information sharing than knowledge creating inter/activities in each of the centers in our sample. We believe that without concrete objects or objectives clearly uniting the work of researchers, particularly researchers of different disciplines, centers have little chance of becoming more than simple reconfigurations designed to attract new funds to old research. And, the end result is a nexus of loosely defined and often only financially connected set of institutions and individuals with no investment in enduring the costs of collaboration and no ongoing purpose for waiting out the benefits of collaboration.

Fourth, a large percentage of researchers reported having learned from their involvement with the center that the gap between the physical and social sciences is not as big in reality as it is in myth. However, many also acknowledge that this myth is often stronger than reality, resulting in comparatively low levels of interaction between the social sciences and the physical sciences or the life sciences within the centers of our sample of centers. We believe that this is due in large part to the fact that centers where there are social scientists (which was only half of our sample to begin with), there is a lack of understanding about what is meant by social sciences versus societal impacts. Despite the significant gap between “social science” and “societal impacts,” many of the natural science-oriented interdisciplinary centers and programs have conflated the two (if they involve social sciences at all). This has resulted not only in a disservice to social science disciplines but feelings of frustration and alienation on the part of social scientists toward such programs and, consequently and more importantly, a lack of involvement and integration of social sciences in a manner that can really push the research on some of the complex interdisciplinary problems toward solution.

In conclusion, we argue that interdisciplinary research centers cannot be expected to succeed in attracting and maintaining quality researchers and in promoting and producing quality research over the long term if they continue to be implemented within a larger university structure and culture that does not recognize the operational goals and reward the intellectual objectives that such centers were designed to accomplish.

As we have noted above, the rise of interdisciplinary research centers challenges the ability of disciplines, departments, and even universities to claim exclusive rights to researcher inputs and outputs as they have in the past. We argue that, in order for researchers to function effectively in these centers within the academic context, the university must learn to accommodate institutionally and professionally what Brown and Duguid (2000) describe as *networks of practice* and *communities of practice* rather than rely on traditional departments alone.

Networks of practice constitute the broad social systems through which researchers share information, whereas communities of practice are tighter-knit groups that work together directly to produce new knowledge. As more researchers divide their time between interdisciplinary centers and disciplinary departments, these collaborative networks and communities will not only become more important sources of ideas and more common arenas of work for researchers, but they will also present more complicated boundaries of responsibility and more conflicted terrains of commitment for students and faculty alike.

The idea of managing interdisciplinary research, therefore, raises a number of fundamental questions about the relationship between these research centers and the university context – as

does the idea of rewarding interdisciplinary researchers. In the current academic structure, the value of research and researcher alike is usually measured by the production of new knowledge as published in learned journals. While such tangible forms of knowledge emerge from individuals and small communities of practice, networks of practice do not generally take action nor produce new knowledge either immediately or directly. However, as we have indicated above, the intangible information sharing that occurs through such networks is perhaps the most central and creative aspect of the interdisciplinary research collectivity. It is the most common output of the interdisciplinary research process, at the same time that it is one of the most under-appreciated and unrewarded activities within the current academy.

Finally, for interdisciplinary research centers to be successful organizations that can address new research problems – rather than simple reconfigurations that may allow old research practices – the centers must be populated with individuals who can serve as both "hubs" and "bridges." As we noted above, these two positions require different skills and assets. Thus, in addition to learning how to manage and reward these centers and their participants, universities will also have to reconsider the priorities and practices of graduate education and training in preparing individuals for such centers. We argue that graduate programs must not only educate future scientists to be experts in the methods, techniques, and content of specific disciplines but must also contemplate how to teach future scientists how to constantly learn, unlearn, and relearn across disciplines.

Moreover, as we have reported, in many cases graduate students are already beginning to take on "bridge" roles and becoming key players in the interdisciplinary research networks of these centers. We do not think that this is either purely coincidental or simply circumstantial. Rather, based on our interview data, we believe that graduate students are turning toward interdisciplinary centers in lieu of departments and in the hope that they will provide alternative platforms where the ideas that interest them can be pursued more readily.

There has been a groundswell of discussion about the current complexity of scientific problems demanding interdisciplinary treatments. And, while this has lead to a clear programmatic shift among many government agencies and university administrators toward funding and founding more interdisciplinary research centers, we believe it has actually signaled a much deeper, truly paradigmatic shift among younger scholars. Our conversations with graduate students indicate that many young scholars today are attracted to interdisciplinary research not only because they identify the potential for scientific discovery, but also because they equate interdisciplinary research with the opportunity to apply these discoveries to societal problems. Without conflating interdisciplinary science with applied science (or social science with societal implications, for that matter), we believe this dynamic between discovery for the sake of science and the application of science for the sake of society presents is a moment of academic redefinition and university reform, at the center of which – if implemented correctly – could and should sit interdisciplinary research centers.

Based on our analysis of the form and function of such centers, to be done correctly, interdisciplinary research centers need to be well-funded, well-respected organizations, which have an independent physical and intellectual center outside of and different from a traditional university department. These centers must have a clearly identified and mutually understood organizing principle – be it a problem, product, or project – around which researchers are then selected on the basis of a specific technical, methodological, topical contribution and to which researchers are fully committed on the basis of a general intellectual, epistemological, personal belief.

While we believe that the center should be established as a long-standing organizational body with continuity in management, its researchers should be appointed for flexible, intermittent but intensive short-term (e.g., week-long) stays that are dictated by the scientific needs of the problem, product, or project rather than by the administrative mandates of the organization. Not only will rotating appointments of this type better serve the science of the center, but they will also allow researchers to experience new communities of practice and build extensive networks of practice that will satisfy their intellectual curiosities without jeopardizing their professional responsibilities. We believe this presents a new model of academic organization that we have not readily observed but for which the university must be ready to support if these interdisciplinary centers are to achieve the success they are designed to deliver.

RESULTS OF STUDY

PARTICIPANTS

The principal participants in this project were the following:

- **Diana Rhoten, Ph.D.** (principal investigator): research director, The Hybrid Vigor Institute and assistant professor of education, Stanford University;
- **Denise Caruso** (co-principal investigator): executive director, The Hybrid Vigor Institute; and,
- **Andrew Parker** (consultant): senior research consultant, IBM Institute for Knowledge-Based Organizations (IKO) and prospective Ph.D. student of sociology, Stanford University.

Additional participants included the following individuals, all of whom served as part-time Project Advisory Committee Members:

- **John Seely Brown, Ph.D.**: former chief scientist, Xerox and former director, Xerox PARC;
- **Lisa Faithorn, Ph.D.**: manager of collaborative research, NASA Astrobiology Institute;
- **Claire Fraser, Ph.D.**: president, The Institute for Genomic Research;
- **Walter Powell, Ph.D.**: professor of education and sociology, Stanford University;
- **Denis Prager, Ph.D.**: president, Strategic Consulting Services and former director of health programs, The MacArthur Foundation;
- **Stephen Schneider, Ph.D.**: professor of biology, Stanford University;
- **Margaret Somerville, Ph.D.**: professor of law and of medicine, McGill University;
- **Richard Zare, Ph.D.**: professor of chemistry, Stanford University.

The Hybrid Vigor Institute – a private, non-profit 501(c)(3) organization founded in April 2000 – was the sole organization involved in the management, administration and implementation of project activities.

ACTIVITIES AND FINDINGS

The activities of this project were exclusively research-based. Below, we describe the methods, sample, and challenges of these activities.

Research Activities – Methods

Our research employed multiple methods from empirical social science research, combining techniques of social network analysis with those of ethnographic fieldwork. While social network analysis was the appropriate method for guiding data collection and analysis given that our focus is on patterns of interaction, ethnographic description was required to explain and add substance to the abstract measures and structures derived from the sociometric data. Together, social network and ethnographic methods offered a valid and reliable approach that allowed us to distill and compare the structural essence of the different networks in our centers as well as describe and explain the individual, relational, and organizational factors that shape and influence the networks.

To manage this mixed-method approach, we divided the study into two sections, or, as we preferred to call them, “strands” (which correctly implies the simultaneous nature of the two activities).

Strand I – the social network analysis component – employed survey and bibliometric methods to collect individual, organizational, and relational data related to the researchers in the centers of our sample. These data were then analyzed using software and techniques of social network analysis.

Full network methods require information about each actor as well as each actor’s connections with all other actors. To gather relevant data on researchers attributes and interactions, we conducted a survey with the population of researchers in each center in our sample by means of census. In the first part of the survey, each researcher was asked a short series of closed-ended questions related to **individual attribute data** (e.g., researchers’ professional history, disciplinary background, and interdisciplinary exposure). In the second part, each researcher was given a full roster of all researchers affiliated with the center. Each respondent was then asked a series of questions designed to collect **relational data** for each person on the roster: What is the nature of your interaction with this person (e.g., data sharing, paper writing, project development, etc)?; How long have you had a relationship with this individual?; With what frequency do you interact with this individual (e.g., monthly, weekly, daily, etc)?; Via what forums do you interact with this individual? (e.g., center-wide meetings, email correspondence, formal project discussions, informal conversation, etc). In the third part of the survey, researchers were asked a series of closed-ended questions pertaining to **organizational practices and processes** of the center (e.g., collaborative projects versus independent projects, mono- versus multi- versus inter-disciplinary research strategies, reward systems and incentives, researcher time commitments, etc). A copy of each researcher’s curriculum vitae was also collected to (a) confirm researcher attributes related to professional background, disciplinary training, and interdisciplinary exposure; and, (b) to explore what, if any, products (e.g., publications, patents) have come from research interactions reported in and identified by the survey.

Once collected and amalgamated, these data were analyzed using the network software packages of *UCINET* to measure and *NetDraw* to draw the structures, positions and relations of the research networks in our sample. We have found that the two most useful group measures for analyzing the structures and relations of our networks have been **density**, which looks at the level of connectivity across the whole network, and **centralization**, which looks at the distribution of links between people in the network. With respect to measuring individual positions, we have used **centrality** to look at how many connections each person has in the network. By overlaying the individual attribute and organizational factors data also collected in the survey, we have been able to assess the effects of different variables on the shape and structure of our networks. Based on the hypothesis we originally proposed, we have used these data to test for the **individual variables of disciplinary affiliation, professional background and interdisciplinary exposure** and the **organizational variables of size and format.** Our analysis has resulted in a set of sociograms and metrics that visually depict and quantitatively measure the research networks within each of the centers in our sample. While the sociograms make visible the otherwise invisible connections between researchers, the quantitative analyses make comprehensible the otherwise incomprehensible complexity of these connections. Together, these products represent a first and important step toward developing a way of measuring and classifying the forms and functionalities across our small sample interdisciplinary research centers.

Although network analysis is an extremely useful way to understand the relationships between people in a particular group it does not necessarily uncover why certain relationships are present or absent. Thus, **Strand II took an ethnographic approach** to understanding the context of and the dynamics between the researchers within each of the centers in our sample. Observations, interviews, and artifacts/documents were used in Strand II to collect additional individual, relational, and organizational data in order to better situate our analysis of the networks above in an understanding of the factors that shape them.

Interviews were conducted with a systematic sample of researchers in each of the centers in our sample ($n \approx 13$). We used the network analysis to determine which people to interview in each center, looking for those who appear to play certain roles within the center (e.g., those who are central, peripheral, and intermediary players). To get a varied but representative sample of perspectives, we also selected people on the basis of disciplinary affiliation, professional rank, seniority in center, and institutional home (in the case of inter-institutional centers). The interviews were semi-structured. In addition to general personal and professional demographic information, categories of inquiry included: motivations for joining center, activities undertaken at the center, tasks in and responsibilities to the center, communications and interactions with center colleagues, structure and culture of working relations, center-based research products (tangible and intangible), personal and collective costs and benefits of center affiliation, influence of center on research and career, personal knowledge values and center knowledge values, organizational management and leadership, etc. Each interview was audio-taped, transcribed, and coded for analysis by Rhoten. Questions related to the researcher's history, background, and exposure as well as current interdisciplinary practices were corroborated with data from his/her vitae collected in Strand I.

Observations of events from day-to-day research activities within the centers to scheduled meetings, presentations, formal and informal social activities, etc. were also made. Like the interviews, the observations were also semi-structured as opposed to unstructured so as to focus specifically on behaviors that are reported to occur (or not) by researchers in the interviews and surveys. Artifacts and documents (e.g., organizational communiqués, research reports, publications, etc.) helpful in our understanding the context and dynamics of the center were also collected.

The data from Stand II were used to illustrate the networks identified in Strand I with an understanding of the factors that condition their structure, positions and relations. The results are being used with the sociograms to describe *how* and *why* the dynamics of information sharing and knowledge creating relations operate in the different centers, based on the conditions and processes of the networks in which the researchers and disciplines are embedded. We have found that the narrative analyses produced in Strand II have dramatically enhanced our ability to explain the overall patterns as well as the unique nuances we have identified in the networks in Strand I of the study.

The following subsections provide more detail on how these methods were applied to our sample and some of the challenges we encountered when applying them.

Research Activities – Sample

Our sample was created, using both purposive and convenience sampling methods, from the population of centers funded by the NSF Environmental Research and Education portfolio. First, "Introductory Study Letters" from the Hybrid Vigor Institute were sent along with "Invitations to Participate" in the study from Margaret Cavanaugh (Staff Associate for the Environment, NSF)

to the population of active NSF ERE centers. Second, from the centers that responded positively to the letter and invitation, we selected eight on the basis of organizational type, composition, and age to create a diverse but representative sample of centers which:

- cut across the eight key initiatives that sponsor centers within the NSF ERE portfolio (e.g., the Science and Technology Centers Program, the Human Dimensions of Global Change Program, the Long Term Ecological Research Program, etc.);
- host various degrees of disciplinary diversity and disciplinary distance;
- represent different organizational ages, sizes, structures, and formats; and,
- house research as well as education and training components.

Our original sample of eight centers was ultimately reduced to six, however. Shortly after the study began, one center dropped out of the project because it had received notification that it would not be awarded renewal funding, and the director felt that affiliate attitudes toward the study would be biased as a result. Midway through the study, a second center was eliminated from the project on the basis of a lack of sufficient data, both in terms of quantity and quality. Although the size of our sample was affected by the loss of these two centers, neither the diversity nor the representativeness of the sample was compromised. (See Table A for details on each of the centers in our sample.)

Initially, we planned to subject all of our sample centers to the social network analysis component of our study (Strand I) but to focus the ethnographic analysis on only two centers (Strand II). For this purpose, we chose two centers from our sample on the basis of the diversity of disciplines represented in the centers. We considered selecting a “more diverse” center — with more disciplines as well as greater epistemic differences and cognitive boundaries between the disciplines — and a “less diverse” center — with fewer numbers of disciplines and disciplines with less distance between them. However, given that gaining a better understanding of interdisciplinarity was our primary interest, we decided to select two “more diverse” centers in order to explore the dynamics of cross-disciplinary information sharing and knowledge integration/creation in more than one setting.

Mid-stream in the project, after reviewing preliminary results of the surveys and site visits, we realized that a more robust analysis would result from a study that looked at the context and dynamics in all six centers in our sample rather than just two. Although this made for a slightly more complex research design, it was clear that the illustrative value of the qualitative fieldwork data was too important to the analysis of the quantitative network data. Based on this determination, as made by both project personnel and project advisors, we altered the final research design to complete the data collection schedule reported in Table B.

As the table reveals, we completed **surveys in six centers** (mean yield rate = 73%) and conducted **site visits in five centers** (mean number of interviews = 13). Due to scheduling conflicts and the seasonal nature of the center, we were not able to visit the sixth center before the close of the grant period.

Research Activities – Challenges

One of the biggest concerns we had when initially formulating the study was whether or not we would be able to gain access to enough centers to create a sufficient sample. We were concerned that (a) despite our efforts to clarify that the study was not an evaluation, prospective centers might fear that future NSF funding could be affected by any findings that could be perceived as “negative”; and (b) because the majority of centers are dominated by engineers,

physical scientists, and life scientists, dominant epistemological biases and preferences might make them resistant to being studied by social scientists. As it turned out, more centers responded to the invitation to participate than could be included in the study. Moreover, once center directors enlisted their centers in the study, the majority of research affiliates with whom we communicated, expressed not only an intellectual but also a personal and professional appreciation of the study. Unsolicited, anecdotal comments included statements such as the following: “I really enjoyed the interaction with [the center] and want to do everything to help showcase the importance of what they do, of what interdisciplinary research can do”; “I have found it very difficult to manage collaborations, I feel like we are flying by the seat of our pants. I am glad that someone is looking into these issues. It is important work not only for us but for interdisciplinary research collaborations in general”; and, “There is a real interest, a real need, to understand how to do [interdisciplinary research] more systematically, to make it more effective. [Interdisciplinary research] is really difficult but so essential to the future of science.”

Having averted the challenge of gaining access to centers, we faced the problem of determining the boundaries of the centers. For many centers, there are lists of “affiliates” that run the gamut from currently active, previously active, sometimes active, and never active researchers. Identifying and standardizing research center populations across centers with different structures and forms was not the simple task we had originally anticipated. We resolved this issue by defining researcher “participation” as meeting a minimum of two of the following three criteria: “attends center-wide meetings, engages in center-related research activities, and/or receives center funding.” Once we determined these criteria, “official” center affiliate lists had to be collected from center administrators, preliminarily edited into “unofficial” but active center affiliate lists by us (based on websites, reports, etc), and then confirmed as “official” and active center affiliate lists by center administration.

Once the center’s population were defined and confirmed, we then faced issues related to surveying that population. For all but two of the centers, the survey was first posted online at the Hybrid Vigor Institute website (for Center 1 and Center 6, the survey was administered on-site and in-person). As soon as the survey was posted online for a center, Rhoten sent all active center affiliates a standardized group-formatted email announcing the survey and providing directions for locating and logging on to the survey. Surveys were fetched from the database on a bi-weekly basis and individual respondents as well as aggregate response rates were recorded in the Internal Project Survey Log. After two weeks, a second standardized, group-formatted went out to all research affiliates in the center, thanking those who had completed the survey and encouraging those who had not yet responded. Within two weeks of that notice, a third email went out only to research affiliates who had not yet responded. Each of these emails was individualized and personalized. This third email also informed the recipients of alternative methods for completing the survey by email, post or fax. Within three weeks of that notice, a fourth email notice – also individualized and personalized – was sent to all remaining non-respondents in the center. Attached to this email was a “short version” of the survey, which gave the researchers yet another option by which affiliates could respond. Within two weeks of the “short version” survey, a fifth and final email – again individualized and personalized – was sent to the non-respondents, explaining the importance of their participation to the overall reliability and validity of the study.

While this multi-phase follow-up strategy resulted in a comparatively high survey response rate given the length of the survey as well as the characteristics of the population surveyed, the process was extremely labor intensive. In the end, our mean response rate of 73%, which would be considered a satisfactory to very satisfactory yield rate for most survey types, was only

enough for us to analyze the bi-directional data (e.g., “with whom do you interact?”) but not the uni-directional data we collected (e.g., “to whom do you go for methodological assistance?”). Parker (project consultant) has found – based on the results of more than 40 previous studies – that, with social network surveys, a response rate of about 85% is needed to produce an acceptable picture of the structure of a network. With lower response rates in the 65% to 80% range, it is possible to use the responses of the respondents to substitute for those of the non-respondents by symmetrizing the data. But as indicated above, symmetrizing the data can of course only be done if the network question asked is bi-directional and not uni-directional. Fortunately, our primary questions were bi-directional in format, and thus we were able to collect and symmetrize enough data for six of the seven centers in our study. That said, of those six centers, the response rate for Center 7 was sufficiently low enough that, even after symmetrizing the data, the results are only of informational value and not of publishable quality. In the future, we plan to use shorter surveys from the beginning in the hopes of simultaneously reducing follow-up strategies and increasing overall response rates.

Once the data were collected, the next major challenge had to do with data coding, specifically data related to respondents’ disciplines. In addition to asking scientists to report the discipline in which they received their highest degree, our survey also asked people to identify the discipline(s) to which they currently consider themselves belonging. Based on feedback from the pilot survey, we made the strategic decision to ask this latter item in the format of an open-ended question. This format was successful in that it allowed respondents to locate themselves as accurately as possible in the universe of potential disciplinary affiliations rather than constraining them to a pre-defined set of fields. The format proved complicated, however, in that (a) respondents often listed multiple disciplinary identifications with varying degrees of relevance and relation to their work and/or their training (we know from comparisons of surveys to CV’s), (b) respondents often listed topics or areas of research rather than disciplines or subdisciplines, and (c) respondents sometimes used dissimilar labels to refer to similar disciplines.

The complexities and discrepancies of respondent answers taught us that what had seemed a basic and unassuming demographic question was in fact a complicated and nebulous phenomenon of inquiry. And, respondent answers to this question revealed some important identity-related problems with which many interdisciplinary researchers and research centers must contend: Does one identify the discipline to which he or she belongs based on one’s discipline(s) of training or retraining, discipline(s) of practice or preference, discipline(s) of publication or position, discipline(s) of department or assignment, or discipline(s) of most recent interest, most rewarding project, or most relevant epistemology? Thus, these complications not only had important implications for how we proceeded with coding our data but also for how proceeded with framing our analysis.

We decided that because all the above influences can and do determine one’s disciplinary affiliation, it was critical that a full profile be developed for each researcher before identifying his or her discipline. This was done through an analysis of each researcher’s survey as well as his or her CV, departmental/institutional materials, project and laboratory websites, personal homepages, etc. Once Rhoten created a profile for each researcher, she analyzed the profile and identified a single and primary discipline for each researcher. It is important to note here that we had to default to a single and primary discipline for each researcher because of the limits of the analytic and visualization software available for social network analysis. This discipline “attributed” by Rhoten was then compared to the researcher’s “reported” discipline. When a discrepancy existed between the two, Rhoten generally deferred to the attributed

discipline in order to assure greater standardization in coding. In instances, where the degree of variance between the attributed and self-reported discipline was great, Rhoten contacted the researcher for verification. Once a single and primary discipline had been attributed to all of the researchers, the disciplines were recorded by Rhoten using a coding sheet she expanded from the Degree Fields and Occupational Categories used in the NSF Scientists and Engineers Statistical Data System. The use of this coding sheet helped to ensure that "recorded" disciplines were coded in the right categories and subcategories, at the same level of specialization and did not use different names to refer to the same field.

From the perspective of the project personnel, analyzing the disciplinary affiliation data was the most difficult and arduous step in the project but also the most essential and influential. And, while we are confident that we have collected and coded the disciplinary data as effectively and accurately as possible, the process has raised questions as well as suggestions about how to improve this step in future studies. In contrast to what our pilot survey suggested, our experience with the project survey suggests that a closed-ended multiple-choice format with write-in answer options would be the best way to have respondents identify their disciplines. This format would allow for a comprehensive range of options but also ensure standardization. Moreover, because the nuances of disciplines and subdisciplines can be complicated and complicating, in the future we would try to facilitate this process by seeking assistance with the development of a coding sheet from professionals in the fields far outside our scope of familiarity. Ideally, we would like to develop a standard code book for disciplines and subdisciplines that could be used by us as well as other researchers. Unfortunately, until more sophisticated network analytic methods and software are developed, we remain confined to single discipline codes for researchers, which we now know is not as reliable and valid as multiple discipline codes might be.

Our last challenges came during the analysis stage. The first challenge at this stage was trying to compare centers of different sizes. Unfortunately, standard metrics of network analysis do not translate well across groups of different size, an organizational variable we consider critical to our study. The second and even more complex challenge was related to trying to compare centers with different structures, another variable we find essential to the understanding of center forms and functionalities. In four of our centers, the researchers are organized as one single center network; in our two largest centers, the researchers are subdivided into multiple project networks. This meant that the data had to be collected and analyzed across the centers in our sample at two different levels (center versus project), thereby not allowing for comparisons to be made between the two types and also making it difficult if not impossible to even make center-level statements for centers of multiple project network type. We are still working on trying to develop a method of analysis and comparison that will accommodate the two centers with multiple project networks but have not accomplished this yet.

Major Findings and Results

The formative theory guiding this study is itself interdisciplinary and was generated from pre-existing findings in the literature on the sociology of knowledge, the sociology of science and innovation, organizational learning and development, and organizational social psychology. The theory argues that the relations and positions of a center's research network are determined by the disciplinary affiliation, professional background, and interdisciplinary exposure of the researchers as well as the institutional context of the research center.

Our first variable – **disciplinary affiliation** – relates to the disciplines represented by the researchers. **We argue that the overall structure of a research network will be shaped by the diversity of disciplines represented as well as the functional distance between them.** Diversity of disciplines refers simply to the number of disciplines present. The concept of functional distance refers to the degree of difference between the vocabularies, concepts, beliefs, methods, and modes of inquiry used by disciplines (Kiesler et al. 1998). We expect networks with greater rates of disciplinary diversity and functional distance to demonstrate less interaction and integration between its researchers than networks with more "like" disciplines. Moreover, where there are researchers of like disciplines, we expect them to form "clusters," or subgroups, of interaction within the network, with "majority" discipline clusters forming in and around the "core" of the network.

Our second variable –**professional background** – is related to professional rank and status of the researchers. **We argue that a researcher's position in a research network will be affected by his/her position in the overall academic hierarchy.** First, we believe that senior researchers (e.g., center directors, tenured professors) will be more "central," or influential, in the network than junior researchers (e.g., assistant professors, graduate students) for two reasons. One, because senior researchers are not concerned with tenure reviews and promotion requirements, they are freer to take risks with non-traditional interdisciplinary research practices and to concentrate on center-related research interests in lieu of disciplinary and departmental requirements. Two, senior researchers are likely to capture more attention from their colleagues, in part due to their reputation capital from which colleagues wish to draw, and in part due to their knowledge bases from which colleagues need to draw. As a corollary to this and the variable above, we add that senior researchers from a center's "majority" discipline will be the "hubs," or the most central researchers in the network.

Our third variable – **interdisciplinary exposure** – relates to a researcher's training in and/or experience with disciplines outside of his/her own primary disciplinary affiliation. **We argue that the relations between researchers and subgroups of different disciplines will depend on researchers in the network who have higher rates of interdisciplinary exposure**. A major goal of interdisciplinary research centers is the development of new cross-disciplinary activities – both in terms of sharing information and generating new knowledge across disciplines. The process of sharing information requires collaborators to participate in the exchange of ideas and/or data in order for each to learn new methods, acquire new theories, or develop new approaches. And, the process of creating knowledge requires collaborators to work together to construct concepts and integrate areas of expertise in order to generate new theories, applications, or methods collectively. Whether researchers of different and distant disciplines engage in either of these interactions – but particularly in knowledge creating relations – is a function of their pre-existing attitudes toward and understandings of the vocabularies, concepts, beliefs, methods, and modes of inquiry used by other disciplines. We believe that researchers who have worked previously with researchers from outside their discipline and thus have greater interdisciplinary exposure will be more open to other disciplines – and not just those specific ones with which they have worked – and will thus act as "bridges," or links, between individuals or groups of "unlike" disciplines.

Our fourth variable – **institutional context** – is an aggregate variable referring to dimensions of organizational size, age and format. **We argue that the degree to which researchers in a network interact at the level of knowledge creating versus information sharing within or across disciplines will be conditioned by the institutional context of the center.** Hollingsworth and Hollingsworth (2000) show that organizations with a high degree of

interaction among scientists of different disciplines depend on a well-integrated organizational structure with high levels of interpersonal trust. Other studies have found, however, that too much interpersonal closeness and too much hierarchical oversight can reduce a researcher's motivation for and dedication to deep collaboration. Thus, we argue that (a) increases in center size may increase researcher interactions but are not likely to increase knowledge creating collaborations, (b) neither very new nor very old organizations are likely to demonstrate higher levels of information sharing than knowledge creating collaborations and (c) both highly distributed as well as highly concentrated centers will demonstrate lower rates of knowledge creating relations between its researchers.

The results presented in the following subsections are derived from a combination of survey and interview/observation data collected in Strands I and II and are focused on the variables discussed above. Before detailing the relational aspects of each center's research networks, we present a few cross-center findings related to their organizational practices and processes.

Cross-Center Organizational Practices and Process

As part of the survey, we asked research affiliates a series of questions related to the organizational practices and processes of the center in order to develop a preliminary picture of the center's (inter)activities and their influence on the researchers' epistemological, intellectual and professional lives. This section highlights some of the key findings related to these questions.

First, research affiliates were asked the following two multiple-choice questions pertaining to the disciplinary nature of the research they do inside as well as outside the center:

> Definitions: "multidisciplinary" implies the *inclusion* of a broad range of discipline-based theories, skills, data and ideas; and, "interdisciplinary" insists on their *interaction* if not their *integration*.
>
> (a) Referring to the definitions above, would you characterize most (more than 50%) of the research that you do in affiliation with the center as interdisciplinary, multidisciplinary, or monodisciplinary? Please mark (i.e., X) one response.
>
> (b) How about the research that you do outside of the center? Would you characterize most (more than 50%) of that research as interdisciplinary, multidisciplinary, or monodisciplinary? Please mark (i.e., X) one response.

Graph A summarizes the responses to these two questions for the six centers in our sample. Taking the mean across our sample, **60% of researchers believe that the research he/she does as part of his/her center is multidisciplinary or interdisciplinary** (min = 50%, max 65%). This compares to **a mean of only 51% who describe the work that they do outside the center as multidisciplinary or interdisciplinary** (min = 46%, max 67%). Thus, on average, just about 10% more of the researchers believe the work they do inside the center is multidisciplinary or interdisciplinary versus the work they do outside the center. In Center 4, however, the difference is 15%. These results suggest that the centers are providing the majority of their researchers with the opportunity to pursue multidisciplinary and interdisciplinary research. Moreover, they imply that researchers are pursuing more multidisciplinary and interdisciplinary research because of the opportunities the centers offer than they would if the centers did not exist. This may be particularly true for the researchers in Center 4.

In the same section of the survey, research affiliates were also asked to respond to the following two closed-ended questions pertaining to center effects on intellectual and professional development:

(a) As a member of the center, how much and what type of influence has the center's "interdisciplinary" or "multidisciplinary" approach had on the development of your own research agenda? Please mark (i.e., X) one option in each of the first two columns or just the Not Applicable option.

(b) As a member of the center, how much and what type of influence has the center's "interdisciplinary" or "multidisciplinary" approach had on the development of your career opportunities and professional options? Please mark (i.e., X) one option in each of the first two columns or just the Not Applicable option.

Graph B provides an overview of the results of the responses to these two questions for our six centers. According these results, **on average 83% of researchers believe that his/her participation in the center has positively influenced the development of his/her own research agenda** (min = 74%, max 89%). However, **a smaller percent – only 74% – believe that his/her participation has positively influenced his/her career trajectory** (min = 70%, max 79%). Again, Center 4 stands out from other centers in the sample, with 15% of the researchers believing that his/her participation has actually *negatively* affected his/her career development.

The findings in Graph A and Graph B suggest that the centers do have some epistemological, intellectual and professional influence on the researchers affiliated with them. Within that, it would appear that a greater proportion of the researchers feel they are benefiting from these influences intellectually rather than professionally. These aggregate findings are perhaps not surprising given the abundant theoretical arguments and anecdotal evidence pointing to the intellectual rewards but professional costs for researchers who affiliate with interdisciplinary programs.

The Center 4 findings highlighted above raise other, more interesting points for consideration, however. One, the fact that a significant proportion of Center 4 researchers believe that the work they do inside the center is multi- or interdisciplinary as compared to the work they do outside the center suggests that the interdisciplinary nature of Center 4 is anomalous given the center's larger institutional context. Such a disjuncture between the center's research practices and the university's research customs could also explain why a significant proportion of the Center 4 researchers report a negative influence of the center on their professional development.

Two, the fact that graduate students make up the largest subgroup of research affiliates in Center 4, a proportion much higher than that in the other centers of our sample, suggests that professional background is also a factor in determining the nature of center influences. Because graduate students are at the beginning of their careers, they may perceive, or actually experience, greater professional risks from their affiliation with an interdisciplinary center than do, say, full professors or non-tenure track research scientists. This idea is corroborated when we compare the results of all the centers while taking into consideration the distribution of affiliates by position.

- Center 4 reports the **highest rates of negative influence** of the center on career development. They also have the **smallest proportion of full tenured professors and non-tenure track research scientists** (21%), and the **largest proportion of graduate students** (57%).
- Center 2 and Center 5 report the **highest rates of positive influence** of the center on career development. They also have the **largest proportion of full tenured professors and non-tenure track research scientists** (59% and 47%, respectively), and the

smallest proportion of graduate students (21% and 32%, respectively).

- Center 3 and Center 7 report the **highest rates of neutral influence** of the center on career development. They also have the **equal ratios of full tenured professors and non-tenure track research scientists to graduate students** (40%:40% and 37%:36%).

We believe that both factors – professional rank and institutional context – are factors at play. We explore these dynamics and other contextual factors in the next section.

Second, affiliates were asked a series of questions pertaining to the time they allocate to the center, the research connections they make through the center, and the interactions they have at the center. The main findings from these questions are presented in Table C. Here, we only present results for centers 1 through 4 because, as mentioned in the section above, there are some analytic challenges associated with comparing centers of different structures. Unlike centers 1 through 4, which are "single whole network" centers, Center 5 and Center 7 are "multiple project network" centers. This fundamental organizational difference makes center-level conclusions and comparisons difficult. While we are still developing a suitable method that will allow us to analyze and compare different center structures, we have, in the mean time, completed analyses for centers 1 through 4.

The highlights of Table C suggest that, with exception of Center 1 where affiliation is a full-time position, **researchers on average commit approximately 50% of their total work time to center-related activities** (min = 44%, max 94%). One could argue that this portion of time is what an affiliate would dedicate to his/her research whether he/she was a member of a center or not, and thus the center is not engaging or enhancing but is simply accommodating the affiliates' pre-existing workload. However, we see this 50% as both a considerable and significant portion of a researcher's total time. Especially given that, based on our fieldwork, we know that: (a) interdisciplinary center-based work regularly includes administrative as well as research tasks, (b) interdisciplinary center-based work often goes unrecognized and unrewarded in the tenure review process, and (c) interdisciplinary center-based work is done (in some cases) under the auspices of a commitment to a second institution, department, and/or discipline.

This finding, combined with the results above related to center influences on researcher agendas and careers, raises two important issues for the university in terms of managing faculty time and interests. One, if 50% of a researcher's time is absorbed by his/her affiliation with such a center, faculty reward systems must take better account of interdisciplinary activities and center commitments during promotion evaluations. If reward systems are not altered in this manner, younger tenure-hopeful and risk-averse researchers may avoid participating in interdisciplinary research centers, perhaps despite their own intellectual interests and in spite of other's financial commitments. We see preliminary evidence of this by the fact that overall there are comparatively low numbers of assistant professors versus associate and full professors in our sample of centers. Two, the fact that the researchers in our sample commit at least 50% of their total time to their center suggests, as other scholars have predicted, that interdisciplinary centers and programs are becoming "primary sites of intellectual work" for many faculty as well as students (Newell and Klein, 1996: 153-163). Thus, disciplines, departments, and even universities may no longer be able to claim exclusive rights to the epistemological heart, intellectual life or the professional time of their faculty. If, or as, interdisciplinary centers become more central, particularly for the research university, they will inevitably stretch if not challenge university structures and policies, which are heavily skewed in favor of traditional departments

and disciplines. We believe this raises fundamental questions about the "goodness of fit" between the strategy of the disciplinary university and the quest of interdisciplinary science.

One of the primary functions of interdisciplinary research centers is, obviously, to foster new research relations between researchers of different disciplines. To test for the center's effectiveness in creating such relations, the survey asked researchers to estimate in years the duration of his/her relationship with each and every center affiliate. Then, for each center, we converted the responses given in years into time periods and qualified them based on the center start date – connections that predate center, connections that postdate center. As Table C indicates, **on average, 84% of the current connections between researchers in a center were initiated after the founding of the center** (min = 62%, max = 94%). Moreover, in all of these centers, a comparison of the network of research relations that predate the center with the network of research relations that currently occupy the center reveals a significant shift in their nature and structure. The pre-center networks of research relations network tend to be characterized by distant and different clusters of actors. Each cluster is generally composed of a few closely connected researchers from the same discipline, and each cluster is linked to the next cluster by only one or two individuals. By contrast, the current networks of research relations is a web of better integrated actors, each with multiple to many connections to other researchers of like and unlike disciplines. While it is impossible to control for the effects of other mechanisms of introduction, this finding suggests that the interdisciplinary research centers in our sample are playing an important and active role in creating new research relationships and specifically new interdisciplinary research relationships. (NOTE: The following section will provide greater detail on the structure and nature of these research networks.)

In addition to wanting to know if centers play an active role in creating new interdisciplinary research relations, we also wanted to know if and how they play a continued role in supporting these research relations. Thus, we asked each research affiliate to approximate the average frequency of his/her interactions (daily, weekly, monthly, less often) with each and every other affiliate in the center. Taking the mean across the centers, as Table C shows, **on average research affiliates have interactions with about 10 other researchers in their center on a weekly or more frequent basis** (min = 6, max = 15)**, and with about 14 on a monthly or less basis** (min = 6, max = 19).[3] That is, **on average a researcher interacts weekly with about 27% of his/her total center population and monthly with 30% of the total center population**.[4]

While the lack of research measuring the frequency and density of interaction in the academic and/or science sectors makes it difficult to assess these rates, we can make comparisons with similar research on knowledge networks in other sectors and organizations. During a two-year research project at IBM's Institute for Knowledge-Based Organizations Robert Cross and Andrew Parker (project consultant) conducted over 50 social network analyses across 35 organizations. Their work concentrated on collaboration and information sharing across a

[3] We asked survey respondents to qualify their relationships to other researchers as close, collegial, familiar, or distant. A "close" relation refers to someone "you count among your closest professional and/or intellectual collaborators … with whom you share notes, data, findings, etc; with whom you develop projects, ideas, and concepts as well as prepare papers, documents, presentations; with whom you engage intellectually and/or from whom you seek research direction and advice." A "collegial" relation refers to "someone with whom you talk and share information, data but you don't count him/her among your closest collaborators." you count among your closest professional and/or intellectual We did not analyze relationships considered familiar or distant as these were defined as having no professional or intellectual nature.

[4] In an effort to attribute these interactions specifically to the center, we asked that researchers should try to approximate on the basis of only those interactions that involve or relate to the center. Of course, this is difficult for respondents to estimate accurately, thus these frequency of interaction rates may be biased upward to some degree.

variety of different types of social networks, such as top leadership groups, communities of practice, research teams and project groups. Although comparison across the groups in their study (as well as ours) is somewhat problematic due to group size and type, they found that the density values for frequent interaction were rarely above 25% and on average were approximately 20%. When looking at less frequent information sharing density figures on average were approximately 40%. While further research with a larger sample of academic networks is required, this suggests that on average the researchers in this sample of centers are interacting at an above average rate on a weekly basis and a below average rate on a monthly basis. And, because an analysis of the researchers' disciplines reveals that the weekly interactions tend to be between researchers of like disciplines whereas the monthly interactions show more interdisciplinary connections, we conclude that the centers may be good at facilitating strong disciplinary research relations, they are comparatively weak at facilitating strong interdisciplinary research relations.

Finally, the survey also asked researchers to select, from a list of 10 pre-defined options, the most common forum by which they interact with each and every other center affiliate (e.g., center-wide meetings in person, center-wide teleconferences, casual conversation, casual email correspondence, etc). Given the interest of funding agencies and other parties in supporting interdisciplinary centers built around inter-institutional collaborations and "cyber-infrastructures," we thought it important to explore what forums researchers in these centers actually use to interact with one another. Thus, in At the analysis stage, we clustered the responses into four categories – formal face-to-face interactions, formal technologically-mediated interactions, informal face-to-face interactions, and informal technologically-mediated interactions – and calculated the percentage of all "close" and "collegial" research relations that rely on each of these categorical forums of interaction. As reported in Table C, in all of the centers, whether concentrated or distributed, **informal face-to-face forums are the most commonly reported mechanism for interaction, either between researchers of the same discipline or between researchers of different disciplines**. The only center in which this forum of interaction is not the overwhelmingly most popular is Center 1, which is the only full-time, fully-concentrated (single institution *and* single department) center in our sample. **In Center 1, informal technologically-mediated forums are as popular as informal face-to-face forums.**

These findings suggest that, contrary to the theories and hopes that inter-institutional centers and "cyber-infrastuctures" make science collaborative at a distance, technologically-mediated communication may be a good complement to face-to-face communication but not a suitable substitute. We know from other research that the sharing of scientific information let alone the construction of new scientific knowledge is highly dependent on the interpersonal relations and spontaneous activities of researchers (Kanfer et al., 2000). We also know that both activities are more difficult across disciplinary boundaries rather than within disciplinary boundaries for all the reasons to do with functional distance and differences in vocabularies, concepts, beliefs, methods, and modes of inquiry used by disciplines. Thus, it is not surprising to us that face-to-face forums, and particularly *informal* face-to-face forums, are the most popular forum of interaction for affiliates of an interdisciplinary research center. However, it is somewhat alarming to us that more and more spatially distributed centers are being constructed on the assumption that knowledge can be made mobile across both institutional and epistemological boundaries simultaneously without attention to strategies for ensuring such.

Center-by-Center Network Structures, Relations, and Positions

Based on the variables introduced earlier, our analysis of network structures and dynamics was guided by five framing questions:

- How is the shape of the research networks influenced by the number, the diversity, and the distance of disciplines of the researchers in the center?
- How are the positions of researchers in the networks influenced by the professional backgrounds of the actors in the center?
- How are the relations in the network affected by the interdisciplinary exposures of the researchers?
- What effect does the center's institutional context have on these patterns at different levels of collaboration (e.g, information sharing versus knowledge creating)?
- What disciplines interact via the networks of information sharing and/or knowledge creating relations between researchers?

The answers to these questions are woven through a center-by-center presentation of our social network and fieldwork data. We have organized our presentation by center because of the challenges associated with trying to make precise comparisons of social network metrics across centers of different sizes let alone different structures. However, we believe that one of the most important requirements for enhancing the utility of network theory is to move beyond mere description or explanation toward the development of a stronger notion about network effectiveness, appropriateness or progress. Thus, in addition to analyzing the network of each center, we attempt to develop some sense of the relative "goodness" of the network factors and features by looking at general trends across the centers in our sample.

We analyzed the networks of each center using three different criteria of composition.

- **Center Research Network – Total (CRN-T)**
  This network allows for all relations between research affiliates REGARDLESS of discipline
- **Center Research Network – Interdisciplinary (CRN-I)**
  This network controls for only those relations between research affiliates of DIFFERENT disciplines
- **Center Research Network – Disciplinary (CRN-D)**
  This network controls only those relations between research affiliates of LIKE disciplines

The CRN-T is the primary network of analysis, depicting the overall network structure, relations and positions in the center as a whole. As subsets of the CRN-T, the CRN-I and CRN-D are secondary networks. The CRN-I isolates patterns and metrics related to the exclusively interdisciplinary interactions of researchers, and the CRN-D provides a control against which the uniqueness of these patterns and metrics can be assessed by comparing them to the disciplinary interactions of researchers. In the interest of time and space, we focus each center discussion on the results of the CRN-T, referring to the CRN-I and CRN-D for illustrative purposes.

As we said earlier, a major goal of the research centers is the development of shared information and the generation of new knowledge. Because these are complementary but distinct levels of communication and collaboration, we analyzed the each of three networks above controlling for these different activities. In the survey, we had asked respondents to qualify their relations to other researchers with whom they had relations as "close," "collegial," "familiar," or "distant" using the following definitions:

- **"Close"** refers to someone "you count among your closest professional and/or intellectual collaborators … with whom you share notes, data, findings, etc; with whom you develop projects, ideas, and concepts as well as prepare papers, documents, presentations; with whom you engage intellectually and/or from whom you seek research direction and advice."
- **"Collegial"** refers to "someone with whom you talk and share information, data but you don't count him/her among your closest collaborators."

Based on these definitions, we consider "collegial" relations between researchers to be information sharing activities and "close" relations to be about knowledge creating activities. Because we are limited at this stage of analysis to examining the researchers' interactions and not the products or innovations that result from them, we only draw conclusions about the presence of these relations and not about the outcomes of the activities embedded in them. (NOTE: We did not analyze relationships considered familiar or distant as these were defined as having no professional or intellectual nature.)

Because we are interested in the individual level variables of **disciplinary affiliation** and **professional background**, we analyzed the networks coding first the researchers' disciplines (e.g., ecology, atmospheric science, sociology) and then for their rank (e.g., professor, assistant professor, graduate researcher). The variable of **interdisciplinary exposure** was estimated on the basis of (a) the "pure" versus "hybrid" nature of a researcher's coded discipline, and/or (b) the diversity of disciplines that were reported by a researcher but left uncoded by project personnel. I Because network analysis software does not facilitate the simultaneous use of multiple codes, these variable estimates were then superimposed on the network sociograms in order to test for its effect. In the future, we would like to codify these indicators of interdisciplinary exposure in order to measure and depict them directly as we have done with the other two attribute variables of disciplinary affiliation and professional background. The effect of the **institutional context** variable was assessed by grounding our analysis of the network data in the insights of our fieldwork data.

Similar to Friedkin (1978), who investigated multidisciplinary research communication networks across six physical science departments, we used several standard network measures to analyze the six networks (coding for both by discipline and by rank) in each center: (1) density, (2) degree centrality, (3) degree centralization, and (4) E-I Index. These metrics are defined below.

Density is the proportion of existing to maximum possible connections or links ("ties") between actors within a network (Wassermann & Faust, 1994). It is a measure of the general level of connectedness between actors within a network, the overall robustness of the network. A more dense a network indicates that more ties exist between actors and thus implies that actors are more connected. It is believed that the more connected actors are, the better the communication is between them and thus the more information that flows between them.

Degree centrality measures an individual actor's relative position ("centrality") by counting the total number of direct connections that he/she has to other actors. Individuals considered "central" (called "hubs" or "connectors") have connections to many other network members; peripheral individuals do not (Degenne & Forsé, 1999). This and other measures of centrality have been developed to "attempt to describe and measure properties of 'actor location' in a social network" (Wassermann & Faust, 1994: 16), particularly actor importance and influence (Freeman, 1979).

Degree centralization, on the other hand, is a measure of the whole network's centralization as an estimate of the dependency of the network on a small number of actors. Degree

centralization measures (in percentage terms) the degree of a network's variance from a perfect "star" network of the same size. A "star" network (100%) is one in which the maximum possible connections are concentrated in one actor such that he/she is maximally close to all others and all others are maximally distant from one another (Freeman, 1979).

Finally, Krackhardt's **E-I index** is used to compare the number of links within cliques or subgroups (Internal) with the number of links between them and other actors (External) in a network (Krackhardt, Blythe, and McGrath, 1996). In our case, we used researcher attribute data to predefine the subgroups by discipline and by science in each center. We then applied the E-I Index to measure the degree to which actors within each disciplinary/science subgroup interact with researchers from their own subgroup versus researchers from other subgroups as a way of estimating the monodisciplinary versus interdisciplinary nature of each discipline and science in a center.

Table D presents the results of the first three measures for the six networks, and Table E presents the results of the E-I Index (for science subgroups). As with earlier results, for the reasons iterated above, these tables present the results for centers 1 through 4 only. Below, with the help of interview/ observation data from our fieldwork, we expound on the key findings presented in Table D and E to create summaries for each of the four centers. Once further analysis of the fieldwork data has been completed, full center narratives will be produced from these summaries.

Center 1 identifies 36 non-administrative center members, ranging from student visitors and postdoctoral fellows to scientists I, II, and III and visiting scientists. Though it was difficult to determine who was "in" and who was "out" in this center, our administrative inquiries as well as our fieldwork investigations resulted in our including only 18 active researchers in the network analyses for Center 1. In addition to being the smallest center in our sample, it is also the oldest (approx. 20 years) as well as the only full-time affiliation and fully-concentrated center (single institution, single department). On average, researchers in Center 1 report committing about 94% of their total work time to center-related activities – twice that of other centers in our sample. And, accounting for the vast variations in center tenure, the mean length of time that researchers have been affiliated with Center 1 is 9.6 years – the longest in our sample.

The mission of Center 1 is to conduct a coordinated research and outreach program on the societal implications of atmospheric and related environmental processes. One might infer from this mission that there would be a range of social, physical, and environmental scientists in this center. And, while this center does have the highest rate of disciplinary diversity in our sample – with just over one researcher per discipline – Center 1 is overwhelmingly dominated by disciplines from the physical sciences (44% of 18). It is only sparsely populated by environmental scientists/ environmental social scientists (22%) and barely inhabited by pure social scientists (<1%). There are eight people and six disciplines from the physical sciences, with three people from the "majority" discipline of climate change science and one person from meteorology, (bio)geochemistry, environmental chemistry, astrophysics, and geographic information systems. There are three researchers from the environmental social sciences, all environmental social policy studies; two people and two disciplines from engineering, including electrical and software engineering; and, two people from mathematical sciences, both statisticians (one applied, one theoretical). There is also one person from each of the following sciences and disciplines: environmental sciences (environmental technology), social sciences (resource economics), and life sciences (paleoecology).

In addition to these different disciplinary affiliations, members of Center 1 represent a number of different professional ranks. One third of the researchers are tenured, in either senior scientist or director-level positions. Another third are non-tenure track research scientists, either visiting scientists or research associates. The last third are graduate research assistants, postdoctoral fellows, and untenured scientists. There is a clear but not perfect correlation between status of rank and length of time at the center: the higher rank scientists and directors emeriti have been at Center 1 for more than 13 years, while the lower rank scientists, research associates, postdoctoral fellows, and graduate students have been there three years or less. There are three exceptions. The current center director has been at Center 1 for only three years and the deputy director for six; one research associate has been there for 22 years.

Looking now at the network data, we see that overall density of the CRN-T at the combined close and collegial level is 63% for Center 1. Breaking this down, we have a density of 36% at the level of collegial connections and 27% at the level of close connections. Thus, we suspect there is a good deal of interaction between researchers when both information sharing and knowledge creating activities are considered but much less so when only these activities are examined separately, particularly at the knowledge creating level. According to the mean degree centrality measures, each researcher in Center 1 has on average 11 close and collegial ties to other researchers in the center, which is significant given the size of the center population. This translates to a mean of 5 close and 6 collegial ties, which suggests to us that on average the researchers in Center 1 engage one another more (but not significantly more) in information sharing than knowledge creating activities. We also know from individual degree centrality measures not reported in the table that only one researcher in Center 1 has 10 or more close connections, whereas most (55%) of the researchers have more than 10 collegial connections. These figures, combined with the degree centralization measures of 41% (close and collegial), 36% (close) and 25% (collegial), suggest to us that relations overall – but particularly the knowledge creating relations – in Center 1 are concentrated in a few researchers rather than dispersed evenly across the network. However, as we will see, the concentration of relations is actually less so than in other centers in our sample.

By looking at the sociogram of the CRN-T for both close and collegial connections in Center 1, we see how these metrics play out in terms of the shape and structure of the center's research relations. First, the CRN-T at the combined level is shaped not like a "star" but more like a "Jewish star" or something close to a hexagram. Basically, we see that the center of the hexagram is occupied by a core group of nine researchers. These nine researchers represent 50% of the center's population but are responsible for 65% of the center's researcher relations. The points of the network hexagram are populated by the other 50% of the center's population. By comparison, these nine researchers have on average eight close and collegial connections compared to the center's mean of 11 and the core's mean of 14 close and collegial ties (See Sociogram A). This suggests to us that half of Center 1's population is comparatively under engaged in the overall collaborative activities of the center. And, as the metrics indicated, looking at the CRN-T for close relations only, there is much less integration between the researchers at the level of knowledge creation alone. Moreover, what interactions exist are again concentrated in a small core, and, in fact, an even smaller core of only four as compared to nine researchers. These four researchers (22%) of the population are responsible for 44% of the knowledge creating activities (See Sociogram B).

If we look at the positions and relations of researchers in these two networks first by discipline and then by rank, we can illustrate the positions and relations of different researchers in Center 1's CRN-T. Sociogram A shows us that all of the disciplines in the center interact with one other

to some (albeit varying) degrees at the close and collegial level. While the network core has representation from most of the sciences in Center 1, the center of the core is clearly dominated by the "majority" discipline of climate change. Conversely, the edges of the core and the periphery of the network are dominated by the environmental sciences/ social sciences and social sciences. This suggests to us that overall the collaborative activities of information sharing and knowledge creating in Center 1 are heavily influenced by individuals from the physical sciences. Sociogram B shows us that this unequal distribution of physical sciences versus the various environmental sciences and social sciences is even more extreme at the level of just knowledge creating activities. Here not only is the core of the network again dominated by physical scientists – primarily from the "majority" discipline of climate change – but the central body of the network is composed almost entirely of physical scientists while the outer periphery of the network is represented by the center's different environmental and social scientists who are not only more weakly linked to the physical scientists in the core but also to one another. **While this supports our hypothesis that the shape of the network will be affected by the diversity and distance of the disciplines represented, we find the centrality of the physical sciences important if not ironic given the center's research focus is related to the societal implications of environmental related issues.**

Applying the attribute of professional rank to these two sociograms, we see the following. At the close and collegial level (Sociogram C), there are five "hubs" in the network. One is the current center director, and four are lower rank scientists. By comparison, four of the seven higher rank scientists are on the outer periphery of the network; three are on the periphery of the core (including one past and one current director). We know from the researcher's individual centrality measures that 100% of the postdoctoral fellows and junior scientists have established as many or more than the center's mean number of close and collegial connections compared to only 43% of the senior scientists (including current and past directors). At the level of close relations, we see that the knowledge creating activities of the network are again dominated by current center directors (1) and lower rank scientists (3) – one postdoctoral fellow, one non-tenure track research associate, and one scientist I-II (See Sociogram D). **Complicating our variable of professional background, this finding suggests that – apart from center directors – the lower rank scientists are more involved and integrated in both the information sharing and the knowledge creating activities of Center 1 than are the higher rank scientists.**

Because disciplinary affiliation and professional background are highly correlated in Center 1, it is difficult to disentangle the effects of the two variables on the structure of the network. Moreover, we know from our fieldwork data that a researcher's length of time at center is also correlated with these two attributes. However, we believe that this is also an important and influential factor in the dynamics of Center 1's research relations. As one interviewee put it, "there is basically the old guard and the new guard." The old guard includes the higher rank scientists and directors emeriti who have been at the center [or the center's larger institution] for more than 13 years. The newer guard represents the center's new director and the lower rank scientists who have been hired by the new director within the last three years. In our interviews, members of the old guard readily reported that, because of the complicated interpersonal relations that have marked the long history of the center, they tend to be more active in their own research networks external to the center than in any of the collaborative research networks internal to the center. **This distribution of researchers in Center 1 raises the variable of institutional context and, specifically, the dimension of organizational age.** It is important to note that disciplinary affiliation, professional rank, and time at center are highly correlated in

Center 1. With the small size of the group, it is difficult to ascertain which has the more powerful effect on the network.

By looking briefly at the CRN-I as well as the CRN-D and EI Index for Center 1, we are able to say more about the center's interdisciplinary interactions specifically. The findings in the Table D suggest a few things. First, researchers in Center 1 appear to be more integrated overall with researchers from outside their discipline rather than with researchers from inside their own discipline, and particularly at the level of information sharing versus knowledge creating activities. In fact, with researchers from outside their own discipline, researchers in Center 1 tend to have about twice as many information sharing relations as knowledge creating relations. Conversely, they appear to have about twice as many knowledge creating relations as information sharing relations with researchers from inside their own discipline. This implies that researchers of different disciplines in Center 1 are consulting with one another but they are not yet collaborating with one another at the level that like researchers of like disciplines do. Finally, according to the centralization measures, interdisciplinary interactions within Center 1 appear to more centralized than monodisciplinary interactions. This suggests that the interdisciplinary activities of Center 1 – particularly interdisciplinary knowledge creating activities – depend on fewer individuals in Center 1 than do the center's disciplinary activities.

While we can see the effects of these metrics on the structure, relations and positions of the Center 1's CRN-I depicted in sociograms E and F, we can also use the sociogram to estimate the effects of our interdisciplinary exposure variable. Sociogram E shows us that the connectivity of the center's interdisciplinary close and collegial network depends on six "bridges." We know from our fieldwork data that four of the six have content-neutral methodological and/or technical skills sought by various researchers in the center – one is a software engineer, one is a GIS specialist, and the other are statisticians. The last two "bridges" in the network have extremely interdisciplinary backgrounds – one is a paleoecologist with a background in economics and religious studies, the second is a biogeochemist who works at the interface of biology and physical chemistry.. Sociogram F shows a similar pattern at the level of close interdisciplinary ties, but with only two "bridges". Here the bridge positions are again occupied by one of the methodologists (an applied statistician) and the paleocologist with the economics and religious studies background (See Sociogram F). **These findings support our hypothesis that researchers with higher rates of interdisciplinary exposure are likely to serve as "bridges" between individuals and subgroups of different disciplines. It also raises the question of whether technical skills as compared to content knowledge are more mobile across disciplines.** It is worth noting that the individuals who occupy the interdisciplinary bridge positions are not the same individuals who play the network hub roles in Center 1, thus suggesting that interdisciplinary collaborations may depend on individual attributes different from those required for general research collaborations.

Finally, together with Sociogram F, the E-I Index metrics in Table 7 indicate that overall researchers from the physical sciences have the most close connections and the most close cross-science connections overall. However, when one controls for the size of the field, we see that on average physical scientists are slightly less collaborative than the life scientist in the center but slightly more collaborative than the computer/math scientists. However, in their collaborations, the physical scientists have fewer inter-science knowledge creating connections as intra-science knowledge creating relations, making it the most insular field in the center next to environmental social sciences. Thus, while Center 1 purports to be a "multidisciplinary group of environmental, social and physical scientists," we would qualify it more as a "multidisciplinary group divided between environmental, social and physical scientists."

The mission of **Center 2** is to (1) merge social and scientific knowledge in order to better understand patterns of human activity and environmental change; (2) address key environmental problems; and, (3) develop new methods for framing and analyzing environmental problems based on the needs of government and industry decision-makers. And, while the center has been structured as both an inter-institutional and interdisciplinary research center in order to achieve this mission, there is some debate as to how well it has performed on either of these dimensions.

Center 2 supports approximately 40 funded researchers and involves more than 20 non-funded affiliated researchers. Together, the population of 66 center affiliates represents more than 20 institutions in eight countries and 19 disciplines from eight fields of science. Of the 20 institutions, 52% of the researchers are currently located in the center's "host" institution, and 48% of the individuals are distributed across the center's "satellite" sites (many of whom have also at one time been located at the "host" institution). Twenty-seven of the center researchers (41%) are now tenured faculty (of which 3 are current or previous center directors), while only 11% are assistant professors. Approximately 17% are non-tenure track research faculty, and 32% are either graduate students or postdoctoral fellows. Across all ranks and positions, affiliates have an average tenure of 4.3 years at the center and spend approximately 44.2% of their total work time on center-related activities (the least in our sample).

Of the 19 disciplines, the majority of the researchers come from engineering broadly (47% – 18% from a "pure" engineering discipline and 29% from the "hybrid" discipline of engineering and public policy) and decision sciences (20% – 11% from decision sciences generally and 9% from risk analysis and assessment). The remaining 33% of the researchers are distributed in small concentrations across various disciplines in the social sciences (15%), physical sciences (8.5%), life sciences (5%), mathematical sciences (1.5%), environmental social sciences (1.5%), and arts and humanities (1.5%). The result is a ratio of about 3.5 researchers to every one discipline, which is a slightly greater rate of disciplinary diversity than the mean for our centers.

Beginning with the network metrics presented in Table D, we see that Center 2 has a density of 23% at the combined close and collegial level, 8% at the close level, and 15% at the collegial level. At every level the researchers of Center 2 are less integrated than the mean for our sample and slightly less integrated than the other center closest to its size, particularly at the level of knowledge creation. We also see from the mean degree centrality measures, that, on average, researchers in Center 2 have 15 connections to other researchers in the center – 5 close and 10 collegial. Thus, despite the fact that the population of Center 2 is about 3.5 times that of Center 1, Center 2 researchers appear to have on average only four more connections than Center 1 researchers and all of them at the level of information sharing. Finally, based on the degree centralization measures (53% for combined connections, 28% for close, and 31% for collegial), we suspect that all the collaborative activities of Center 2 are concentrated in some small and modest portion of the center's overall population.

Compared to the hexagram for Center 1, the sociogram of the close and collegial CRN-T for Center 2 resembles the shape of a Venn Diagram (see Sociogram C). To the left of the figure, there is a larger, more tightly connected group of researchers representing approximately 60% of the center's population; to the right is a smaller, less integrated group of researchers. And, in the center of the network, as was suspected from the network metrics, there is a distinct core of 15 very tightly connected researchers. Though not obvious from either the sociogram or the

table, we know from the researchers' individual centrality measures that each of these 15 core researchers has approximately twice the center's mean number close and collegial connections. Indeed, this group of 15 represents only 23% of the center's population but 50% of all the close and collegial connections between the researchers in this population. At the level of close relations, the network is much less integrated overall and the connections between researchers much more distributed. Nevertheless, there is still a small but distinct core of researchers in the center of the networks. This core group of nine researchers represents 14% of the center's population and 42% of all the knowledge creating relations in the center (Sociogram G).

If we look at these two networks controlling for disciplinary affiliations, we see the following. First, at the combined level (Sociogram F), both the core of the network and the larger of the two clusters are both dominated by researchers from the center's "majority" disciplines (engineering and public policy, civil/environmental engineering, and risk analysis and assessment). In that cluster, there are also a few straight decision scientists, mechanical engineers, applied economists as well as an applied mathematician, applied anthropologist and industrial engineer on the periphery. The smaller cluster represents an assortment of individuals from the center's "minority" disciplines. Researchers in this cluster come mainly from land use geography, with a splattering of individuals from resource economics, hydroengineering, resource management, and applied anthropology. At the close level (Sociogram G), we see a similar pattern. Again, the core of the network is dominated by researchers from the center's "majority" disciplines. Around this core, there are five noticeable clusterings of disciplines, four of which also represent the center's "majority" disciplines (engineering and public policy -2, decision sciences, and risk analysis/assessment). The fifth clustering represents a "minority" discipline (land use geography).

The presence of the center's numerous disciplines in both the combined and the close CRN-T indicates that at the very least the collaborations in Center 2 are multidisciplinary. The presence of the connections between these different disciplines suggests that these collaborations may even be interdisciplinary. However, the obvious divides between what is roughly a cluster of "public policy-oriented" researchers and a cluster of "natural resource-related" at the combined level suggests that the center's information sharing relations more often (if not only) cross boundaries that separate fields with less rather than more functional distance between them. Moreover, the clear clusterings of disciplines at the close level suggests that the center's knowledge creating activities tend to respect rather than cross disciplinary boundaries. **These findings lend further support to our hypothesis that the structure of research networks will be affected by the diversity and the distance of the researchers' disciplines, with greater rates of functional distance between actors yielding less connectivity between researchers.**

It is important to note, however, that discipline is not the only variable at play here. While not visibly obvious from these sociograms, we know from other network and fieldwork data that the patterns of disciplinary affiliation in these two networks also follow the contours of institutional divide. In both the combined and the close CRN-T, all of the core researchers are from Center 2's "host" institution. Moreover, 37 of the 41 researchers in the larger cluster of the combined network have been based at the center's "host" institution within the last three years and only two of the "host" institution's 34 researchers are not in this cluster. While it is difficult to separate out disciplinary affiliation from institutional membership as they are highly correlated, we suspect that both factors are at play given that, at the periphery of the network, we see instances of researchers from like institutions but different disciplines not connecting as well as cases of researchers from different institutions but like disciplines not connecting.

To the extent they have been achieved, the synergies of the center have been limited, if not complicated by the very inter-institutional structure that the center has sought to create. There is a strong sense among center members that there are porous (if any) boundaries between the "host" institution and the center. As a result, "host" institution members and disciplines dominate the center. Some members of the center even argue that the "host" institution is nepotistic, populating itself with its own faculty, graduates and students. This has created what several individuals referred to as a "we" versus "them" dynamic between the "host" and the "satellite" institutions. The end result is that the inter-institutional arrangement has not only obviously hampered the opportunities for serendipitous collaboration between people from different disciplines, but it has also hampered the potential benefits of even structured occasions for any synergistic collaboration between them. **Thus, this finding lends support to our hypothesis that the structure of interdisciplinary research networks will be conditioned by the institutional context of the centers, pointing specifically to the dimension of organizational format (concentrated versus distributed).**

Turning to variable of professional background, we look again at the close and collegial CRN-T coded for professional rank (Sociogram I). Here, we see that the three center directors are in the center of the Venn Diagram, at the intersection of the two research clusters described above. In addition to these three key individuals, there are two other "hubs," both of whom are senior faculty. Moving out the core of the network toward the periphery, there are several concentric circles surrounding these "hubs" ordered by rank – the closest ring around the core is primarily senior faculty and the furthest ring on the perimeter is primarily graduate students. According to individual degree centrality measures, 79% of the graduate students, 71% of the postdoctoral fellows, and 57% of the assistant professors have established less than the center's mean number of close and collegial connections as opposed to only about 50% of the professors/associate professors and 50% of the non-tenure track research scientists. This means that junior researchers – with the exception of non-tenure track scientists – as a whole may not be engaging in many of the collaborative activities of the center as are senior researchers.

Looking at the CRN-T at the close level only (Sociogram J), we see that, again, the center directors are primary "hubs" in the network. However, at this level, the other two "hubs" are junior researchers – one being a graduate student and the other a non-tenure track researcher. And, from the individual centrality measures, we know that, as compared to the close and collegial level, approximately one-third of professors/associate professors and one-third of assistant professors have two or fewer close ties as compared to only one-quarter of the graduate students and one-half of non-tenure tack researchers. Thus, at the level of knowledge creation, graduate students appear to be more central to and better integrated in the center's knowledge creating activities than the center's information sharing activities. Moreover, they appear to be more central to and more integrated in these activities than do senior faculty or junior faculty, including non-tenure track scientists. **As with the results of Center 1, these findings do not negate but they certainly complicate the hypotheses related to our variable of professional background, suggesting that the professional status of directors may be a determining factor in researcher centrality but that professional seniority may actually be a predictor of a researcher's peripheral rather than central position.**

A brief summary of some results related to the CRN-I, CRN-D, and the E-I Index for Center 2 furthers our understanding of the specifically interdisciplinary nature of this center. Referring to the density measures of Table D, we see that, overall, the researchers of Center 2 – like the researchers of Center 1 – appear to be more integrated with researchers from outside their

discipline than with researchers from inside their own discipline. Moreover, researchers of Center 2 – like the researchers of Center 1 – tend to have more information sharing connections than knowledge creating connections with researchers from other disciplines. However, unlike Center 1 researchers, Center 2 researchers also tend to have more information sharing relations than knowledge creating relations with researchers from inside their own discipline, albeit at a less significant rate. Thus, we are led to be believe that in general researchers in Center 2 engage in less collaboration and more communication regardless of disciplinary boundaries. Finally, like Center 1, the information sharing relations and knowledge creating relations of Center 2 appear to more centralized between researchers of different disciplines than between researchers of like disciplines. This suggests that there are a few key individuals in Center 2 who are the primary links in the center's interdisciplinary collaborative activities, particularly at the knowledge creating level.

Because we are interested in mapping the interactional "hotspots" of significant interdisciplinary collaboration rather than passing interdisciplinary communication for our future analysis of the results that emerge from these activities, we have focused only on close interdisciplinary connections for this and the other centers in our sample. As Sociogram K indicates, approximately 20% (12) of the center's researchers do not participate at all in the interdisciplinary knowledge creating activities of Center 2 but all of the fields of sciences in the centers are represented by the 80% that do. Only at a finer grain of analysis do we know that one discipline (behavioral economics) of the center does not interact with other disciplines at this level of collaboration. Second, while on average, each researcher has three close interdisciplinary ties, there are five individuals who have more than 10 close interdisciplinary connections. As the primary "bridges" in the network, these five individuals account for more than 30% of all the close interdisciplinary connections in the center. All of these "bridges" have high rates of interdisciplinary exposure. Three come from the "hybrid" discipline of engineering and public policy studies, one from the "hybrid" discipline of risk analysis/ assessment, and one is an engineer with a background in geography and microbiology. As a demonstration of the importance of these "bridges" to Center 2's interdisciplinary network, we turn to Sociogram L. This picture shows that when the five "bridges" are removed, only 71% of the researchers remain, and 66% of those remaining have two or fewer interdisciplinary ties. **These findings add further support to our hypothesis that connections between researchers and subgroups of different disciplines will depend on researchers who possess interdisciplinary exposure.**

It is worth noting that, in addition to the fact that one of these bridges is a graduate student, only about 55% of the graduate students and postdoctoral fellows have two or fewer close interdisciplinary connections as compared to approximately 65% of the senior faculty (professors and associate professors) and 65% of the junior faculty (assistant professors and non-tenure track researchers) have two or fewer close interdisciplinary connections. This suggests that as a population graduate students and postdoctoral students may be somewhat more engaged in interdisciplinary knowledge creation activities than either senior or junior faculty.

Historically, Center 2 has focused on environmental engineering and physical sciences. Only recently has it incorporated the social sciences in any sort of strategic manner. As the director noted, the objective has been to "develop a system that is inclusive of both the natural and social sciences … to not separate them out, to recognize that they are co-evolutionary." In part, this shift toward the inclusion of social sciences is due to the fact that, like Center 1, Center 2 has undergone a leadership change. Whereas Center 1 changed from a director based in the

social sciences to one based in physical sciences, Center 2 shifted from a director trained in physical sciences to one from the social sciences. And, while it is too early to discuss the impact on social sciences on Center 2, the plurality and centrality of the social sciences should be noted in the networks reported above. However, plurality and centrality, of course, do not necessitate interdisciplinarity. Center 2 researchers from engineering and the social sciences alike reported a long standing history and an everpresent concern that "while the social sciences are so critical to this [center's research], they have not tended to work out very well with the other fields."

By looking at the E-I Index measures reported in Table E in conjunction with Sociogram K, we suspect that the trouble may lie in the insular nature of the social sciences in Center 2. While researchers from the social sciences possess the most close connections (internal and external) of any field of researchers in Center 2, they have next to physical scientists the least external ties per person of any field in the center. In fact, on average, each Center 2 social scientist has about twice as many connections to other social scientists as he/she does to researchers from any and all other fields combined. This compares to environmental scientists/engineers who have almost the same number of researchers in their subgroup as the social scientists and who on average have about the same number of knowledge creating collaborations per person as the social scientists but who have more inter-science rather than intra-science knowledge creating collaborations. And, physical scientists – who represent a comparatively small portion of the population and thus have more opportunity for cross-science connections – actually have the fewest external ties per person and the second highest number of internal ties, making it the most insular science in the center.

As part of the recently-developed NSF Integrative Graduate Education and Research Training program (IGERT), **Center 3** is designed to provide doctoral students with enhanced interdisciplinary training in the skills required for conducting research at the interface of biological and atmospheric sciences. Its focus is on training students to adopt an interdisciplinary approach and to develop expertise in a wide range of biosphere-atmosphere interactions.[5] It is the youngest center in our sample, with a mean tenure of 2.3 years for center affiliates.

Given that it is an IGERT program, it is not surprising that the majority of Center 3 affiliates are full professors (40%) and graduate students (40%). The other 20% includes six associate professors and two non-tenure track research scientists. There are no assistant professors or postdoctoral fellows. And, although the center's 40 members hail from 13 different institutions, we consider Center 3 to be a "concentrated/distributed" center because affiliates spend a portion of their time together at a common site engaging in various collaborative research activities and a portion of their time pursuing these activities from their home institutions. As a result of this combination of activities, Center 3 affiliates report that on average they commit 57.8% of their total work time to these different center-related activities.

There are only nine disciplines represented by the 40 researchers in the center, resulting in a ratio of 4.4 researchers to every one discipline. This is the lowest rate of disciplinary diversity for the four centers we present here. Of these nine disciplines, the majority of the center's affiliates are ecologists (37.5%) and atmospheric scientists (25%). The other seven disciplines are each represented by three of fewer researchers coming from the physical sciences (i.e., analytic

[5] Please note that we have not collected fieldwork data for Center 3.

chemistry - 2, (micro)meteorology - 2, (bio)geochemistry - 2, limnology - 1), the life sciences (i.e., developmental biology - 1, neurobiology - 1, environmental biology – 1), the environmental sciences (i.e., forestry science – 2), and engineering (civil/environmental – 3). There are no social sciences nor computer/math sciences in Center 3.

As Table D reveals, the CRN-T for Center 3 has a density of 39% at the combined close and collegial level, and 21% and 17% at the close and collegial levels, respectively, suggesting that (controlling for size) there may be more integration between Center 3 researchers than between Center 1 or Center 2 researchers, particularly at the level of knowledge creating relations. Moreover, it seems that, like Center 2 researchers, Center 3 researchers have 15 direct connections to other members in the center. However, unlike Center 2 or Center 1 researchers, Center 3 researchers tend to have more close rather than collegial connections (8 and 7, respectively). This implies that, unlike the other two centers examined thus far, the connections between researchers in Center 3 may be more about actually integrating concepts than simply exchanging data. We argue that this difference is likely due to the Center 3's comparatively low rate of disciplinary diversity *as well as* its hybrid concentrated/distributed organizational format. And, finally, Center 3 has comparatively high degrees of centralization, leading us to believe that Center 3's information sharing and knowledge creating activities may even be slightly more concentrated than in Center 1 or even Center 2. This is supported by individual centrality measures, which tell us that 40% of the researchers have more than 10 collegial relationships, whereas less than 5% have more then 10 close relationships.

Based on these metrics, the close and collegial CRN-T sociogram for Center 3 translates to a shape somewhere between the hexagram of Center 1 and the Venn Diagram of Center 2 (See Sociogram M). In the center of the network, as with the other sociograms, there is a core group of researchers. The nine members of this core represent only 22% of Center 3's population but are responsible for 40% of the center's connections. Like Center 2, there is a cluster to the left of the diagram and a cluster to the right. However, unlike Center 2, these two clusters are less clearly divided and thus create more of an integrated web such as we saw in Center 1 than two segregated subgroups as we saw in Center 2. As our highlighting suggests, the resulting network shape resembles a "target- and-arrow," with the target being the primary cluster and the arrow the secondary cluster. In Sociogram N, we see a core of ten researchers, who as a group represent 25% of the center's population but are responsible for 49% of the center's close connections. These ten individuals are surrounded by an inner ring of about another dozen researchers each of whom have between eight and 12 close connections and an outer ring of researchers who have six or fewer such ties.

Looking again at Sociogram M and controlling for the disciplinary affiliation of the researchers in the center, we see one core and two clusters of researchers at the level of close and collegial relations. The core is centered around researchers from the center's two "majority" disciplines, and the clusters are divided between them. On the left, the primary cluster ("target") consists primary of ecologists; on the right, the secondary cluster ("arrow") consists primarily of atmospheric scientists. The ecology cluster has a splattering of other disciplines, mostly from the biological sciences. Other key disciplines in the atmospheric science cluster include meteorology and civil/environmental engineering. At the close level, Sociogram N shows that, again, there is a small network core which is dominated by researchers from the center's "majority" disciplines of ecology and atmospheric science. Apart from this core and the one noticeable clustering of ecologists, there are no other significant disciplinary clusters in the network. And, indeed, if we look at the network in terms of fields of science, the right side of the network is dominated by disciplines from the physical and engineering sciences, while the right

side of the network hosts all of the center's life science disciplines (neurobiology, environmental biology, developmental biology). Thus, Center 3 provides additional support to our variable of **disciplinary affiliation, demonstrating that networks with lower rates of diversity will demonstrate greater rates of "density" overall but that, within that network, the organization of researchers is dictated by the functional distance between their disciplines.**

However, earlier, the two-cluster structure of Center 2's CRN-T reflected divisions between researchers on the basis of disciplinary affiliation and institutional affiliation. However, disciplinary and institutional affiliation are not strongly correlated in Center 3 as they were in Center 2. Thus, the two-cluster structure in Center 3 reflects the organization of researchers on the basis of disciplinary affiliation only. The fact that the two disciplinary clusters of Center 3 (atmospheric science versus ecology) are at least as functionally distant but are yet more integrated than the two thematic clusters of Center 2 (engineering policy and decision sciences versus land use geography and resource management) suggests that institutional context may have an intervening effect and that disciplinary affiliation alone does not determine the shape of the network structure. Without proper fieldwork data we cannot conclude but **we can surmise that the hybrid concentrated/distributed format may enhance the collaboration opportunities and thus the connections of researchers.**

With respect to professional background, Sociogram O shows the CRN-T for Center 3 at the close and collegial level coded for professional rank. We see here a clear if not dramatic division between Center 3 researchers on the basis of academic position. On the left we see most of the graduate students; and, on the right, most of the senior faculty (professors and associate professors). These two groups are connected at the interface by the center's three directors. There are two other network "hubs" in addition to the center directors, which surprisingly are both graduate students. Moreover, this drawing of the network suggests that the graduate students of Center 3 are more connected than the senior faculty. And, we see from individual centrality measures, that this is in fact true. Thirteen of the 16 graduate students (81%) have as many if not more close and collegial ties than the center mean as compared to only 43% of the senior faculty (including the center directors). This same pattern is replicated in the CRN-T for close relations (see Sociogram P). As with the close and collegial level, professors and graduate students form two notable sub-groups at the close level. And, again, the primary "hubs" of the network are the center directors and graduate students. And, even at the level of close connections, 75% of the graduate students have more than the mean number of close ties whereas only 43% of senior faculty do (including directors). This suggests to us that most of the information sharing and most of the knowledge creating relations in Center 3 depend on the three center directors and on the graduate students. **Thus, along with the results of Center 1 and Center 2, these findings challenge our variable of professional background by suggesting that – apart from center directors – junior researchers, specifically graduate students, may be more central to and more engaged in the activities of the research network than are senior faculty.**

In terms of the interdisciplinary relations and positions of Center 3 researchers, we look summarily at the results of the CRN-I and the E-I Index analysis. As with Center 1 and Center 2, the researchers in Center 3 appear to be better integrated with researchers from outside their own discipline as opposed to inside their own discipline. However, unlike either Center 1 or Center 2, the researchers in Center 3 tend to have about the same number of close as collegial interdisciplinary connections. Because researchers in Center 3 also have more knowledge creating relations than information sharing relations with researchers inside their own discipline,

this suggests to us that there is comparatively more collaboration than communication between Center 3 researchers, both within and across disciplinary boundaries. Finally, as with Center 1 and Center 2, the connections between researchers of different disciplines appear to more centralized than the connections between researchers of like disciplines. This suggests that, as with the other centers, while there more interdisciplinary than disciplinary interactions between researchers overall in Center 3, these interactions are the purview of a comparatively small group of individuals.

Again, in an effort to identify only a few of the most significant interactional "hotspots" with which to study the outcomes of interdisciplinary collaboration in the next phase of research, we have chosen to look only at the close interdisciplinary research relations for Center 3. From a review of Sociogram Q, a few noteworthy patterns emerge related to knowledge creating activities in Center 3. First, nine of the center's researchers (22%) have no close interdisciplinary connections at all. Thus, like Center 2, about 80% of the center is active in interdisciplinary knowledge creating activities. This 80% of the population represents all of the sciences in the center, and all but one of the disciplines (environmental biology). Second, while on average each researcher has four close interdisciplinary ties, there are five researchers who have 10 or more such ties. And, just as we saw in Center 2, collectively, these individuals are responsible for over 30% of all the interdisciplinary knowledge creating connections in Center 3. Third, we know that the three of these five "bridges" have what we consider to be high rates of interdisciplinary exposure: one is a chemistry professor with an adjunct post in biology (director), one is atmospheric science professor with experience large-scale "hybrid" environmental science collaborations (director), and one is a chemistry graduate student who has experience working with ecologists and biologists via other "hybrid" ecosystem science research projects. Unfortunately, we are missing sufficient data for the other two researchers due to lack of fieldwork data for this center. However, we do know that these other two "bridges" are both graduate students and that they are students of the faculty "bridges" identified above. To demonstrate the importance of these individuals to the interdisciplinary research relations of Center 3, Sociogram R shows us that when the five "bridges" are removed only 75% of the researchers remain, and 46% of those remaining have two or fewer interdisciplinary ties. **Thus, as with the other centers, these findings further support our hypothesis that relations between researchers and subgroups of different disciplines will depend on the presence of researchers with high rates of interdisciplinary exposure.**

In addition to the fact that three of the five "bridges" in Center 3's interdisciplinary knowledge creating activities are graduate students, it is also important to note that 70% of the senior faculty (including professors and associate professors) have two or fewer close interdisciplinary connections as compared to 0% of the graduate students. Thus, like Center 2, these findings **suggest that, as a population, graduate students may be more engaged in interdisciplinary knowledge creation activities than are the senior or junior faculty (including even non-tenure research scientists).**

The E-I Index metrics reported in Table E indicate that in Center 3 that the life scientists and the physical scientists have just about the same number of connections in total and per person (about 8.6 per person), which makes both groups on average more collaborative than the engineers. However, where as the life scientists in Center 3 tend to have about one more intra-science connection versus inter-science connection, the physical scientists tend to have about one more inter- versus intra-science connection. Thus, while equally collaborative, the physical scientists tend to have more knowledge creating connections outside their field than the life scientists. This compares further to the engineers and environmental scientists. While both

fields represent a small proportion of the center's population, it is not surprising that they are both more externally than internally focused just by the sheer number of potential inter- versus intra-connections. However, wheres on average the engineers in Center 3 are almost as collaboratively generally speaking as the physical and life scientists, they are 15 times more collaborative than the environmental scientists.

Center 4, like Center 3, is also part of the NSF Integrative Graduate Education and Research Training program (IGERT). The mission of Center 4 is to understand factors that affect the fate and transport of contaminants in the environment. Its mission is to (1) perform interdisciplinary research that provides cutting edge solutions to important environmental problems for industries and government agencies; (2) transfer this technology to industry; and (3) provide multi-disciplinary, innovative, research-based, graduate education and training to produce a diverse group of new scientists for a broad range of opportunities.[6]

Center 4 has 61 participants, about the same number as Center 2. Unlike Center 2, however, Center 4 is dominated by graduate students (58%), followed by professors (23%), assistant professors (10%), associate professors (8%) and one non-tenure track research scientist. There are no postdoctoral students in the center. On average, Center 4 affiliates have been involved with the center for 2.8 years and spend about 50% of their total time on center-related tasks, which puts Center 4 close to the mean on both measures.

All of Center 4's affiliates come from and are housed at the center "host" institution, making it a concentrated center like Center 1. Unlike Center 1, however, affiliates of Center 4 represent nine different departments at this institution rather than one. In addition, they represent 18 different disciplines. This translates to a disciplinary diversity ratio of 3.4 researchers to every discipline, basically the same as that of Center 2. However, most of this disciplinary diversity is explained by differences between disciplines within the field of engineering science, thus creating a somewhat exaggerated sense of multidisciplinarity. In fact about 60% of the researchers in Center 3 come from the engineering sciences: 31% in the "majority" discipline of civil/environmental engineering, 15% in the "majority" discipline of chemical engineering, 8% in bioengineering, and two researchers in agricultural engineering and one in mechanical engineering. Another 33% of the affiliates come from various fields in the physical sciences, primarily soil science (10%) and analytical chemistry (5%). The other physical science disciplines – including, hydrology, mineralogy, general chemistry, atmospheric chemistry, (bio)geochemistry, radio chemistry and inorganic chemistry – are all represented by one or two researchers. Finally, four researchers represent two disciplines in the life sciences – microbiology (3) and fisheries science (1). There is one applied mathematician and no social scientists of any kind.

As we have done for the other centers, we begin by summarizing the metrics reported in Table D for Center 4's CRN-T. The density measures for Center 4 are very similar to those we saw in Center 2: 26% at the combined close and collegial level, 10% at the close level, and 16% at the collegial level. Likewise, the mean degree centrality measures for Center 4 are similar to that of Center 2: like researchers in Center 2, researchers in Center 4 have on average 15 connections to other researchers in the center, with more at the level of information sharing than knowledge creating relations. These figures suggest that like Center 2 researchers researchers in Center 4

[6] Please note that we have not finished analyzing all of the fieldwork data for Center 4.

are reasonably well-connected overall but better connected around information sharing activities than knowledge creating activities. However, based on the degree centralization measures for Center 4 (42% for combined connections, 26% for close, and 25% for collegial), we suspect that, unlike Center 2, connections between Center 4 researchers are slightly better distributed across a broader proportion of center's total population as we saw in Center 1. This is corroborated by individual centrality measures, which indicate that less than 5% of the researchers have 10 or more close relationships, and only 20% have 10 or more collegial relationships.

Before proceeding with the sociograms, it is worth noting that, despite the fact that Center 4 (like Center 2) is almost 3.5 times that of Center 1, Center 4 researchers (like Center 2 researchers) have on average only four more connections than Center 1 researchers – almost all of which are at the level of information sharing. Moreover, while Center 4 (like Center 2) is 1.5 times the size of Center 3, researchers have the same mean number of total connections but average more relations at the level of information sharing versus knowledge creating than Center 3 researchers. **These comparisons point to the variable of institutional context, suggesting that increases in a center's organizational size from small to medium may increase the average number of relations between researchers but primarily at the level of information sharing. Moreover, increases in organizational size from medium to large are likely not to increase the average number of overall relations between researchers and could negatively affect the overall ratio of information sharing to knowledge creating relations.**

While the metrics for Center 4's close and collegial CRN-T suggest many parallels to that of Center 2, we can see from the following sociograms that Center 4's lesser degree of centralization has important implications for the structure of the network. As with all centers in our sample, the Center 4 CRN-T is structured around one central core. However, compared to the other centers in our sample, this core is smaller and less influential as it has only five members (8% of the population) and holds only 20% of the center's total ties. And, because the connections between Center 4 researchers are slightly more distributed than those in Center 2 or Center 3, the Center 4 network, like the Center 1 network, takes the shape of one cluster rather than two. As opposed to the almost star-shaped hexagram of Center 1, however, the network in Center 4 resembles (as our highlighting suggests) an egg-shaped oval (see Sociogram S). We believe this difference in the shape of the hexagram and the oval between Center 1 and Center 4 is due to the different rates of disciplinary diversity between Center 1 and Center 4. Indeed, looking at Center 4's CRN-T coded by the disciplinary affiliation of the researchers, we see that the core and the cluster of the network are both dominated by the center's two "majority" disciplines from engineering sciences (civil/environmental engineering and chemical engineering) with a much smaller representation of other engineering and physical science disciplines. If we then look at the network, coding for the researchers' fields of science rather than their disciplines, we see that the physical scientists actually form their own small cluster within the body of the larger egg shaped network, thus showing not only comparatively less centralization than Center 2 and 3 but also perhaps slightly more integration than Center 1 if we were to account for network size (See Sociogram T).

Sociogram U displays the CRN-T for Center 4 at the level of close connections only. Here, as we saw in the other centers, the network of knowledge creating relations reveals small clusters of researchers structured around a core group of individuals. The core of Center 4's close CRN-T has five researchers (8% of the population) who are collectively responsible for 24% of the center's close connections. This is about half the relative size of the core we saw in the close CRN-T for either Center 2 or Center 3. In addition to the core in the center of the network of

knowledge creating activities, there are four clear but comparatively small clusters of researchers. If we look at this network coded by disciplinary affiliation, we see that the core and the most central cluster of the network are each dominated by one of the center's "majority" disciplines (chemical engineering and civil engineering). The other three clusters are either single discipline (soil science) or single science clusters from the physical and engineering sciences (See Sociogram U). If we then look at Center 4's close network coded for science, we can see that, not only are each of these clusters structured around various disciplines from the engineering sciences or physical sciences, there is a very clear and noticeable split between the engineering and the physical science disciplines in the network at the level of knowledge creating activities. In fact, Sociogram V reveals a divide right down the middle of the network between the two sciences, with the life scientists as the interface between them. **Thus, these findings further support our hypothesis that the structure of interdisciplinary research networks will be affected by the diversity and the distance of the researchers' disciplines and that greater rates of functional distance between actors will result in less connectivity between those researchers. These results, along with those of Center 3, also suggest a corollary to this hypothesis: the negative effect of the functional distance between disciplines on network connectivity will be more powerful at the level of knowledge creating versus information sharing activities.**

Looking at the Center 4 CRN-T at the close and collegial level coded for professional rank, we see that there are four "hubs" in the network – two center directors (past and present), one original center founder, and one graduate student. In addition to this one graduate student "hub," it seems that Center 4's entire network of close and collegial relations is dominated by graduate students, both in number and centrality. Except for three faculty identified above and a second center founder, all of the center's senior and junior faculty are closer to the periphery of the network whereas graduate students are closer to the core (see Sociogram W). The speculation of our drawing is confirmed by the actual measures of individual degree centrality: 60% of the graduate students compared to only 50% of the senior faculty and 30% of the junior faculty have at least if not more than the mean number of knowledge creating activities for Center 4. In the network of close relations for Center 4, we see the same pattern of relations between graduate student researchers and senior faculty at the level of knowledge creating activities, but even more exaggerated. By the individual degree centrality measures, we know that 54% of the graduate students compared to only 29% of the senior faculty and 30% of the junior faculty have at least the mean number of knowledge creating activities for Center 4. Moreover, we know that 41% of the professors compared to only 14% of the graduate students have one or fewer close ties. This suggests to us that apart from the two center directors and two other center founders, much of the information sharing and most of knowledge creating activities in Center 4 depend on the graduate students. **Thus, as with all of the previous centers, the results of Center 4 complicate our variable of professional background, adding further evidence that graduate students may in fact be more involved and integrated than either senior or junior faculty in both information sharing and knowledge creating activities of the centers.**

The picture of Center 4 research relations as presented by these network sociograms is consistent with the story told in our fieldwork narratives. We were told repeatedly by those we interviewed that, as one faculty put it: "The student-to-student interactions are really the key to what makes this center a center." Another faculty agreed, telling us that the center features designed to promote information sharing and knowledge creating relations within the center (e.g., brown bag lunches, laboratory rotations, common core courses, shared office space) were really targeted toward "increasing cross-exposure for the students not the faculty." Students

agreed with faculty that the student-to-student interactions were the lynchpin of the center but had different interpretations as to why. As one student stated: “There are not enough interactions among faculty … I mean, there are some very small groups of faculty but…mostly, we [students] end up having our own meetings, our own brown bags because very few faculty show up even though they are supposed to.” Thus, while faculty portrayed themselves as exempt from center interactions, students saw them as evading them.

Finally, looking back briefly at the metrics reported in Table D, we close with a summary of the CRN-I, CRN-D, and the E-I Index results for Center 4. First, we see that, unlike any of the previous centers, the researchers in Center 4 appear to be better integrated with others from inside their own discipline as opposed to researchers from outside their own discipline at both levels. In fact, of all the centers, Center 4 demonstrates the fewest interdisciplinary connections overall and the fewest interdisciplinary knowledge creating connections in particular despite its comparatively high (albeit exaggerated) rate of disciplinary diversity. Moreover, like Center 2, Center 4 is the only other center in the sample where researchers tend to have more information sharing relations with researchers from inside their own discipline as well as with researchers from outside their own discipline. Together, these findings suggest two things. One, there less interdisciplinary versus disciplinary interactivity between researchers of Center 4 as compared to the other centers. Two, there is less knowledge sharing than information sharing between researchers in general, both within as well as across disciplinary boundaries. We suspect that the former has to do with the newness of the relations in the center (only 6% of the current relations predated the start of the center), and the latter with the organizational format of the center.

Again, we only look at only close interdisciplinary connections for Center 4 (Sociogram Y) for the same reasons mentioned in reference to Center 2 and 3. Here, we see a few noteworthy patterns. First, 21 researchers (34% of the center) do not participate in interdisciplinary knowledge creating activities at all, and another 20% have two or fewer relations of this type. Thus, only 66% of the center’s researchers participate in the center’s interdisciplinary knowledge creating activities as compared to 80% of the researchers in Center 2 and Center 3 and about 90% of the researchers in Center 1. Despite this lower rate of interdisciplinary involvement, all of the sciences present in Center 4 are represented in the interdisciplinary knowledge creating connections that do exist in Center 4. However, four disciplines are not– inorganic chemistry, biochemistry, mechanical engineering and applied mathematics. Second, on average researchers in Center 4 have six close interdisciplinary connections, and only seven individuals have more than that and only one who has 10 or more. Thus, as the metrics above indicate, the interdisciplinary knowledge creating relations are less connected and less centralized in Center 4 as compared to the other centers. Third, the seven interdisciplinary “bridges” in Center 4 all have high rates of interdisciplinary exposure: two are physical science professors who are housed in the engineering department. The other five “bridges” are current or very recent graduate students who, as suggested by Sociogram V, (a) are in the life sciences working on projects at the interface of the physical or engineering sciences, or (b) have transferred from the life sciences into the engineering or physical sciences. Their importance to the network is demonstrated by Sociogram Z, which shows us that only 19 researchers (31% of the population) and 16 interdisciplinary knowledge creating connections (10% of the total) remain. **These findings, along with the fact that that only two of the “bridges” in Center 4’s interdisciplinary collaborations are also “hubs” in the center’s general collaborations, provide further support to our hypothesis that connections between individuals and subgroups of different disciplines depend on researchers with high rates of interdisciplinary exposure and not just disciplinary expertise.**

In addition to the fact that five of the seven "bridges" in Center 4's interdisciplinary knowledge creating activities are graduate students, it is also important to note that 58% of the senior faculty (including professors and associate professors) have one or fewer close interdisciplinary connections as compared to 48% of the graduate students. Together, **these findings lend additional support to the notion that graduate students as a population may tend to be more engaged in interdisciplinary knowledge creation activities than senior faculty. The results of Center 4 do not support the argument that graduate students are more engaged in interdisciplinary collaborations than junior faculty, however.**

Finally, in Center 4, according to the results reported in Table E, on average the life scientists not only have the most knowledge creating collaborations per person but they also have more inter-science versus intra-science collaborations of this kind. This latter point is not surprising given that the opportunities for cross-science connections are much greater than the opportunities for in-science connections just by virtue of the relative size of the life scientist subgroup to the rest of the center population. If we look at the engineers and the physical scientists, we see that on average the engineers are more collaborative than are the physical scientists. And, while both physical scientists and engineers tend to have more knowledge creating connections within rather than across the boundaries of their fields, a Center 4 engineer tends to have almost four more intra-science connections than inter-science connections compared to a Center 4 physical scientist who has only about one thereby making engineering more insular than the physical sciences.

Summary of Cross-Center and Center-by-Center Findings

In his 1998 book, E.O Wilson lays out an argument and a plea for full interdisciplinary collaboration across the sciences *and* the humanities. Borrowing the term from 19th century philosopher William Whewell, Wilson claims that *consilience* – the 'jumping together of knowledge… across disciplines to create a common groundwork of explanation' – is the most logical, parsimonious, historically productive and potentially enlightening research agenda in which to invest our intellectual future. It is argued by Wilson and others that, in many fields, the easy work is finished and ambitious scholars are now confronted with problems that cross the boundaries of traditional disciplines and challenge the structures of previous organizations. Thus, for them – but not for all, interdisciplinary collaboration has become, synonymous with all things modern, creative and progressive about scientific research.

Some analysts of scientific research posit that not only has academic science fully embraced interdisciplinary collaboration but has also now actually engaged in Wilson's process of consilience. They argue that a transformation is underway from the "old" way of doing research – characterized as homogeneous, disciplinary, hierarchical, and permanent – to a new way that is heterogeneous, inter- or trans-disciplinary, horizontal, and fluid (see for example, Gibbons et al1994, Etzkowitz 1998, Cooke 1998, Edquist 1997).

While the findings suggest that such a transformation toward interdisciplinary research is in fact underway in the centers we have examined, we also conclude from this small sample that, like other recent studies have found in Europe and the United States, the metamorphosis toward interdisciplinary collaboration is less prevalent and progressive than some analysts speculate (Hakala and Ylijoki 2001, Hicks and Katz 1996, Shinn 2000, Slaughter and Leslie 1997, Ylijoki 2000). And, this is true even in the realm of environmental research such as we have studied here, where it is increasingly acknowledged that pressing problems related to global climate change, biodiversity preservation, organic and inorganic contaminants, hydrologic cycle, sustainable development, etc cannot be adequately addressed without collective input from

researchers in agriculture, forestry, hydrology, geology, resource economics and management, chemistry, engineering, biology, etc (see for example, Carpenter 1998, Daily and Ehrlich 1999, Lubchenco 1998, Michael 1995, Schneider 1995). And, some would even argue, not without the insights of sociology, anthropology, and political science (*Nature* 1997).

So, where and why has this transformation stalled where it has started? Table F provides a very preliminary typology of the key network factors and features as well as the research practices and processes of the centers examined above. The plan is to develop this typology further into a tool that can be used to classify and measure the forms and functionalities of different research collaborations. While this step of the analysis is not yet complete, we provide below a very brief summary of the key findings we have reported above with an equally brief overview of the connections we see between the different center factors, features, and practices and processes presented in Table F.

One, as we hypothesized, all of the research networks in our sample were shaped by the diversity of and the distance between the disciplines of the researchers represented. And, as we predicted, researchers with greater rates of functional distance between their disciplines demonstrated less connectivity than researchers with less functional distance between them. However, and to our surprise, all of our centers except Center 4 demonstrated greater rates of connectivity between researchers of different disciplines than between researchers of like disciplines. While this may be explained more by circumstance than preference due to the fact that centers with higher rates of disciplinary diversity offer researchers more opportunity to connect with someone in any one of several disciplines outside their own versus within just their own, the fact is that researchers are still making the choice to pursue those opportunities rather than ignore them. This suggests to us that researchers are seeking out interdisciplinary connections and that centers do facilitate their making such connections.

Examination of fieldwork data complicates the story of interdisciplinary collaboration, however. First, when asked to describe the nature of their “interdisciplinary” work at the center, faculty and students alike most often described what we could consider to be “multidisciplinary” projects. Rather, than insisting on the *interaction* or, better, the *integration* of different discipline-based theories, skills, methods, and ideas, “multidisciplinary” as compared to “interdisciplinary” projects simply involve the *inclusion* of these practices from different disciplines. It was common to hear stories where, for example, a geologist, an ecologist, and a physicist served as co-investigators on a project to study rainfall over arid landmasses but would, in fact, conduct their pieces of the research apart from each other and discrete from the whole. Conversely, it was rare to hear instances where, for example, a hydrologist, a geologist, and an economist worked together to develop comprehensive understandings of river salinity sources in the Rio Grande and river desalination analyses that included fiscal and political/economic factors as well as engineering and ecological cost-benefit calculations. Thus, we caution too much enthusiasm about the interdisciplinary nature of these centers at this time until we go further into our deeper analysis of they dynamics and the outcomes of the interdisciplinary interactional hotspots we have identified in our centers.

Two, as we hypothesized, the position of researchers in the network would be influenced by professional rank and status. However, the results did not support the direction of our original hypothesis as much as it complicated our variable. On the one hand, our prediction that “star” researchers representing the “majority” discipline(s) of a center – most likely to be center directors – would represent central “nodes,” or points of contact, within a network was proven correct. On the other hand, however, our belief that senior researchers versus junior researchers would be more central to the network was proven incorrect. In all of the centers

except Center 2, junior researchers – particularly the graduate student researchers – were more integrated and more involved than senior researchers in the information sharing and knowledge creating activities of the centers. And, in Center 2, junior researchers were more involved and more integrated than senior researchers at the level of knowledge creating alone. However, while patterns in the social network survey data indicate that graduate students are playing critical roles in the research networks, the fieldwork data suggested that they may not be experiencing the types of roles, relations, and responsibilities in these centers they need in order to develop sound intellectual competencies, solid research capacities, or clear epistemic identities and career trajectories. Many of the students reported, and we also observed, that because the student-to-student connections tend to be stronger than faculty-to-faculty connections or student-to-faculty connections, and because students have not yet fully developed the theories, skills, methods, and ideas of their own "home" disciplines, they argue (and we agree) that these interactions are not even "disciplinary" let alone "interdisciplinary." Rather, as a consequence, they are almost "adisciplinary" in their exposures and exchanges. Moreover, the observed faculty-to-student-to-faculty connections were discussed by both students and faculty as more "multidisciplinary" in the personal exposure gained than "disciplinary" let alone "interdisciplinary" in terms of the educational experience provided.

There are several possible explanations for such patterns. They could reflect, for example, a critical problem in graduate education and training in general, a natural phase of graduate education and training, or an inevitable stage in the development of a new type of interdisciplinary education and training program. It is also possible that what is happening in these centers is that students are learning to navigate diverse teams and negotiate complex problems, the skills they will carry forward and mature to change the practice of science. Or, it could be that they are not finding beneficial research positions or building satisfactory mentorships, which may lead to frustrating and dissatisfying doctoral experiences that take a toll on students, faculty, and universities (Connolly, 2002). Perhaps through exposure alone students are acquiring the right mix of insights and ideas from different fields to generate new research technologies, ask novel research questions, or discover research breakthroughs. Or, perhaps they are not developing sufficient skills and competencies within or between any disciplines, thus jeopardizing their performance in any position as well as their service to any field.

In any event, we find this complication of our variable not only surprising but important for obvious reasons, particularly in light of the fact that we identified a strong and negative correlation between the proportion of graduate students in a center and the percentage of researchers who reported a positive influence of center activities on career development. We cannot determine causal order from our data – Are the graduate students more involved and more integrated and therefore actually suffering more negative consequences of interdisciplinary affiliation? Or, do the graduate students fear more career risks in the future because of the interdisciplinary activities they are choosing to engage now? Regardless, we believe that this finding raises an important implications for how graduate student training in interdisciplinary activities are presented to graduated students and evaluated for graduate students in the future.

Three, our findings both supported and extended our hypothesis that the structure of interdisciplinary research networks would be affected by the interdisciplinary exposures of actors. We argued that researchers with higher rates of interdisciplinary exposure would more likely to serve as "bridges," or ties between researchers and subgroups of different disciplines. And, while we saw this to be true in every center, the results of Center 1 also suggested that the

nature of one's expertise – applied versus basic, technical versus substantive – may also be a decisive factor in determining one's ability to connect researchers of unlike disciplines. We do not have sufficient data at this point to confirm this tentative finding. However, we suspect that, if we had a larger sample where we could test this, we would find that individuals who specialize in technical skills will tend to serve more often as bridges between different disciplines due to the explicit and thus more mobile nature of their expertise versus the tacit and thus more embedded nature of a content specialist's knowledge base.

Moreover, in line with point two above, we found that graduate students as a whole were far more central to the interdisciplinary research networks than senior faculty an in some cases junior faculty. This is not something we had anticipated in our hypotheses. And, given our anticipation that junior faculty would be deterred by professional risks of interdisciplinary research in the context of current reward structures, this finding (along with preliminary results of our fieldwork data) raises important questions for us around generational differences in knowledge values and intellectual motivations with which we believe the university is not ready to contend. On several occasions, we were told by various junior researchers things such as "interdisciplinary research is where my heart is, even if it is not where my department wants my head to be;" and "it's not like it used to be, societal risks require intellectual and professional risks."

Four, with respect to the aggregate organizational variable of institutional context, our findings lend support to the dimension of organizational format as we conceived it but complicate our concepts of organizational size and age. First, our findings suggest that increases in organizational size may increase the number of information sharing connections but is unlikely and may even dilute a center's knowledge creating activities. However, our findings also suggest that it is less a question of organizational size and more a question of group size. In all of our centers, regardless of their overall center size, we found that on average researchers do not interact with more than 15 other researchers overall. Moreover, on average researchers in our centers interact with about 10 other researchers weekly or more and with 14 monthly or less. Together, these findings suggest that when establishing a collaborative group in which the intent is to have both knowledge creating and information sharing activities, one should think about a group size between 10 and 15 researchers.

Second, while our findings suggest that we were right to assume that the age of a collaboration will influence the nature of its activities, we were mistaken when applying the variable at the level of organization. Based on our findings, it seems that the average age of researcher relations is more significant that the overall age of a center in determining the rate at which researchers engage in knowledge creating versus information sharing activities. This clarification is essential in that, unlike our previous hypothesis, our finding advocates long life cycles for centers but shorter life spans for center members. Longer center life cycles allow time for organizations to perfect research practices and processes that will support collaborative relations between individuals while shorter researcher life spans can help affiliates avoid the ambivalent feelings about collaboration that often emerge after too much time with and too much exposure to others. Moreover, these findings and our modified hypothesis support recent theories on the process of collaboration which suggest that *too* high degrees of interpersonal closeness among team members may actually suppress knowledge creation and innovation. The theory is that highly close groups focus more on maintaining relationships and thus tend to seek concurrence of rather than difference in ideas. A recent study of innovation in the business place found that as social ties between R & D members intensify, the innovativeness of the group's new products tends to diminish.

Third, our findings do suggest that a hybrid concentrated/distributed model may be the most beneficial for achieving higher rates of knowledge creating and particularly interdisciplinary knowledge creating overall. We argue that this format is essential because while the concentrated aspect of the center enables the interpersonal relationships and the critical face-to-face exchanges that allow for the construction of new knowledge to take place, the distributed aspect of the center not only allows for the introduction of different disciplines but the introduction of new and more innovative relationships across disciplines. We believe this combination is the only way to make science collaborative across both geographical and functional distances.

Finally, we have identified a few other factors, which we are now in the process of exploring based on the findings we presented above. These include (a) the influence of a charismatic leader versus the importance of a more collective and constant governance body, (b) the proper ratio of senior to junior researchers in terms of the dual but different priorities of creating new scientific knowledge versus developing new scientific practices, and (c) the relationship of balancing disciplinary diversity with functional distance for scientific production and innovation. While the first two factors require a larger sample before we can draw even tentative conclusions, the third requires further analysis of the interactional hotspots we have identified in the centers above.

Outreach Activities

Apart from communicating results to center directors and affiliates as requested and responding to invitations to present results to university, research, and scholarly association audiences interested in learning more about collaboration techniques in general and interdisciplinary collaboration methods in particular, we have had no formal strategy by which outreach activities have been organized or implemented.

PUBLICATIONS AND PRODUCTS

Due to the prolonged and intense data collection and analysis period of this project, our publication preparation and dissemination schedule has been delayed. However, project personnel are currently working on the following manuscripts for submission based on the analysis detailed in this report as well as the analysis related to Center 5 not presented above:

(1) “Universal and University Difficulties Associated with of Implementing Interdisciplinary Research Collaborations” (Rhoten for *Journal of Higher Education*)

(2) “Social Network Analysis: Assessing the Impact of Diversity versus Collegiality in Research Contexts” (Rhoten and Parker for *Social Networks*), and

(3) “Knowledge Transfer: From Institution to Institution and Discipline to Discipline” (Rhoten and Parker for *Research Policy*).

We hope to have publication 1 and 3 submitted by December 2003. Publication 2 may be later due to the methodological challenges we have outlined above.

CONTRIBUTIONS

While analyses of the findings from this project are still underway, the project has already begun to have an impact on the larger community of interest in various ways. Most importantly, from the perspective of informing current debates in science, research, and policy about what interdisciplinary research "is and can be" and providing the participating centers as well as other interested parties with observations and recommendations that will be directly useful to them in their ongoing efforts to develop and catalyze interdisciplinary research and research training, the preliminary results of this study have been increasingly sought after and readily used by participating and non-participating center directors, university deans and departments, scholarly associations, and NSF as well as National Academy of Sciences staff in site visits, annual reports, center meetings, strategy planning sessions, technical publications, and new center design proposals.

In June 2002, Jeffrey Brainard, of the *Chronicle of Higher Education*, published a piece on interdisciplinary science research centers and peer reviews, in which the HV NSF study was featured prominently for its groundbreaking work on understanding the challenges of interdisciplinary research.

- June 14, 2002. "US Agencies Look to Interdisciplinary Science." *Chronicle of Higher Education*. http://chronicle.com/weekly/v48/i40/40a02001.htm

Since the publication of this article, Rita Colwell, director of the National Science Foundation, has mentioned the HV NSF study in her speech entitled, "NSF's investment in Converging Frontiers," as an example of one of the ways in which the NSF is confronting the challenge of taking interdisciplinarity beyond being just a buzzword in science. Thus far, to our knowledge, this speech has so far been delivered at the American Chemical Society Presidential Symposium in Boston, Massachusetts on August 18, 2002 and used in a lecture at the University of California-Santa Cruz on June 21, 2002. Colwell, Rita.

- August 18, 2002. "NSF's investment in Converging Frontiers." Speech at the American Chemical Society Presidential Symposium. Boston, Massachusetts. http://www.nsf.gov/od/lpa/forum/colwell/rc020818acsboston.htm

- Colwell, Rita. June 21, 2002. "NSF's investment in Converging Frontiers." Lecture: University of California-Santa Cruz. Santa Cruz, California. http://www.nsf.gov/od/lpa/forum/colwell/rc020621ucsantacruz.htm

This speech has also been reproduced in the September 9th issue of *New Technology Week*. This reprinting has lead to several inquiries about the study from various interested individuals and academic organizations as well as science and technology agencies, including the Directorate for Science Technology and Industry at the Organisation for Economic Cooperation and Development and the Science and Technology Officer of the Dutch Embassy in Washington, D.C.

Table A

	Center 1	Center 2	Center 3	Center 4	Center 5*	Center 7
Center Founding Date	~1970	1996	1999	1997	1995	2000
Center Type	Cooperative	HDGC	IGERT	IGERT	Cooperative	STC
Center Home	National research center	Private university	Public university	Public university	National research center	Public university
Center Structure	Single Whole Network	Single Whole Network	Single Whole Network	Single Whole Network	Multiple Project Networks	Multiple Project Networks
Center Format	Concentrated	Distributed	Concentrated / Distributed	Concentrated	Distributed	Distributed
# of institutions in center / center sample	1	20	13	1	259	28
# of researchers in center	18	66	40	61	619 (unique actors) 684 (w/ duplicates)	153 (unique actors) 180 (w/ duplicates)
# of disciplines in center	13	19	9	18	56	24
Disciplinary diversity (researcher: discipline ratio)	1.4:1	3.5:1	4.4:1	3.4:1	11.1:1	5.5:1
# of sciences in center	6	8	4	4	8	7
Science diversity (researcher: science ratio)	3	3.5	10	15.3	77.4	21.9
Mean length of time researchers affiliated with center **	9.6 years*** (min .5, max 28.5)	4.3 years (min .5, max 6)	2.3 years (min .5, max 4)	2.8 years (min .5, max 6)	2.7 years (min .5, max 8)	2.3 years (min .5, max 3)
Distribution of researchers in center by rank	Director (3) Sr. Scientist (3) Scientist III (1) Scientist I-II (1) Res Sci (6) Postdoc (2) Grad Res (1) Undergrad (0) Other (1) Unknown (0)	Director (3) Professor (20) Assoc Prof (4) Asst Prof (7) Res Sci (11) Postdoc (7) Grad Res (14) Undergrad (0) Other (0) Unknown (0)	Director (2) Professor (14) Assoc Prof (6) Asst Prof (0) Res Sci (2) Postdoc (0) Grad Res (16) Undergrad (0) Other (0) Unknown (0)	Director (2) Professor (12) Assoc Prof (5) Asst Prof (6) Res Sci (1) Postdoc (0) Grad Res (35) Undergrad (0) Other (0) Unknown (0)	Director (1) Professor (169) Assoc Prof (59) Asst Prof (53) Res Sci (195) Postdoc (68) Grad Res (55) Undergrad (3) Other (10) Unknown (12)	Director (5) Professor (19) Assoc Prof (8) Asst Prof (9) Res Sci (38) Postdoc (9) Grad Res (55) Undergrad (6) Other (0) Unknown (4)
distribution of researchers in center by discipline	Astrophys (1) Chem (Env) (1) Software Eng (1) Electric Eng (1) Climate Chg (3) (Micro)Meteor (1) (Bio)Geochem (1) Paleoecol (1) Env Sci Pol (1) Statistics (2) GIS (1) Env SS Pol (3) Res Econ (1)	Chem Eng (1) Civ/Env Eng (3 Mech Eng (3) Ecology (2) Eng Pub Pol (17) Sust Res Mgt (2) App Math (1) App Anthro (3) Hist of Sci (1) Decisiion Sci (7) Risk Assess. (6) Epidemiology (1) Res Econ (6) Env SS Pol (1) Hydro Eng (4) Land Use Geo (4) App Phys (1) Industrial Eng (2) Behav Econ (1) *1 unknown and uncounted	Anal Chem (2) Civ/Env Eng (3) Atmos Chem (10) (Micro)Meteor (2) (Bio)Geochem (2) Develop Biol (1) Ecology (15) Neurobio (1) Forestry Sci (2) Limnology (1) Env Bio (1)	Anal Chem (3) Gen Chem (2) Inorgan Chem (1) Chem Eng (9) Civ/Env Eng (19) Mech Eng (1) Agr Eng (2) Bio Eng (5) Atmos Chem (2) (Bio)Geochem (1) Hydrology (2) Mineralogy (1) Soil Science (6) Biochem (1) Microbio (3) App Math (1) Radio Chem (1) Fisheries Sci (1)	(Bio)Geochem (4) Ag Sci (1) App Anthro (1) App Math (3) Archaeology (4) Bio/Ecoinform (2) Biogeography (5) Bio Ocean (2) Biostatistics (4) Botany (9) Chem Ocean (2) Climate Chg (1) Conserv Bio (38) Ecology (291) Ecosys Sc (10) Entomology (4) Chem (Env) (2) Env Sci, Pol (3) Env Soc Sci (2) Epidemiology (5) Evol Bio (22) Fire Science (4) Fisheries Sci (15) Forestry Sci (8) Geology (1) GIS (3) Hydro Eng (1) Hydrology (8) Info Sys Mgt (4)	Chem Eng (1) Hydro Eng (19) Civ/Env Eng (4) Climate Chg/ (1) Atmos Sci (2) (Micro)Meteor (4) Geology (3) (Bio)Geochem (6) Hydrology (61) Soil Science (8) Agriculture (1) Botany (4) Ecology (8) Microbiology (1) Physiology (1) Ecosys Sci (4) Sust Res Mgt (1) App Math (2) Nuclear Phys (1) App Anthro (1) Env Soc Sci (4) Res Econ (8) Human Geog (2) Watersh Sci (4) Unknown (2)

					Library Sci (1) Mammology (3) Marine Bio (6) Marine Geo (1) (Micro)Meteor (1) Molecular Bio (1) Ornithology (1) Paleoanthro (1) Paleobio (15) Paleobotany (3) Paleoecol (8) Paleontology (35) Paleoocean (2) Phys Geog (3) Pop Bio (7) Programming (1) Remote Sens (5) Res Econ (10) Soil Science (3) Statistics (6) Sust Res Mgt (9) Systematics (13) Tropical Bio (1) Wildlife Bio (1) Zoology (6) Unknown (17)	
Distribution of researchers in center by science	Comp/Math (2) Engineering (2) Env Sci/Eng (1) Env Soc Sci (3) Life (1) Physical (8) Social (1)	Comp/Math (1) Engineering (12) Env Sci/Eng (19) Env Soc Sci (1) Life (3) Physical (5) Social (23) Arts & Hum(1)	Engineering (3) Env Sci/Eng (2) Life (18) Physical (17)	Comp/Math (1) Engineer (36) Life (4) Physical (20)	Comp/Math (10) Engineer (1) Env Sci/Eng (36) Env Soc Sci (2) Information (5) Life (461) Physical (71) Social (16) Unknown (17)	Comp/Math (2) Engineer (24) Env Sci/Eng (5) Env Soc Sci (4) Physical (92) Life (15) Social (9) Unknown (2)

* The data presented for Center 5 in this table reflects only the 48 working groups that were "live" at the time of our study. This center averages 45-60 working groups per year, with 3-20 members in each group. In addition to these groups (which meet 2 or 3 times for 3 to 5 days each), there are 4-6 full-time fellows at the center at any one time and 15-20 postdoctoral researchers.
** These calculations reflect the mean value of the respondents' answers only not of the all center affiliates.
*** There is a wide distribution in the time that researchers have been affiliated with Center 1, which may skew the mean value to some degree. As a comparison, the median period of affiliation at Center 1 is 3.5 years.

Table B

	STRAND I	STRAND II
Center 1	Administered on site Initiated May 2002 / Completed May 2002 100% (18 of 18 total affiliates)	April - May 2002 18 Interviews
Center 2	Administered online, via email & post Initiated June 2002 / Completed October 2002 70% (46 of 66 total affiliates)	May 2002-June 2002 26 Interviews
Center 3	Administered online, via email & post Initiated June 2002 / Completed September 2002 73% (29 of 40 total affiliates)	N/A*
Center 4	Administered online, via email & post Initiated June 2002 / Completed November 2002 69% (42 of 61 total affiliates)	April 2003 12 Interviews
Center 5	Administered online, via email & post Initiated June 2002 / Completed September 2002 70% (480 of 684** total affiliates)	May 2003 12 Interviews
Center 6	Administered at on site meeting Initiated June 2002 / Not completed	Not conducted due to due to insufficient response rate with survey
Center 7	Administered online Initiated December 2002 / Completed May 2003 54% (97 of 180*** total affiliates)	March 2003 13 Interviews

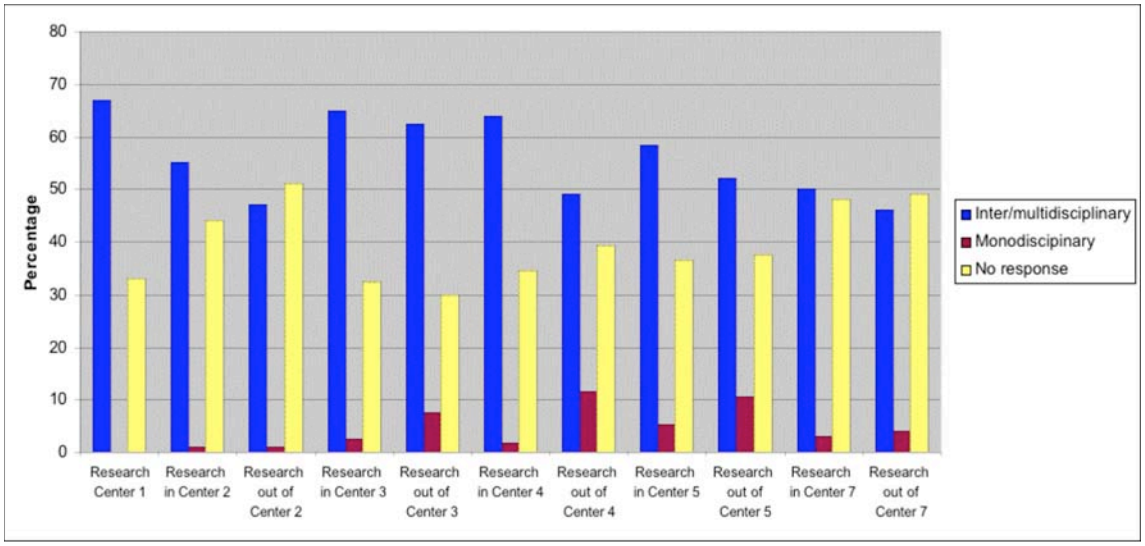
* Site visits were not conducted at Center 3 due to the fact that the center is only in observable operation during the summer months. Due to scheduling conflicts visits were not possible before June 30, 2003.

** There are 619 unique individuals in Center 5. However, because of the group-based structure of the center and because some of the researchers participate in more than one group surveyed, the total survey sample was 684.

*** There are 153 unique individuals in Center 7. However, because of the group-based structure of the center and because some of the researchers participate in more than one group surveyed, the total survey sample was 180.

NOTE: These total affiliate figures are based on calculations made from official center membership lists but which exclude researchers who (a) have self-identified as “non participants,” (b) who have been identified by center leadership as “non participants,” and (c) who have passed away.

Graph A



Graph B

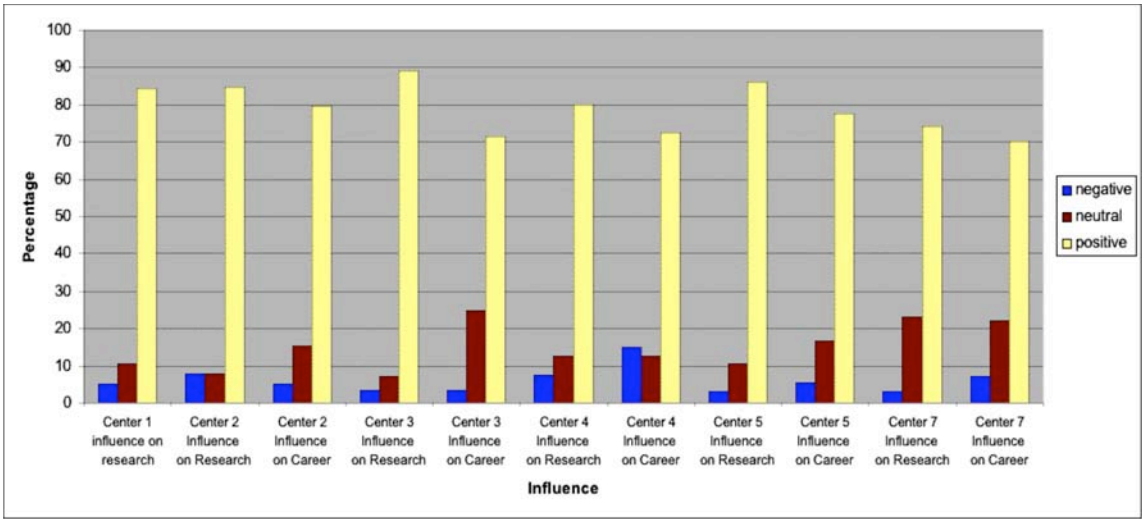


Table C

	Center 1 (18)	**Center 2** (66)	**Center 3** (40)	**Center 4** (61)	**Mean** (~46)
Mean % of total work time dedicated to center-related work	93.7%	44.2%	57.8%	49.4%	50.3%
% of all possible research connections that predate center**	14%	16%	28%	6%	16%
Mean # of other researchers that any researcher contacts weekly or more	10	6	8	15	9.75
Mean % of other researchers that any researcher contacts weekly or more	55.6%	9.1%	20.0%	24.6%	27.3%
Mean # of other researchers that any one researcher contacts monthly or less	6	19	12	17	13.5
Mean % of other researchers that any one researcher contacts monthly or less	33.3%	28.8%	30.0%	27.9%	30.0%
% of researchers who interact with other researchers via **formal face-to-face** forums	66% (close/collegial)	55% (close/collegial)	83% (close/collegial)	58% (close/collegial)	65.5% (close/collegial)
% of researchers who interact with other researchers via **formal technologically mediated** forums	66% (close/collegial)	38% (close/collegial)	72% (close/collegial)	40% (close/collegial)	56.5% (close/collegial)
% of researchers who interact with other researchers via **informal face-to-face** forums	76% (close/collegial)	66% (close/collegial)	92% (close/collegial)	69% (close/collegial)	75.75% (close/collegial)
% of researchers who interact with other researchers via **informal technologically mediated** forums	77% (close/collegial)	48% (close/collegial)	60% (close/collegial)	50% (close/collegial)	58.75% (close/collegial)
% of researchers who interact with other researchers of **different disciplines** via **formal face-to-face** forums	67% (close/collegial)	51% (close/collegial)	79% (close/collegial)	51% (close/collegial)	62% (close/collegial)
% of researchers who interact with other researchers of **different disciplines** via **formal technologically mediated** forums	67% (close/collegial)	33% (close/collegial)	70% (close/collegial)	32% (close/collegial)	50.5% (close/collegial)
% of researchers who interact with other researchers of **different disciplines** via **informal face-to-face** forums	76% (close/collegial)	66% (close/collegial)	92% (close/collegial)	77% (close/collegial)	77.75% (close/collegial)
% of researchers who interact with other researchers of **different disciplines** via **informal technologically mediated** forums	78% (close/collegial)	49% (close/collegial)	60% (close/collegial)	36% (close/collegial)	55.75% (close/collegial)

Table D

Network & Network Metrics	Center 1 (18)	Center 2 (66)	Center 3 (40)	Center 4 (61)	Mean (~46)
CRN-T Close & Collegial Ties					
Density	63%	23%	39%	26%	37.5%
Mean Degree Centrality	11	15	15	15	14
Degree Centralization	41%	53%	58%	42%	48.5%
CRN-T Close Ties					
Density	27%	8%	21%	10%	16.5%
Mean Degree Centrality	5	5	8	6	6
Degree Centralization	36%	28%	35%	26%	31.25%
CRN-T Collegial Ties					
Density	36%	15%	17%	16%	21%
Mean Degree Centrality	6	10	7	9	8
Degree Centralization	25%	31%	32%	25%	28.25%
CRN-I Close & Collegial Ties					
Density	47%	15%	23%	11%	22.75%
Mean Degree Centrality	8	10	9	7	8
Degree Centralization	46%	37%	46%	32%	40.25%
CRN-I Close Ties					
Density	16%	5%	11%	4%	9%
Mean Degree Centrality	3	3	4	2	3
Degree Centralization	35%	18%	23%	17%	23.25%
CRN-I Collegial Ties					
Density	31%	10%	12%	7%	13.75%
Mean Degree Centrality	5	7	5	5	5
Degree Centralization	25%	22%	31%	24%	25.5%
CRN-D Close & Collegial Ties					
Density	16%	8%	16%	16%	14%
Mean Degree Centrality	3	5	6	9	6
Degree Centralization	28%	20%	26%	29%	25.75%
CRN-D Close Ties					
Density	10%	4%	10%	7%	7.75%
Mean Degree Centrality	2	2	4	4	3
Degree Centralization	28%	13%	19%	21%	20.25%
CRN-D Collegial Ties					
Density	6%	4%	6%	9%	6.25%
Mean Degree Centrality	1	3	2	5	3
Degree Centralization	13%	10%	15%	22%	15%

Table E

Close Ties ONLY Center / Science	Number People	Internal Ties	External Ties	Total Ties	# Sciences interact w/	Internal Ties per Person	External Ties per Person	Total Ties per Person	EI Index
CENTER 1									
Engineering	2	0	3	3	2	0.00	1.50	1.50	1.00
Physical Sciences	8	30	22	52	5	3.75	2.75	6.50	-0.15
Life Sciences	1	0	8	8	3	0.00	8.00	8.00	1.00
Social Sciences	1	0	1	1	1	0.00	1.00	1.00	1.00
Comp & Math Sciences	2	0	9	9	2	0.00	4.50	4.50	1.00
Environmental Sciences/Engineering	1	0	1	1	1	0.00	1.00	1.00	1.00
Environmental Social Sciences	3	2	6	8	2	.67	2.00	1.67	0.50
Arts & Humanities	0	NA	NA	NA	NA	NA	NA	NA	0
CENTER 2									
Engineering	12	6	33	39	4	.50	2.75	3.25	0.69
Physical Sciences	5	12	8	20	3	2.40	1.60	4.00	-0.20
Life Sciences	3	2	6	8	4	.67	2.00	2.67	0.50
Social Sciences	23	90	67	157	6	3.91	1.91	6.83	-0.15
Comp & Math Sciences	1	0	2	2	2	0.00	2.00	2.00	1.00
Environmental Sciences/Engineering	19	59	69	128	6	3.11	3.63	6.74	0.08
Environmental Social Sciences	1	0	2	2	1	0.00	2.00	2.00	1.00
Arts & Humanities	1	0	2	2	2	0.00	2.00	2.00	1.00
CENTER 3									
Engineering	3	2	21	23	2	.67	7.00	7.67	0.83
Physical Sciences	17	66	80	146	2	3.88	4.71	8.59	0.10
Life Sciences	18	84	70	154	3	4.67	3.89	8.56	-0.09
Social Sciences	0	NA	NA	NA	NA	NA	NA	NA	0
Comp & Math Sciences	0	NA	NA	NA	NA	NA	NA	NA	0
Environmental Sciences/Engineering	0	NA	NA	NA	NA	NA	NA	NA	0
Environmental Social Sciences	0	NA	NA	NA	NA	NA	NA	NA	0
Environmental Sciences	2	0	1	1	1	0.00	.50	.50	1.00
Arts & Humanities	0	NA	NA	NA	NA	NA	NA	NA	0
CENTER 4									
Engineering	36	192	58	250	2	5.33	1.61	6.94	-0.54
Physical Sciences	20	54	40	94	2	2.70	2.00	4.70	-0.15
Life Sciences	4	6	24	30	2	1.50	6.00	7.50	0.60
Comp & Math Sciences	1	0	0	0	0	0.00	0.00	0.00	0
Environmental Sciences/	0	NA	NA	NA	NA	NA	NA	NA	0

Engineering									
Environmental Social Sciences	0	NA	NA	NA	NA	NA	NA	NA	0
Environmental Sciences	0	NA	NA	NA	NA	NA	NA	NA	0
Arts & Humanities	0	NA	NA	NA	NA	NA	NA	NA	0

Table F

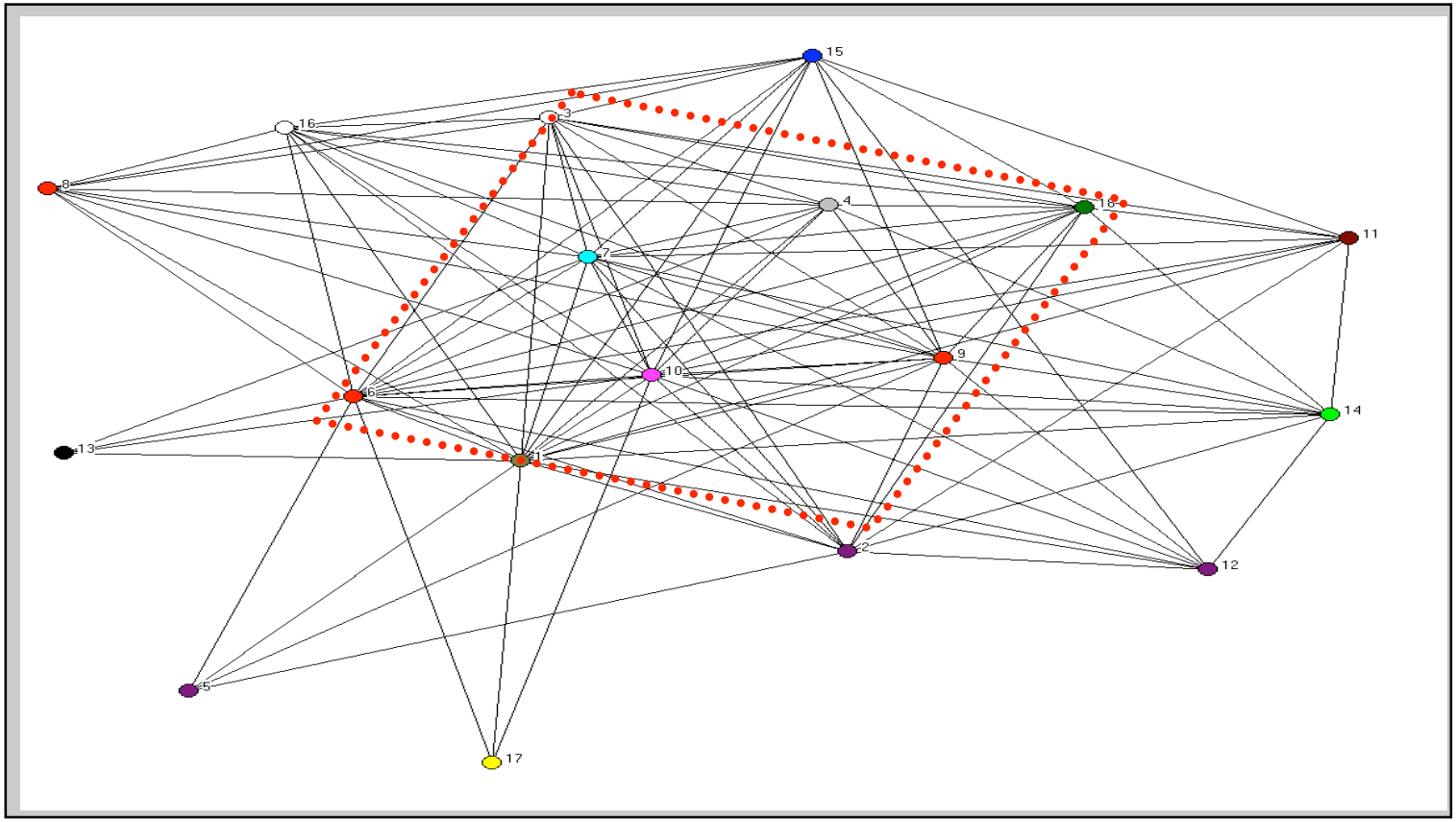
Factors	**Center 1**	**Center 2**	**Center 3**	**Center 4**
Organizational Size	Very Small	Large	Average	Large
Organizational Age	Old	Average	Young	Young
Duration of relations	Very Long	Long	Average	Short
Organizational Format	Concentrated	Distributed	Hybrid	Concentrated
Disciplinary Diversity	Very Diverse	Diverse	Not Diverse	Diverse
Science Field Diversity	Very Diverse	Very Diverse	Not Diverse	Not Diverse at all
Hierarchy of Researchers	Flat	Steep (more junior than senior)	Flat	Steep (more junior than senior)
Interdisciplinary Exposure	NA	NA	NA	NA
FEATURES				
Information Sharing Versus Knowledge Creating				
Shape of Network Overall	Hexagram	Venn Diagram	Target and Arrow	Egg
Overall Integration of Researchers	More collaboration around information sharing than knowledge creating activities	Much more collaboration around information sharing than knowledge creating activities	More collaboration around knowledge creating than information sharing activities	Much more collaboration around information sharing than knowledge creating activities
Overall Distribution of Connections between Researchers	Knowledge creating collaborations are far more concentrated than information sharing activities	Information sharing collaborations are a little more concentrated than knowledge creating activities	Knowledge creating collaborations are a little more concentrated than information sharing activities	Knowledge creating and information sharing activities are equally de-concentrated
Most Central Research Groups	New director and lower rank scientists at all levels	Directors and senior faculty overall/ Directors and junior researchers (non-tenure and graduate students) at knowledge creating	Directors and junior researchers, specifically graduate students , at all levels	Directors and graduate students at all levels, and graduate students even more so at knowledge creating level
Interdisciplinary versus Monodisciplinary				
Overall Integration of Researchers	Researchers are better integrated with researchers from other disciplines than own disciplines, particularly around information sharing activities	Researchers are better integrated with researchers from other disciplines than own disciplines, particularly around information sharing activities	Researchers are better integrated with researchers from other disciplines than own disciplines, but equally so around information sharing and knowledge creating	Researchers are better integrated with researchers from their own disciplines than other disciplines, particularly around information sharing activities
Overall Distribution of Connections between Researchers	Interdisciplinary information sharing activities are the most concentrated	Interdisciplinary information sharing activities are the most concentrated	Interdisciplinary information sharing and knowledge creating activities	Monodisciplinary information sharing activities are the most concentrated

			are the most concentrated	
Most Central Research Groups	Lower rank scientists most central to interdisciplinary creating activities	Graduate students most central to interdisciplinary knowledge creating activities	Graduate students most central to interdisciplinary knowledge creating activities	Graduate students most central to interdisciplinary knowledge creating activities

PRACTICES AND PROCESSES				
Multi/Interdisciplinary inside versus outside	NA	Average Difference	Below Average Difference	Above Average Difference
Positive Influence on Research Agenda	Average	Average	Above Average	Below Average
Positive Influence on Career Trajectory	NA	Above Average	Below Average	Below Average
Weekly Interactions	Far Above Average	Far Below Average	Below Average	Average
Monthly Interactions	Average	Average	Average	Average
Most Popular Forum for Interactions	Informal face-to-face / Informal technologically-mediated	Informal face-to-face	Informal face-to-face	Informal face-to-face

Sociogram A

Within center 1 researchers on average have 11 close *and* collegial connections. Most of these interactions are concentrated in a small "core" researchers (red). As a result, researchers of all disciplines do interact with each other but not equally. Disciplines from the physical sciences dominate the core of hexagram network, environmental scientists/social scientist dominate the periphery.



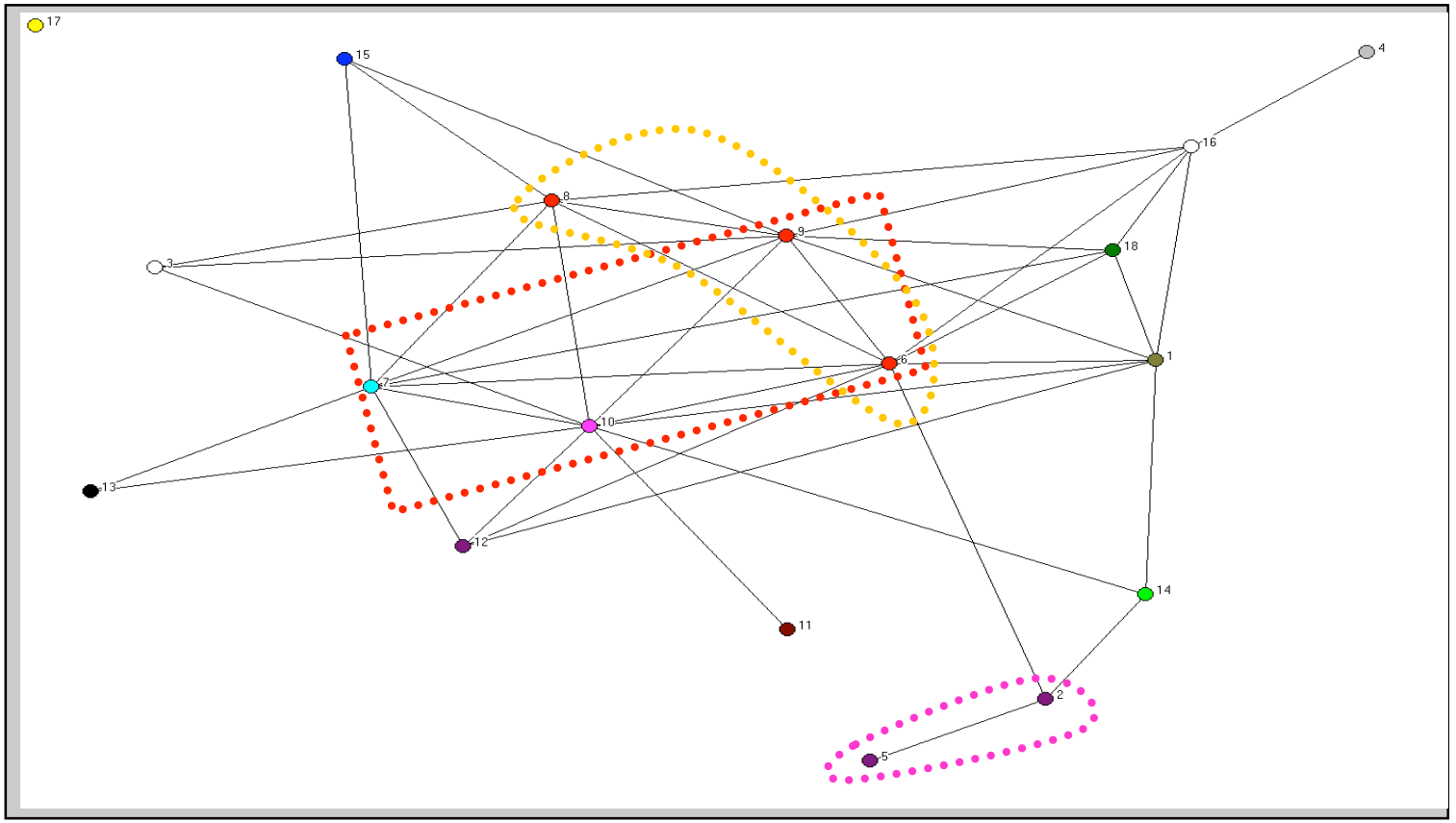
Discipline
- = Astrophysics
- = Environmental Chemistry
- = Software Engineering
- = Electrical Engineering
- = Climate Change
- = Meteorology
- = (Bio)Geochemistry
- = Paleoecology
- = Enviro Sci Eng Policy
- = Statistics
- = Geographic Info Systems
- = Enviro Soc Sci & Policy
- = Resource Economics

Network Measures
Density = 63%
Cohesion = 1.4
Ave. Centrality = 11

CENTER 1 CRN-T: shows all "close and collegial" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram B

Center 1 researchers have on average 5 close relations. The most central disciplines (indicated by circles) are three core climate variability/change researchers, one a (bio)geochemist, one applied statistician, and one paleoecologist. Environmental scientists/social scientists and resource economists have among the fewest "close" relations.



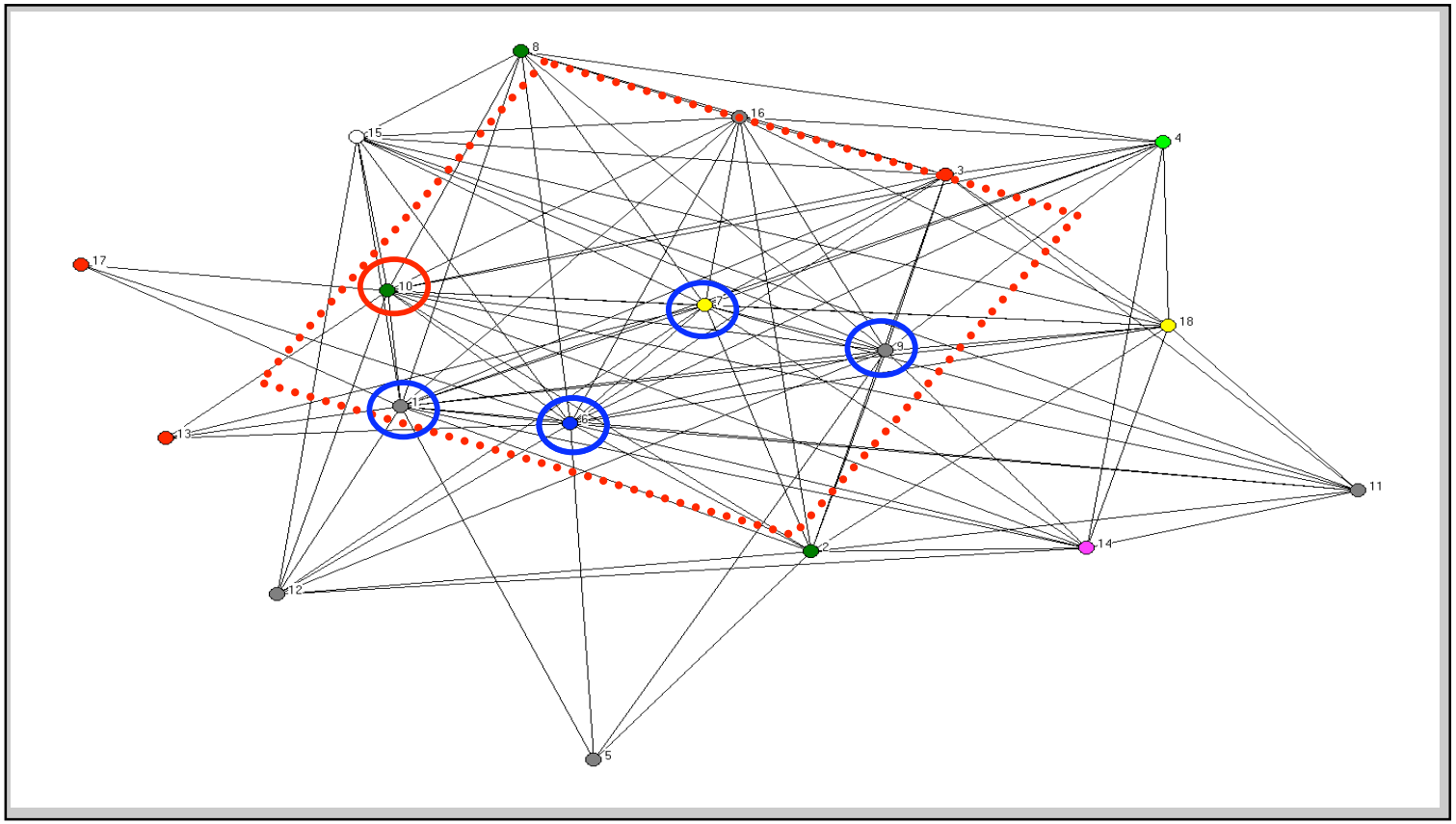
Discipline
- = Astrophysics
- = Environmental Chemistry
- = Software Engineering
- = Electrical Engineering
- = Climate Change
- = Meteorology
- = (Bio)Geochemistry
- = Paleoecology
- = Enviro Sci/Eng Policy
- = Statistics
- = Geographic Info Systems
- = Enviro Soc Sci & Policy
- = Resource Economics

Network Measures
Density = 27%
Cohesion = 2.0
Ave. Centrality = 5

CENTER 1 CRN-T: shows all "close" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram C

There are five "hubs" with the most close and collegial connections to other researchers in the center. One is the current center director and four are lower rank scientists. Four of the seven higher rank scientists are on the outer periphery of the network; three are on the periphery of the core (including one past and one current director) .



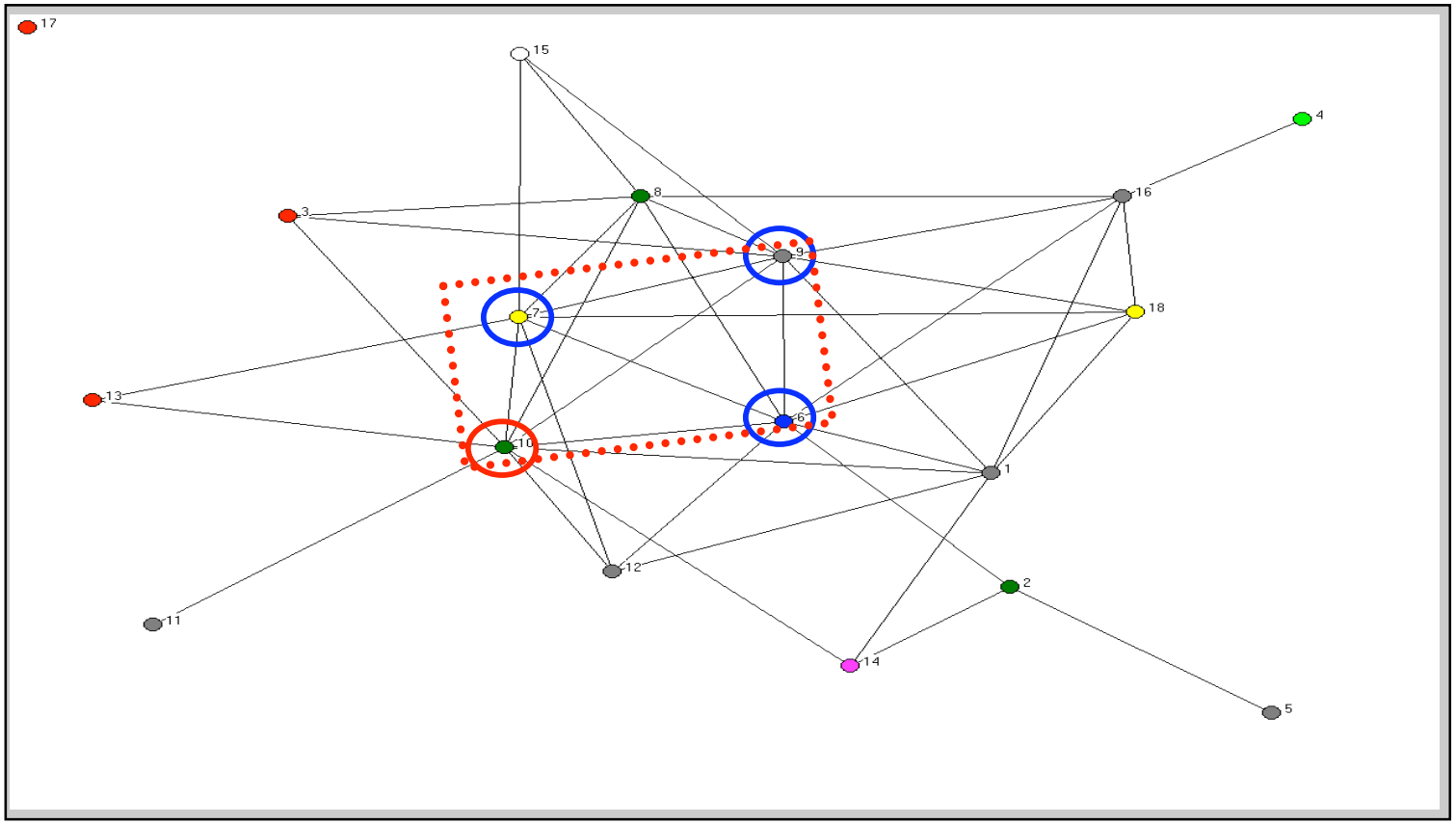
Position
- = Senior Scientist
- = Scientist III
- = Scientist I or II
- = Post Doctoral Researcher
- = Graduate Researcher
- = Non-Tenure Researcher
- = Directors (past/present)
- = Other

Network Measures
Density = 63%
Cohesion = 1.4
Ave. Centrality = 11

CENTER 1 CRN-T: shows all "close"and "collegial" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram D

At the level of close relations, the connections of the network are dominated by one of the current center directors (red) and three lower rank scientists (blue).



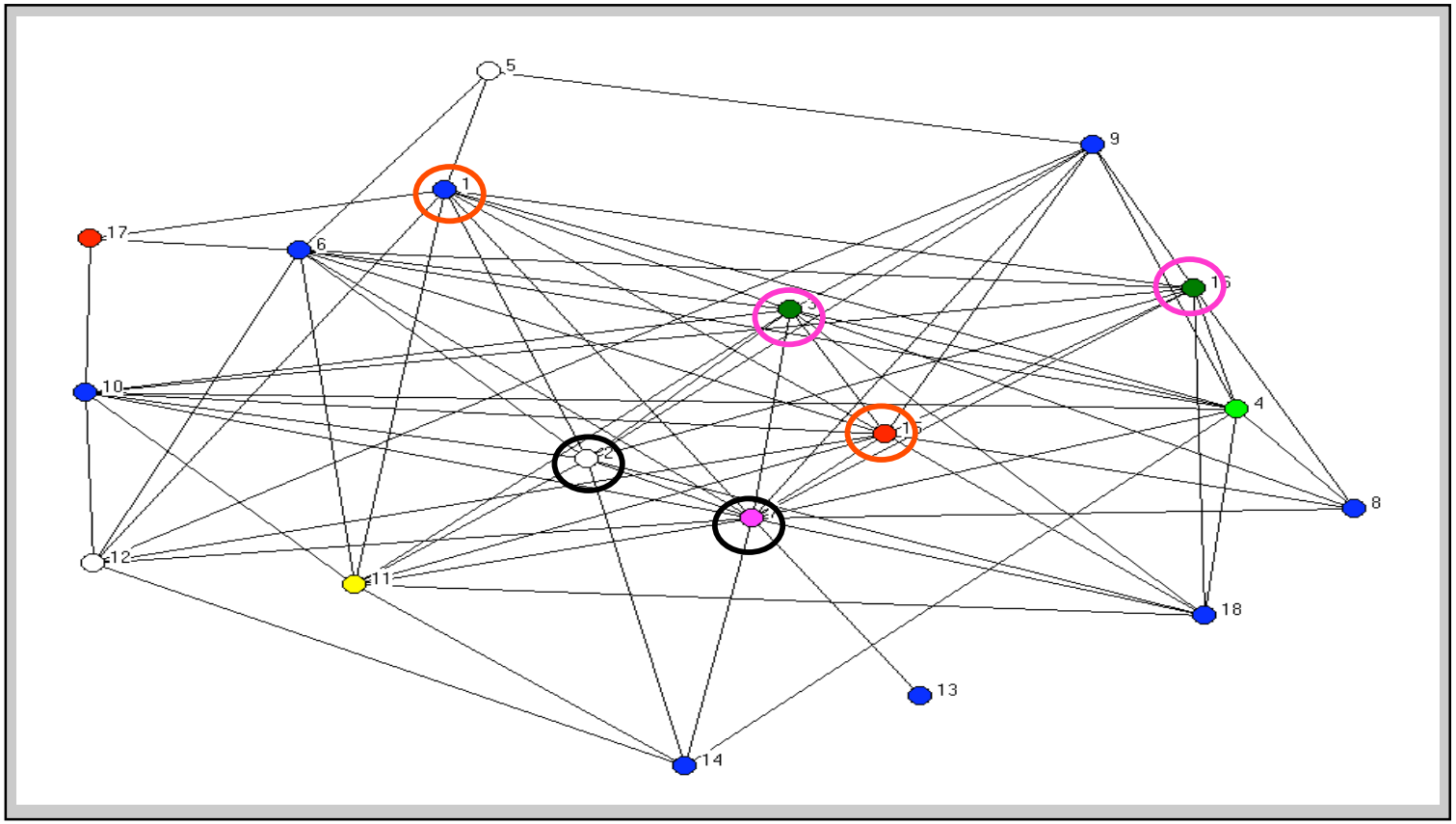
Position
- = Senior Scientist
- = Scientist III
- = Scientist I or II
- = Post Doctoral Researcher
- = Graduate Researcher
- = Non-Tenure Researcher
- = Directors (past/present)
- = Other

Network Measures
Density = 27%
Cohesion = 2.0
Ave. Centrality = 5

CENTER 1 CRN-T: shows all "close" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram E

On average each researcher has 8 close and collegial interdisciplinary connections. There are six researchers with the most interdisciplinary connections representing a variety disciplines and sciences. Two are methodologists (pink), two are technicians (orange), and two have extremely interdisciplinary backgrounds (black).



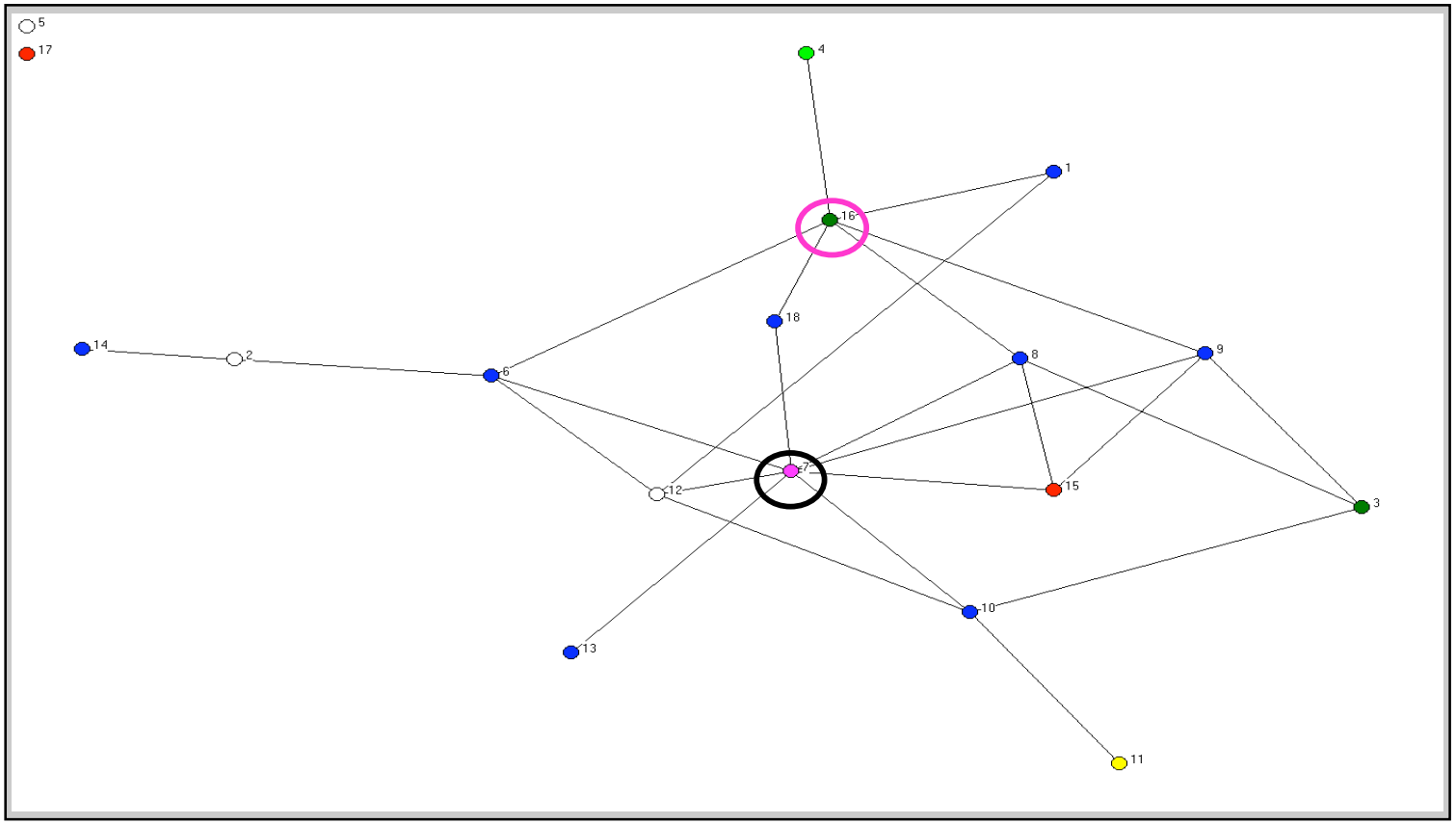
Science
= Engineering
= Physical Sciences
= Life Sciences
= Social Sciences
= Comp & Math Sciences
= Environmental Sci Eng
= Environmental Soc Sci
= Arts & Humanities

Network Measures
Density = 47%
Cohesion = 1.6
Ave. Centrality = 8

CENTER 1 CRN-I: shows "close" and "collegial" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram F

On average each researcher has 3 close interdisciplinary connections, and 50% of the researchers have two of fewer. There are two "bridges" in the interdisciplinary network. One is a methodologist (an applied statistician) the other is a paleoecologist with an interdisciplinary background in economics and religious studies.



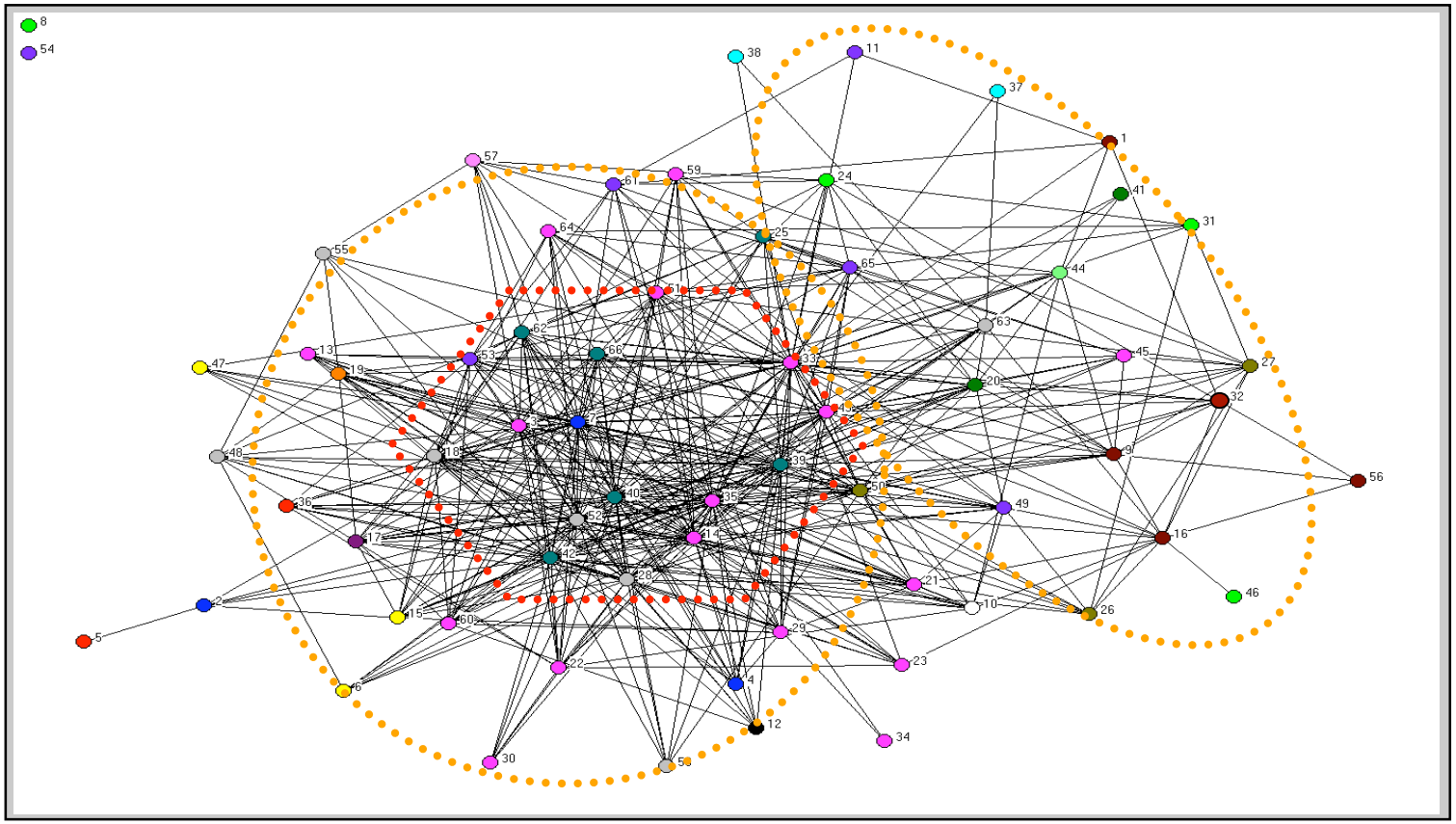
Science
= Engineering
= Physical Sciences
= Life Sciences
= Social Sciences
= Comp & Math Sciences
= Environmental Sci Eng
= Environmental Soc Sci
= Arts & Humanities

Network Measures
Density = 16%
Cohesion = 2.3
Ave. Centrality = 3

CENTER 1 CRN-I: shows "close" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram G

Center 2 researchers on average have 15 close and collegial relationships. There are two disciplinary based clusters (orange) and a small "core" of central researchers (red). The larger of the two clusters and the "core" are both dominated by the center's "majority" disciplines (engineering and public policy, decision sciences, and risk analysis/assessment).



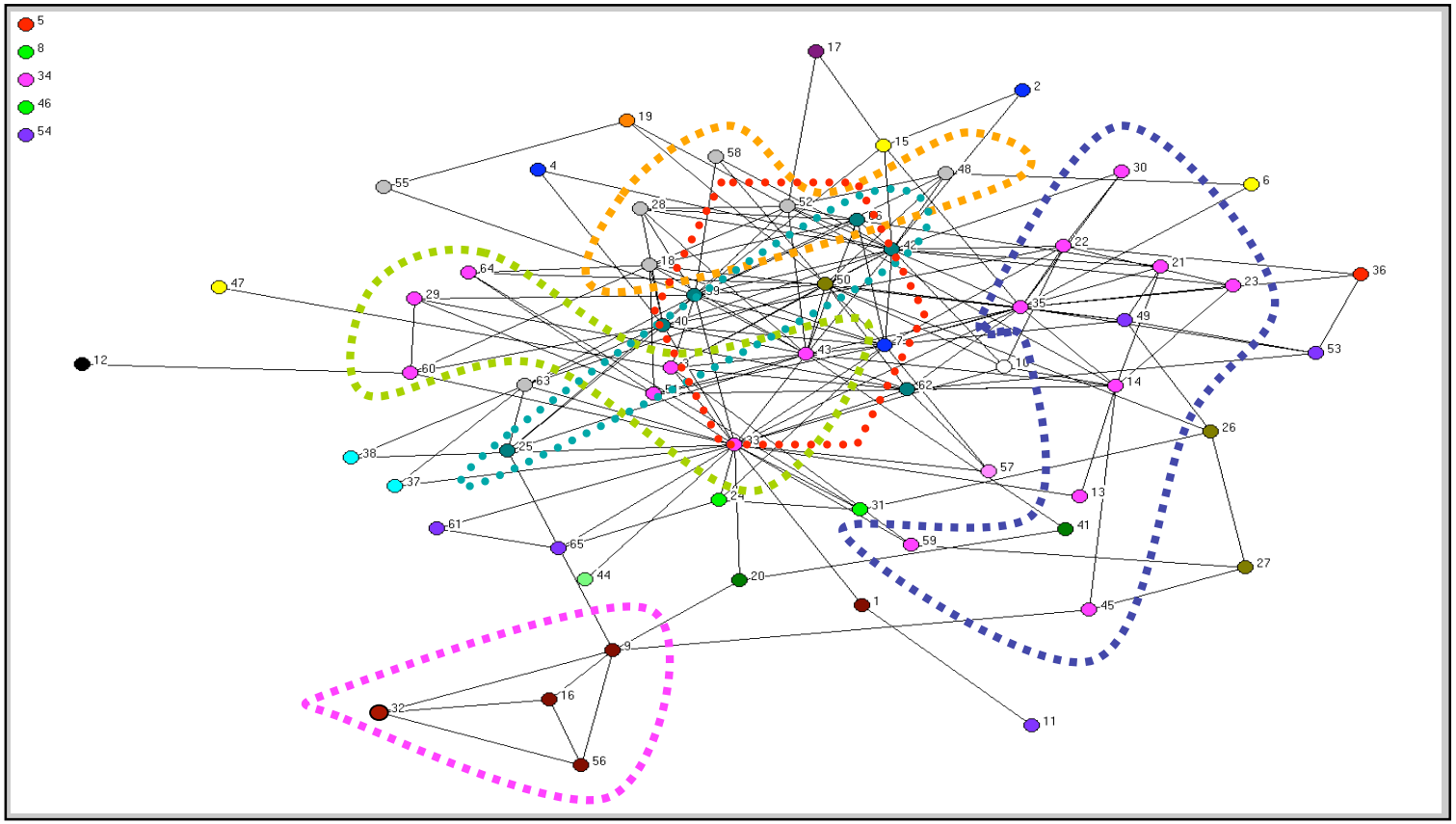
Discipline
- = Chemical Engineering
- = Hydro Engineering
- = Civil/Enviro Engineering
- = Mechanical Engineering
- = Industrial Engineering
- = Ecology
- = Eng Public Policy
- = Sustain/ Resource Mgt
- = Applied Mathematics
- = Applied Physics
- = Applied Anthropology
- = History of Science
- = Decision Science
- = Risk Analysis/Assess
- = Epidemiology
- = Env Soc Sci Policy
- = Resource Economics
- = Land Use Geography
- = Behavioral Economics

Network Measures
Density = 23%
Cohesion = 1.9
Ave. Centrality = 15

CENTER 2 CRN-T: shows all "close and collegial" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram H

Center 2 researchers have on average 5 close relationships. In addition to a clear network core (red) dominated by researchers from the center's "majority" disciplines, there are five noticeable clusterings of disciplines. Four of these five represent center "majority" disciplines (engineering and public policy -2, decision sciences, and risk analysis/assessment). One represents a "minority" discipline (land use geography).



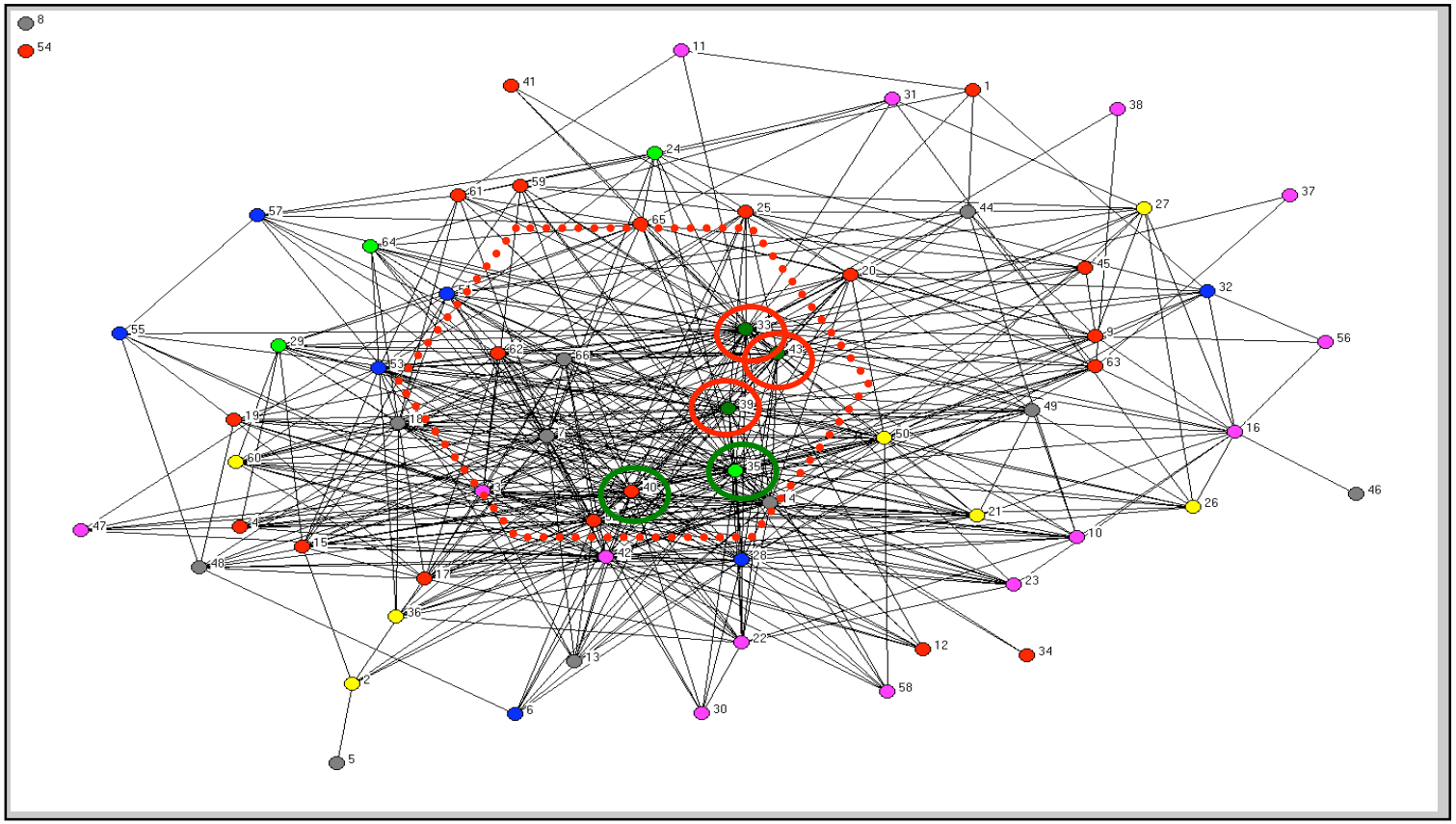
Discipline
- = Chemical Engineering
- = Hydro Engineering
- = Civil/Enviro Engineering
- = Mechanical Engineering
- = Industrial Engineering
- = Ecology
- = Eng Public Policy
- = Sustain/ Resource Mgt
- = Applied Mathematics
- = Applied Physics
- = Applied Anthropology
- = History of Science
- = Decision Science
- = Risk Analysis/Assess
- = Epidemiology
- = Env Soc Sci Policy
- = Resource Economics
- = Land Use Geography
- = Behavioral Economics

Network Measures
Density = 8%
Cohesion = 2.6
Ave. Centrality = 5

CENTER 2 CRN-T: diagram shows all "close" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram I

The three center directors are the central "hubs" of the close and collegial network (red). The two other "hubs" are both senior faculty (green). There are several concentric circles surrounding these "hubs" ordered by rank -- the closest ring around the core is mostly senior faculty and the ring around the perimeter is primarily graduate students. There are important exceptions to this pattern.



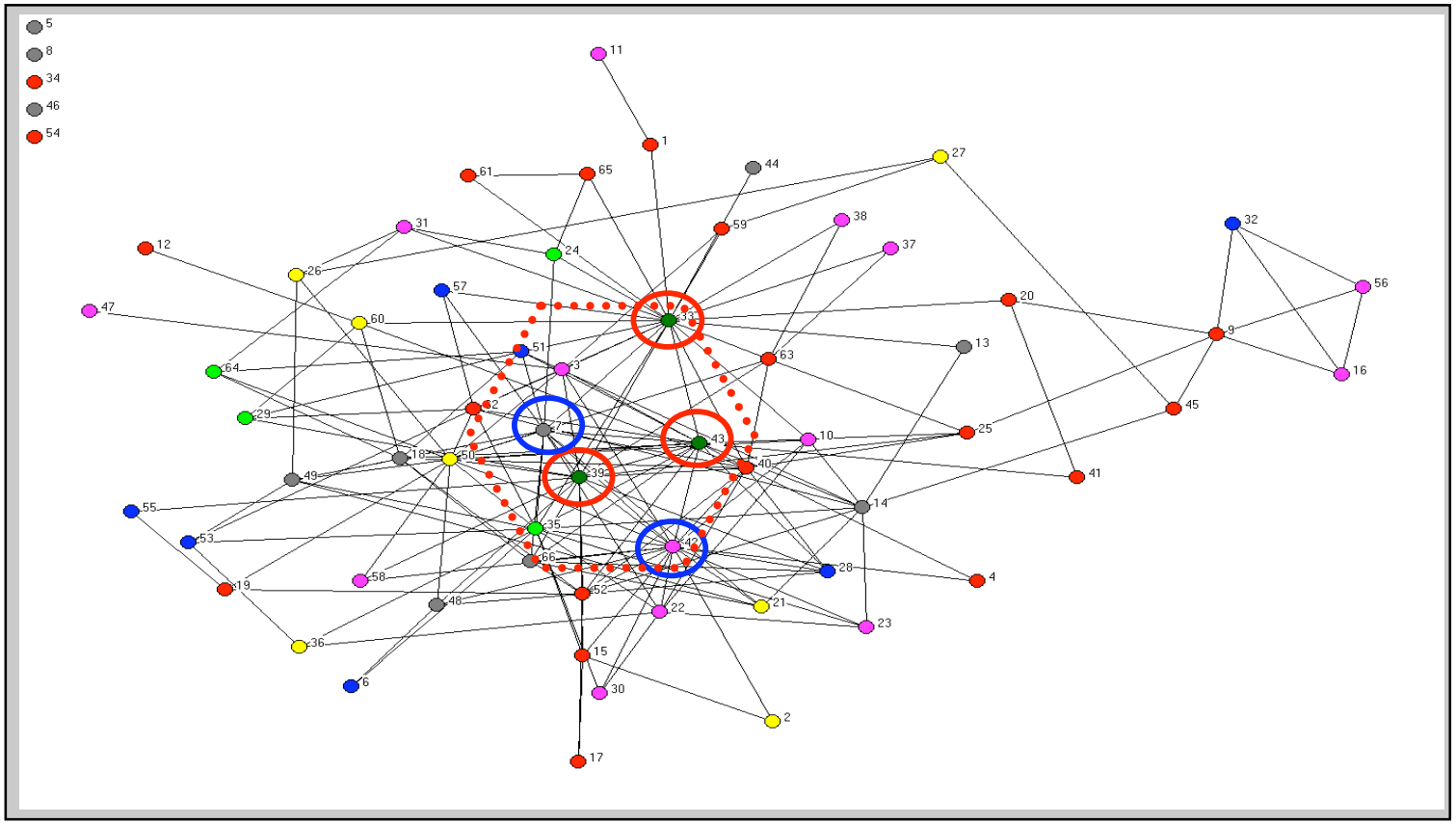
Position
- = Professor
- = Associate Professor
- = Assistant Professor
- = Post Doc
- = Graduate Researcher
- = Researcher
- = Center Director

Network Measures
Density = 23%
Cohesion = 1.9
Ave. Centrality = 15

CENTER 2 CRN-T: diagram shows all "close" and "close" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates.

Sociogram J

Unlike the close and collegial network, the primary "hubs" in the core of the close network are represented by the three center directors and two junior researchers (1 graduate student, 1 non-tenure track researcher). The core and the periphery of the network are both populated by both senior and junior faculty.



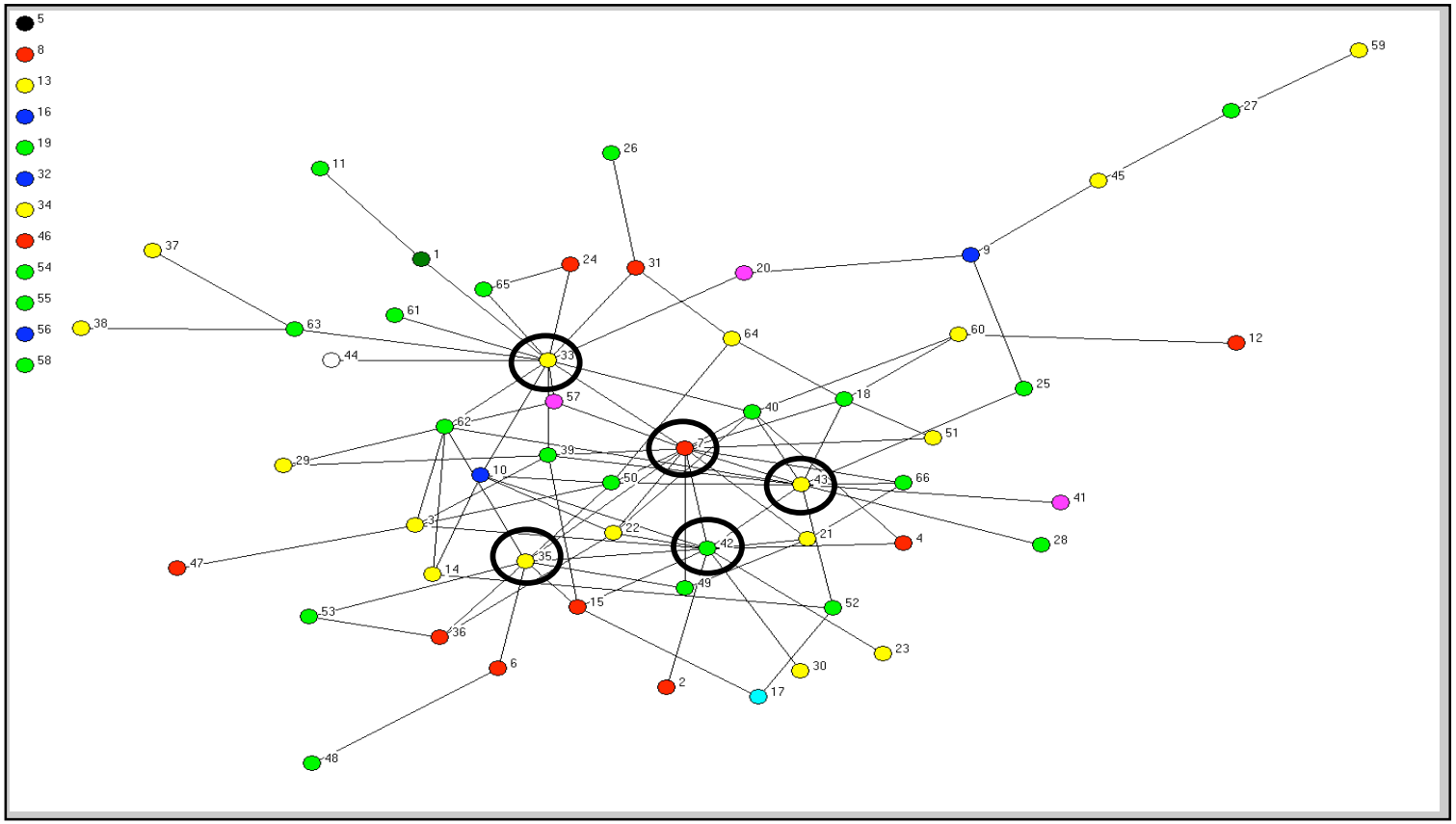
Position
= Professor
= Associate Professor
= Assistant Professor
= Post Doc
= Graduate Researcher
= Researcher
= Center Director

Network Measures
Density = 8%
Cohesion = 2.6
Ave. Centrality = 5

CENTER 2 CRN-T: diagram shows all "close" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates.

Sociogram K

On average each researcher has 3 close interdisciplinary ties. All five of the primary interdisciplinary "bridges" in the network have high rates of interdisciplinary exposure. Three come from the "hybrid" disciplines of engineering and public policy studies, one from the "hybrid" discipline of risk analysis/assessment, and the last is an engineer with a in geography and microbiology.



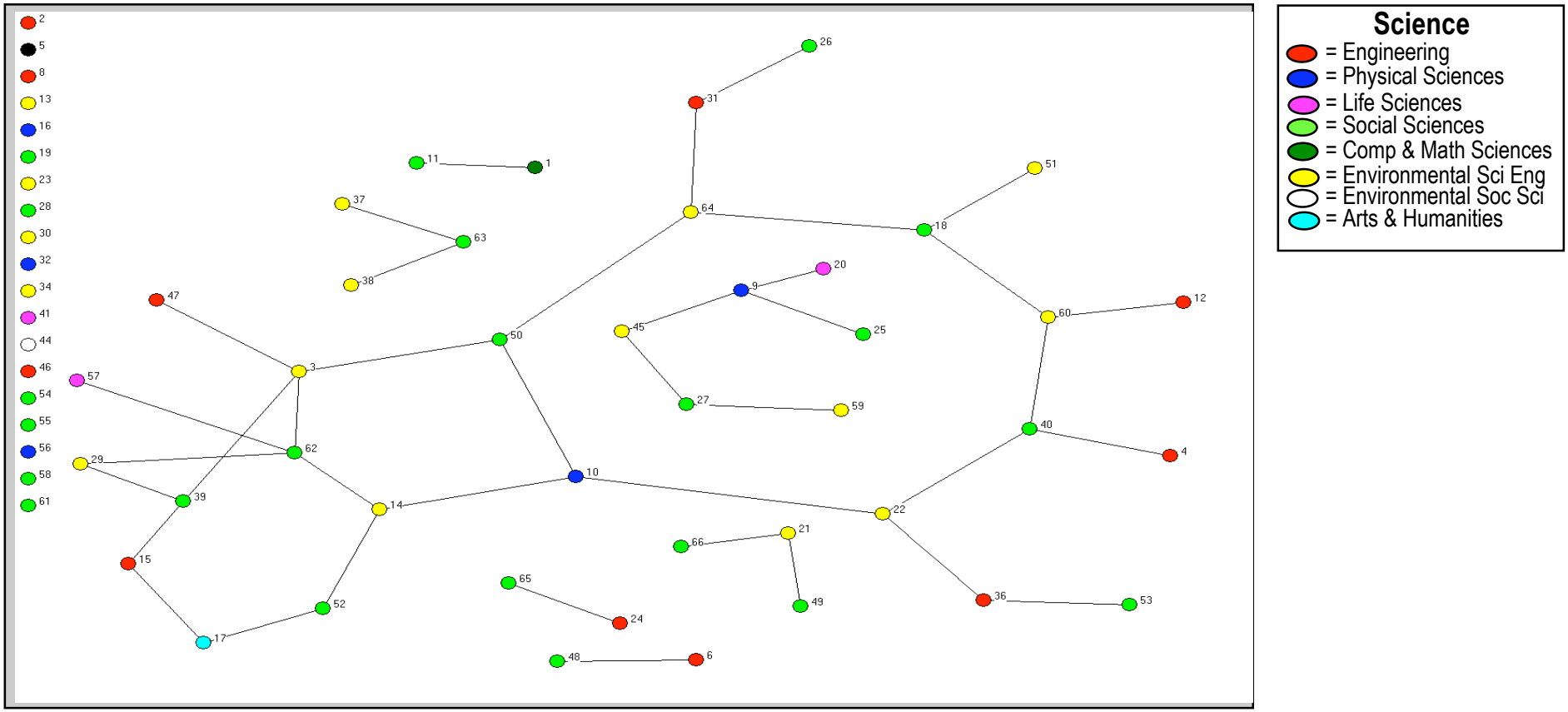
Science
= Engineering
= Physical Sciences
= Life Sciences
= Social Sciences
= Comp & Math Sciences
= Environmental Sci Eng
= Environmental Soc Sci
= Arts & Humanities

Network Measures
Density = 5%
Cohesion = 3.4
Ave. Centrality = 3

CENTER 2 CRN-I: shows "close" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram L

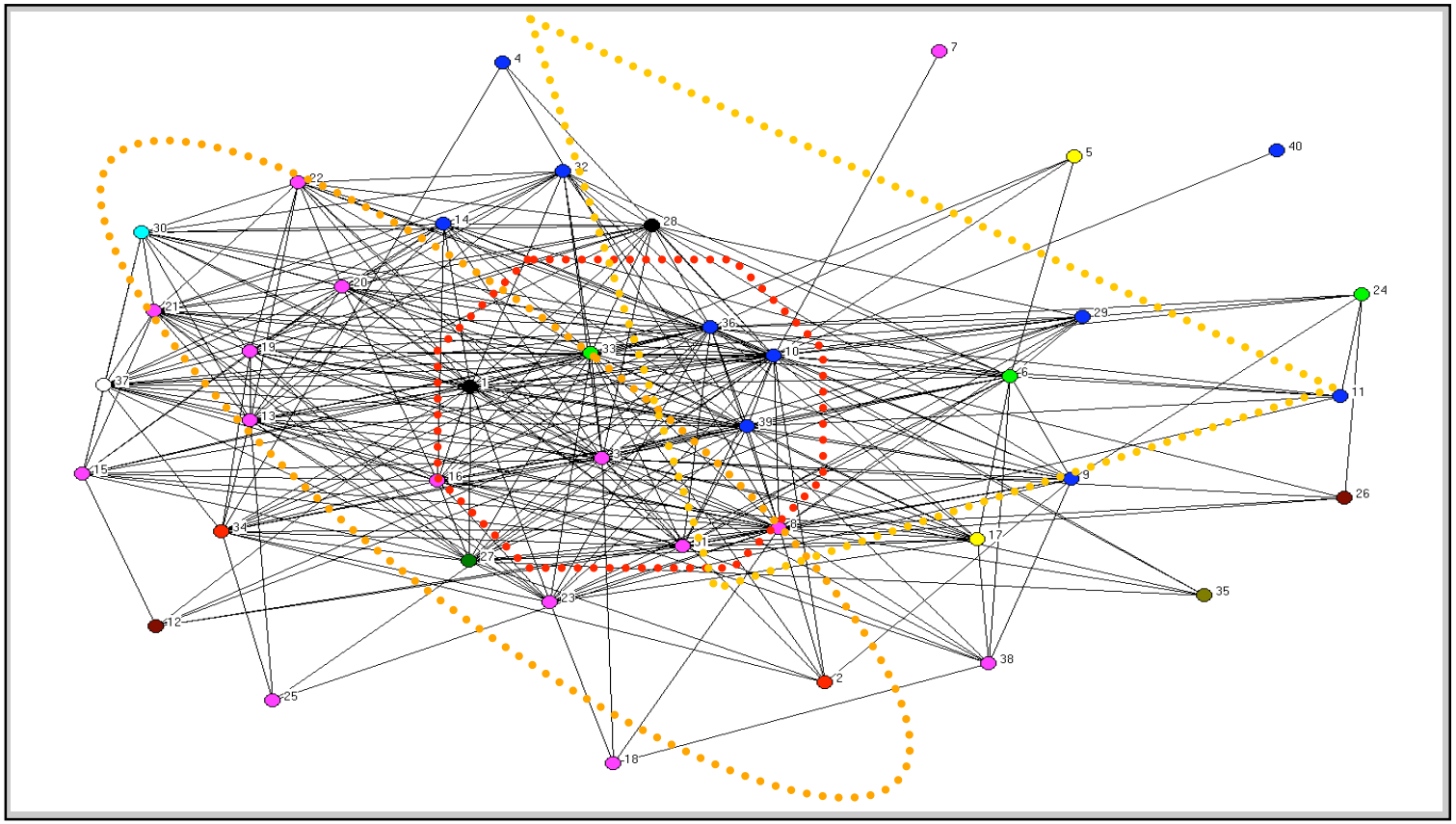
When the five interdisciplinary hubs are removed, only 71% of the researchers in the center share close interdisciplinary ties. And, 66% of those remaining have two or fewer close interdisciplinary ties.



CENTER 2 CRN-I: shows "close" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram M

Center 3 researchers on average have 15 close and collegial relations. The center is divided into two primary clusterings represented by the center's "majority" disciplines -- atmospheric chemistry and ecology (orange). The "core" of the network is also dominated by these two disciplines.



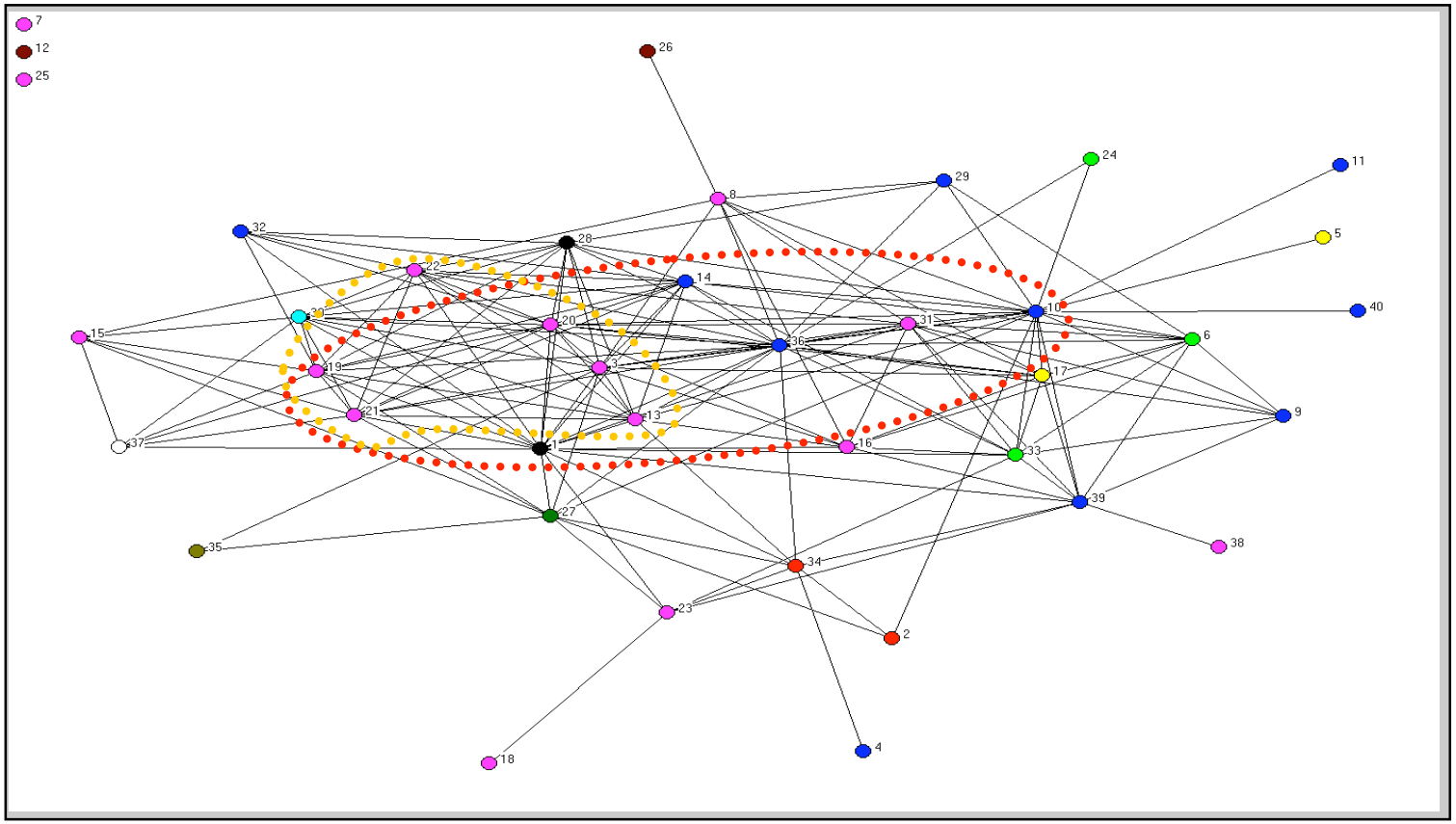
Discipline
- = Analytical Chemistry
- = Civil/Enviro Engineering
- = Atmospheric Chemistry
- = (Micro)Meteorology
- = (Bio)Geochemistry
- = Developmental Biology
- = Ecology
- = Neurobiology
- = Forestry Science
- = Limnology
- = Environmental Biology

Network Measures
Density = 39%
Cohesion = 1.6
Ave. Centrality = 15

CENTER 3 CRN-T: diagram shows all "close" and "collegial" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram N

Center 3 researchers have on average 8 close relations. There is a clear network core (red) dominated by researchers from the center's "majority" disciplines (ecology and atmospheric science). Apart from this core and the one noticeable clustering of ecologists, there are no other significant disciplinary clusters in the network. However, the right side of the network is dominated by physical and engineering sciences, while the right side of the network hosts the life scientists.



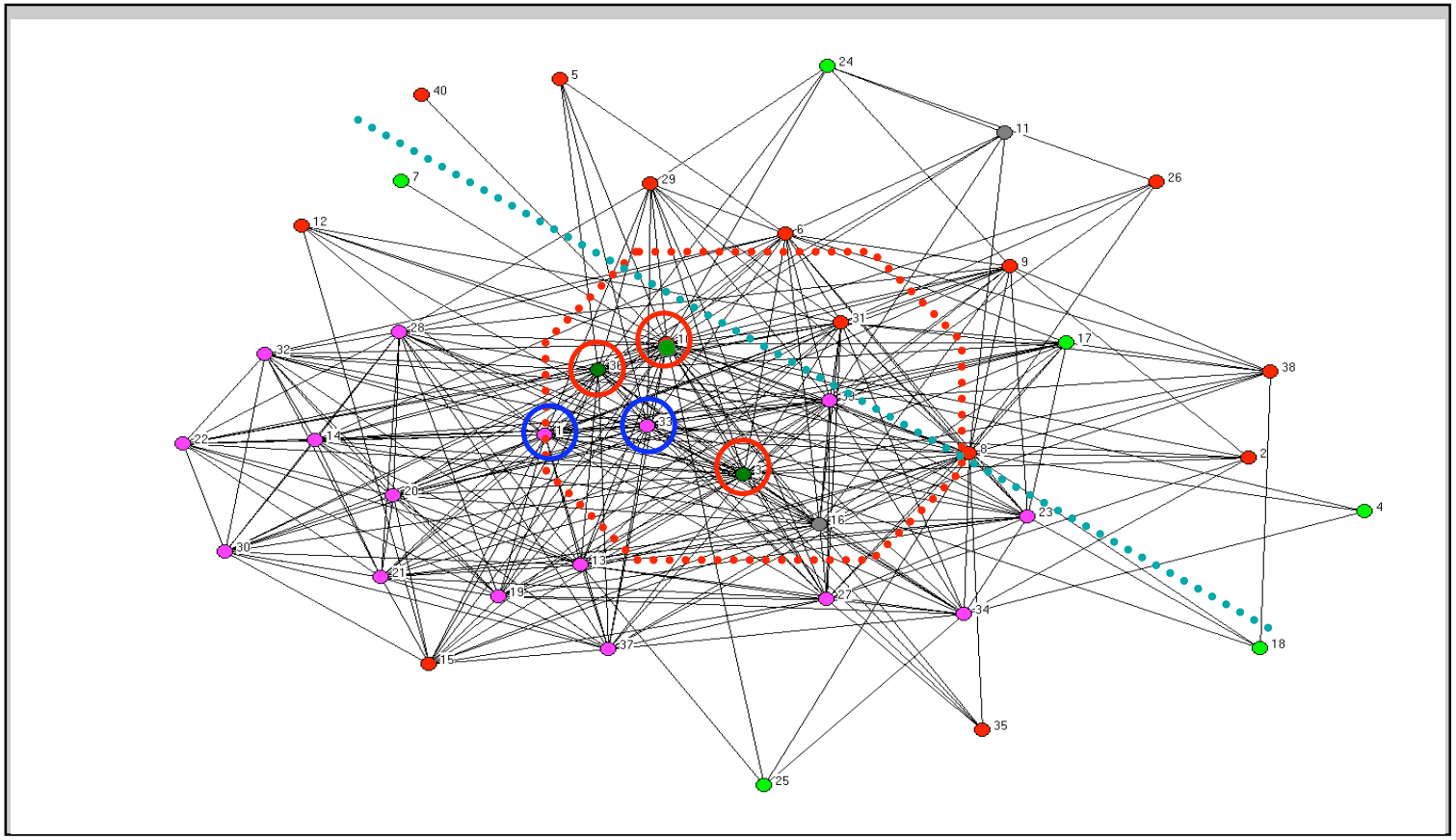
Discipline
= Analytical Chemistry
= Civil/Enviro Engineering
= Atmospheric Chemistry
= (Micro)Meteorology
= (Bio)Geochemistry
= Developmental Biology
= Ecology
= Neurobiology
= Forestry Science
= Limnology
= Environmental Biology

Network Measures
Density = 21%
Cohesion = 2.0
Ave. Centrality = 8

CENTER 3 CRN-T: diagram shows all "close" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram O

Thirteen of the 14 graduate students have as many if not more close and collegial ties than the center mean as compared to only 7 of the 16 of the professors, including the three directors.
The three center directors are the central "hubs" of the close and collegial network (red). The two other "hubs" in the core are both graduate students (blue). As a whole, the network appears generally divided by rank -- graduate students to the left and senior faculty to the right of the blue line.



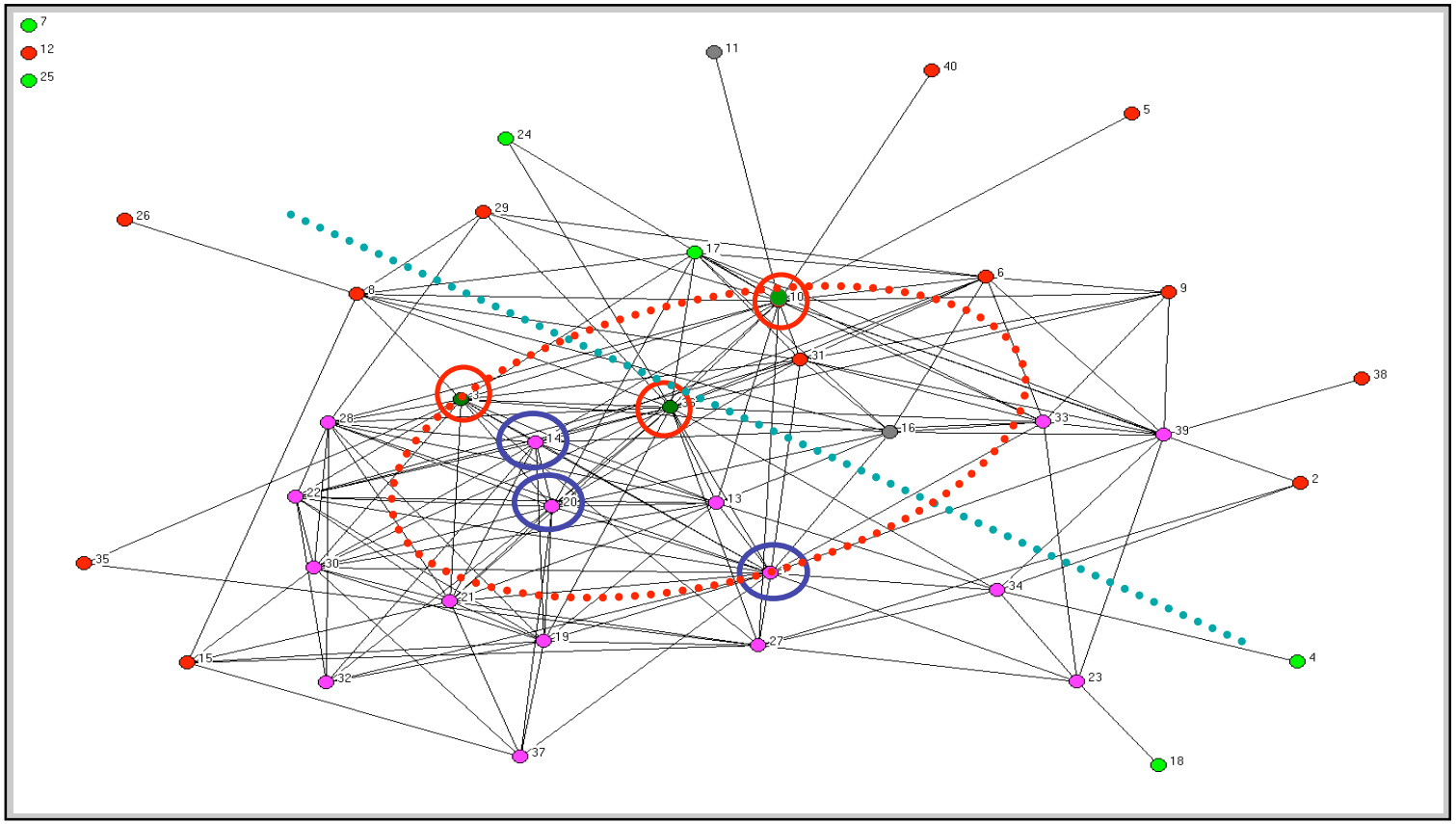
Position
= Professor
= Associate Professor
= Assistant Professor
= Post Doc
= Graduate Research Asst
= Non-Tenure Researcher
= Center Director

Network Measures
Density = 39%
Cohesion = 1.6
Ave. Centrality = 15

CENTER 3 CRN-T: diagram shows all "close" and "collegial" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram P

At the close level like the close and collegial level, professors and graduate students form two notable sub-groups. The primary "hubs" of the network core are represented by the three center directors and three graduate students.



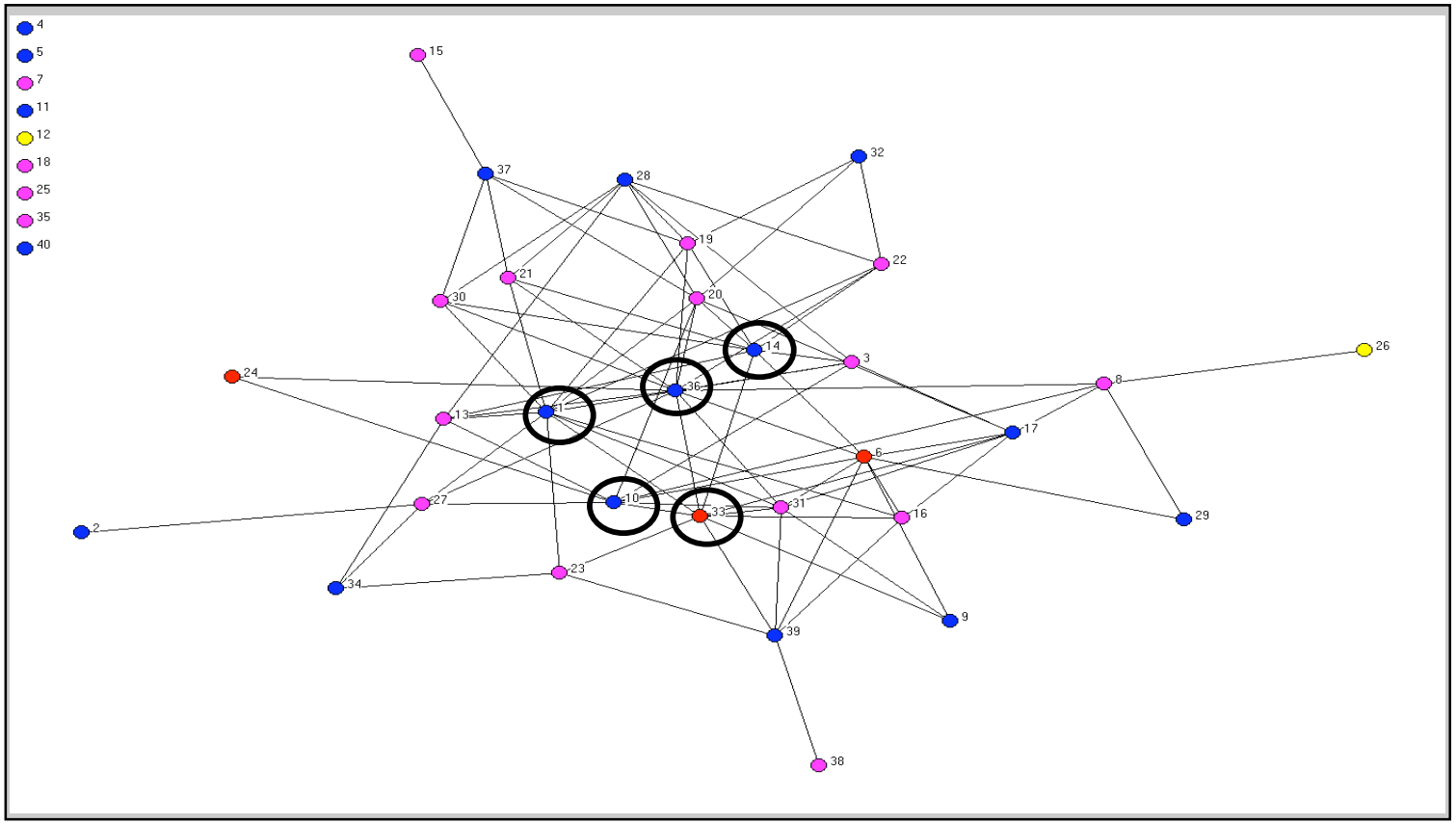
Position
- = Professor
- = Associate Professor
- = Assistant Professor
- = Post Doc
- = Graduate Research Asst
- = Non-Tenure Researcher
- = Center Director

Network Measures
Density = 21%
Cohesion = 2.0
Ave. Centrality = 8

CENTER 3 CRN-T: diagram shows all "close" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram Q

Center 3 researchers have on average 4 close interdisciplinary ties. There are five "bridges" in the network. Two are senior faculty and three are graduate students. Three have high rates of interdisciplinary exposure: one is a chemistry professor with an adjunct post in biology, one is atmospheric science professor with experience "hybrid" environmental science collaborations, and one is a chemistry graduate student with experience "hybrid" ecosystem science research projects. (Two are missing data).



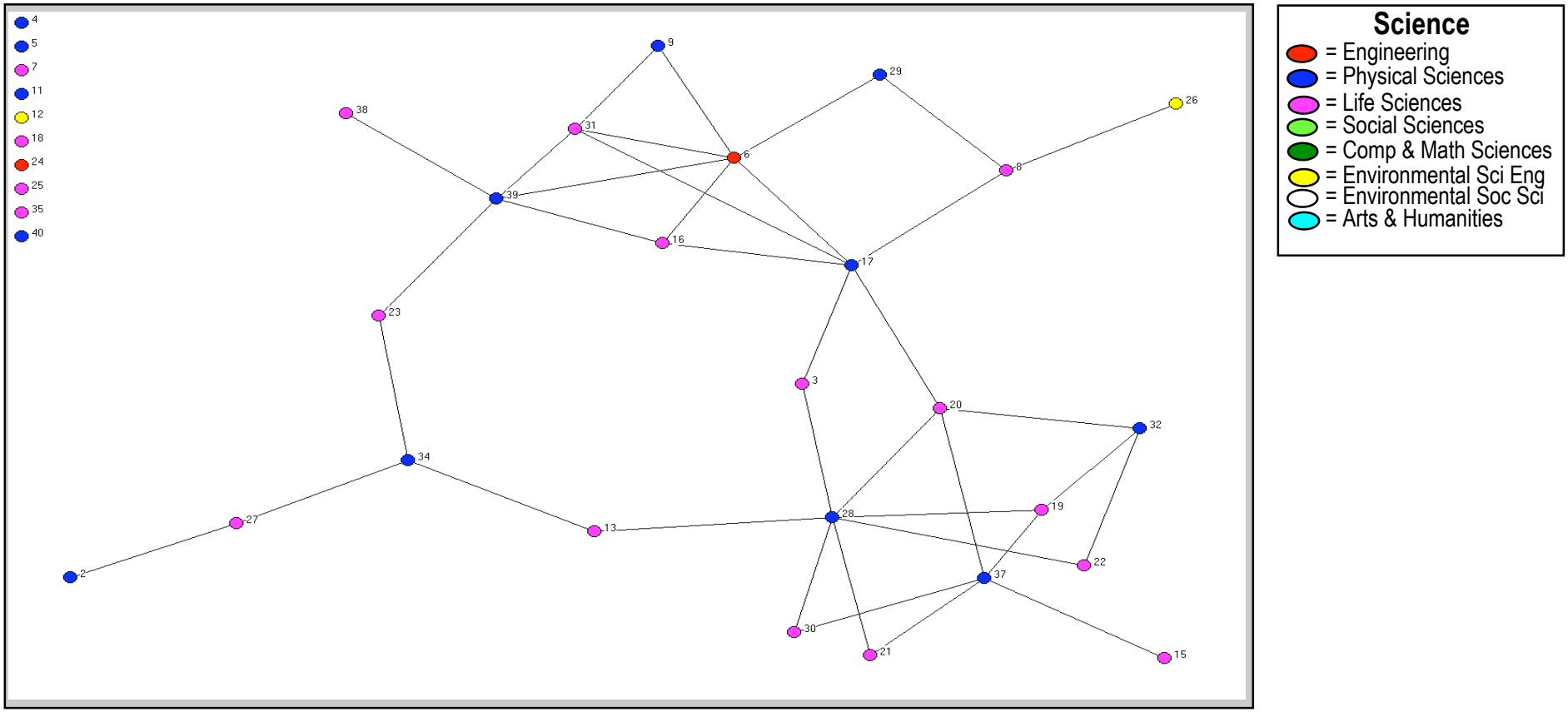
Science
= Engineering
= Physical Sciences
= Life Sciences
= Social Sciences
= Comp & Math Sciences
= Environmental Sci Eng
= Environmental Soc Sci
= Arts & Humanities

Network Measures
Density = 11%
Cohesion = 2.4
Ave. Centrality = 4

CENTER 3 CRN-I: shows "close" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram R

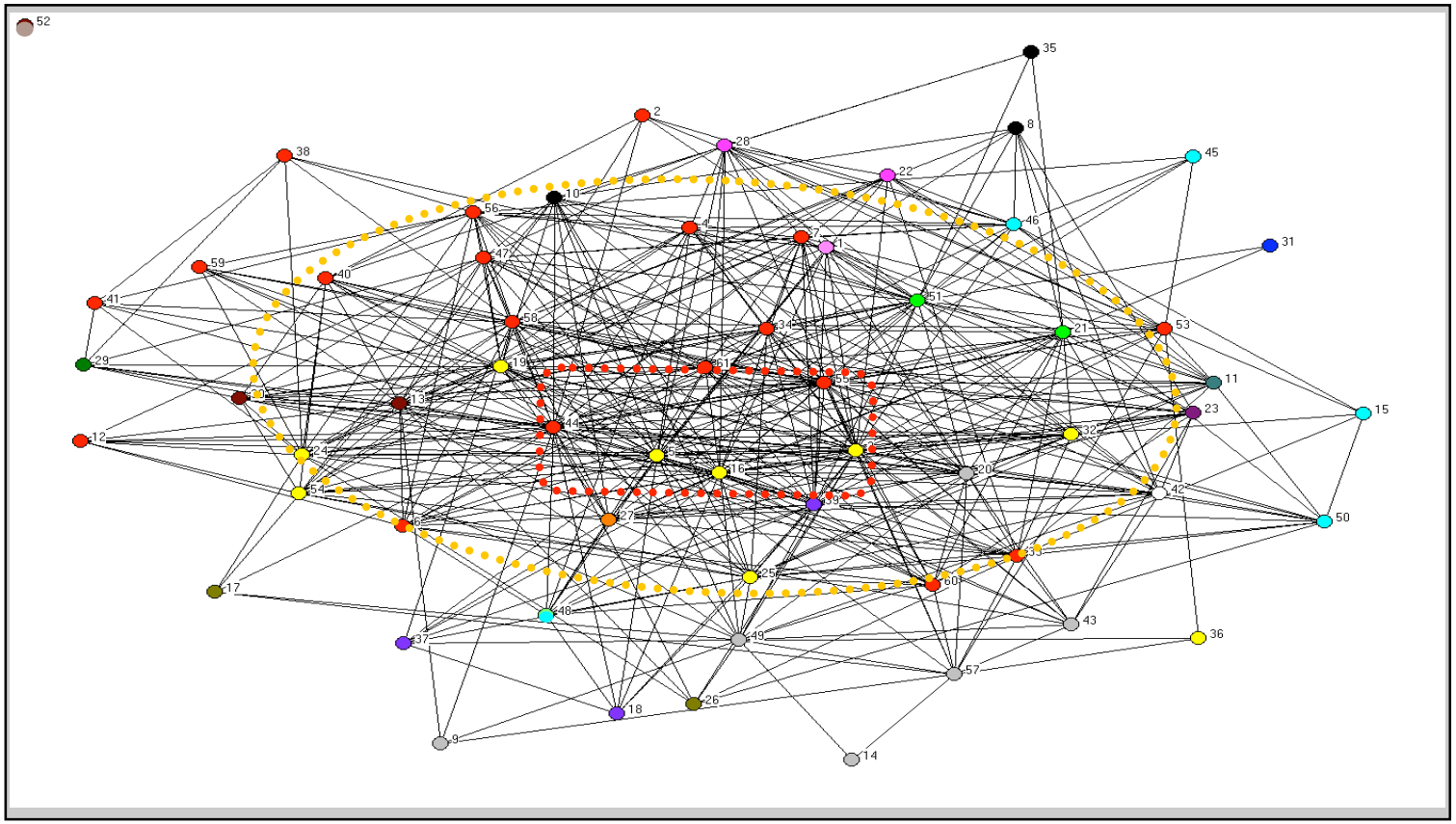
When the five interdisciplinary hubs are removed, only 75% of the researchers in the center share close interdisciplinary ties. And, 46% of those remaining have two or fewer close interdisciplinary ties.



CENTER 3 CRN-I: shows "close" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram S

Center 4 researchers on average have 15 close and collegial relationships. There is one primary cluster (orange) and a small "core" of central researchers (red). The "core" and the cluster are both dominated by the center's "majority" disciplines from engineering sciences (civil/environmental engineering and chemical engineering) with a smaller representation of other engineering and physical science disciplines.



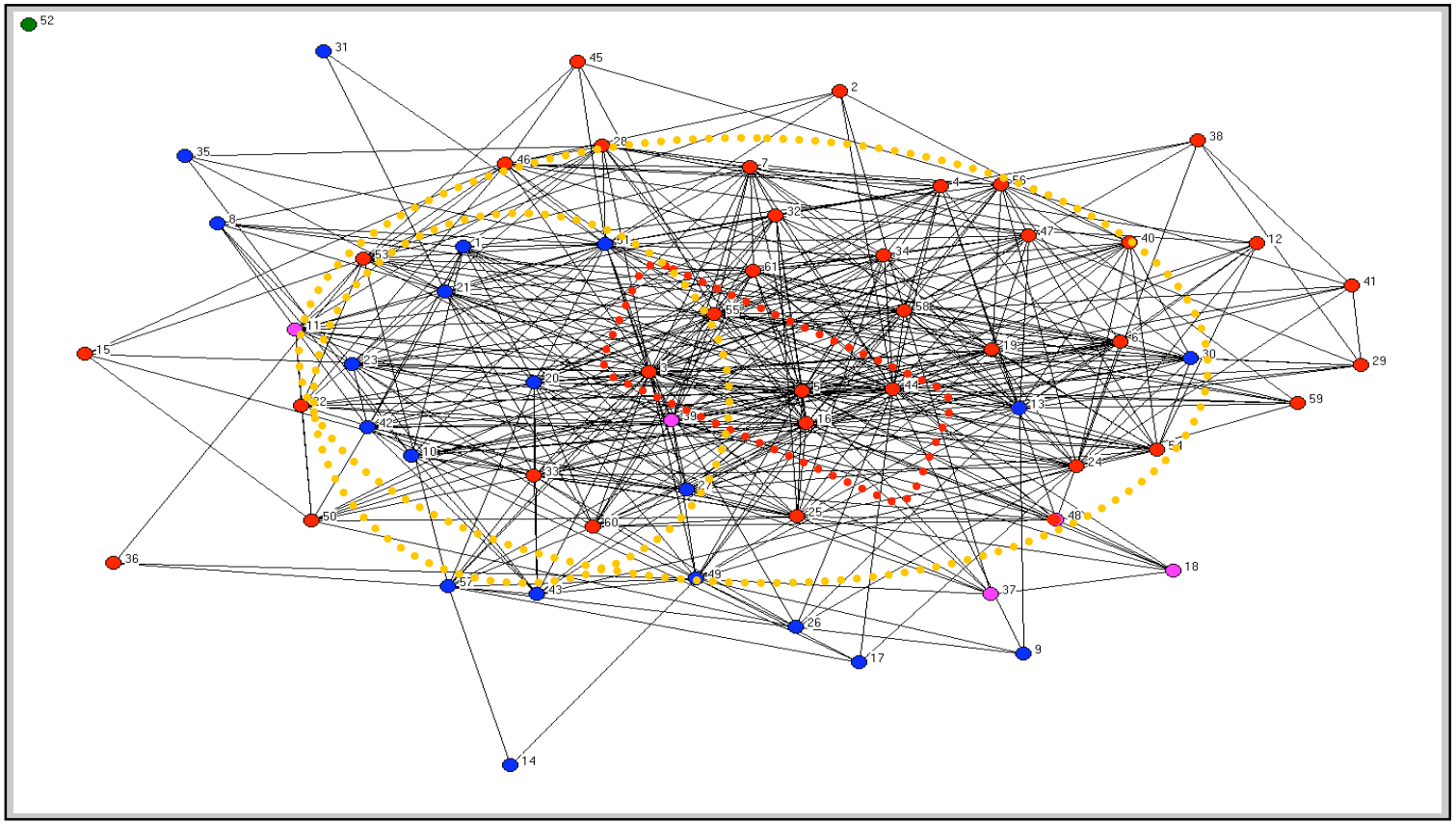
Discipline
- = Analytical Chemistry
- = General Chemistry
- = Inorganic Chemistry
- = Chemical Engineering
- = Civil/Enviro Engineering
- = Mechanical Engineering
- = Agricultural Engineering
- = Bioengineering
- = Atmospheric Chemistry
- = (Bio)Geochemistry
- = Hydrology
- = Mineralogy
- = Soil Science
- = Fisheries Science
- = Biochemistry
- = Microbiology
- = Applied Mathematics
- = Radio Chemistry

Network Measures
Density = 26%
Cohesion = 1.8
Ave. Centrality = 15

CENTER 4 CRN-T: diagram shows all "close" and "collegial" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram T

At the level of science, we can see that the cluster from Sociogram S is actually subdivided into researchers from the engineering sciences and researchers from the physical sciences. (Note: The two physical scientists in the engineering area of the network are housed in the engineering department)**.**



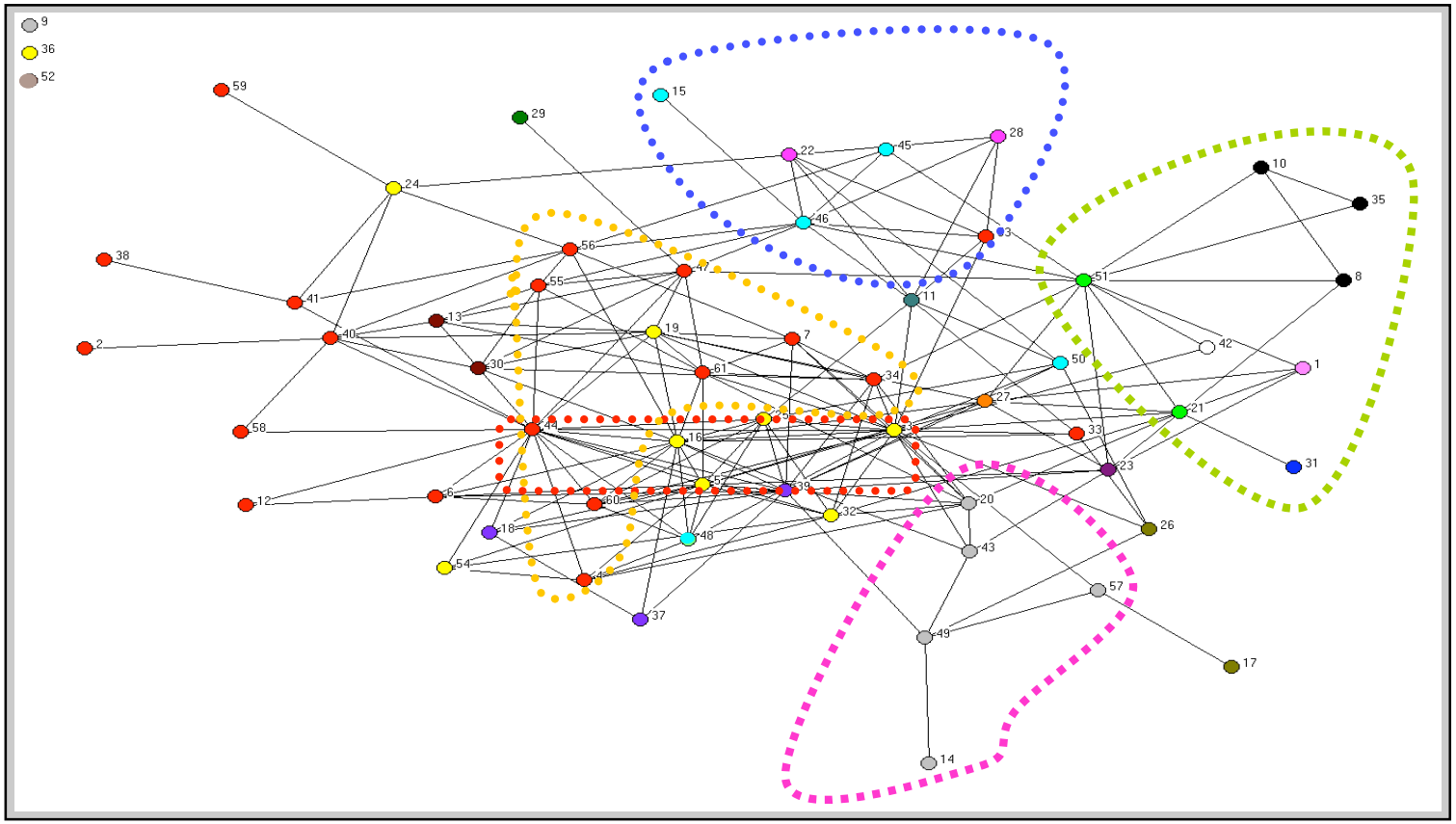
Science Field
= Engineering
= Physical Sciences
= Life Sciences
= Social Sciences
= Comp & Math Sciences
= Environmental Sci Eng
= Environmental Soc Sci
= Arts & Humanities

Network Measures
Density = 26%
Cohesion = 1.8
Ave. Centrality = 15

CENTER 4 CRN-T: diagram shows all "close" and "collegial" connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram U

Center 4 researchers have on average 6 close relations. In addition to the "core" in the center of the network, there are four clear but small clusters of researchers. The core (red) and most central cluster (orange) are each dominated by one of the center's "majority" disciplines (chemical engineering, civil engineering). The other three clusters are either single discipline (soil science - pink) or single science clusters from the physical and engineering sciences (physical - green, engineering - blue).



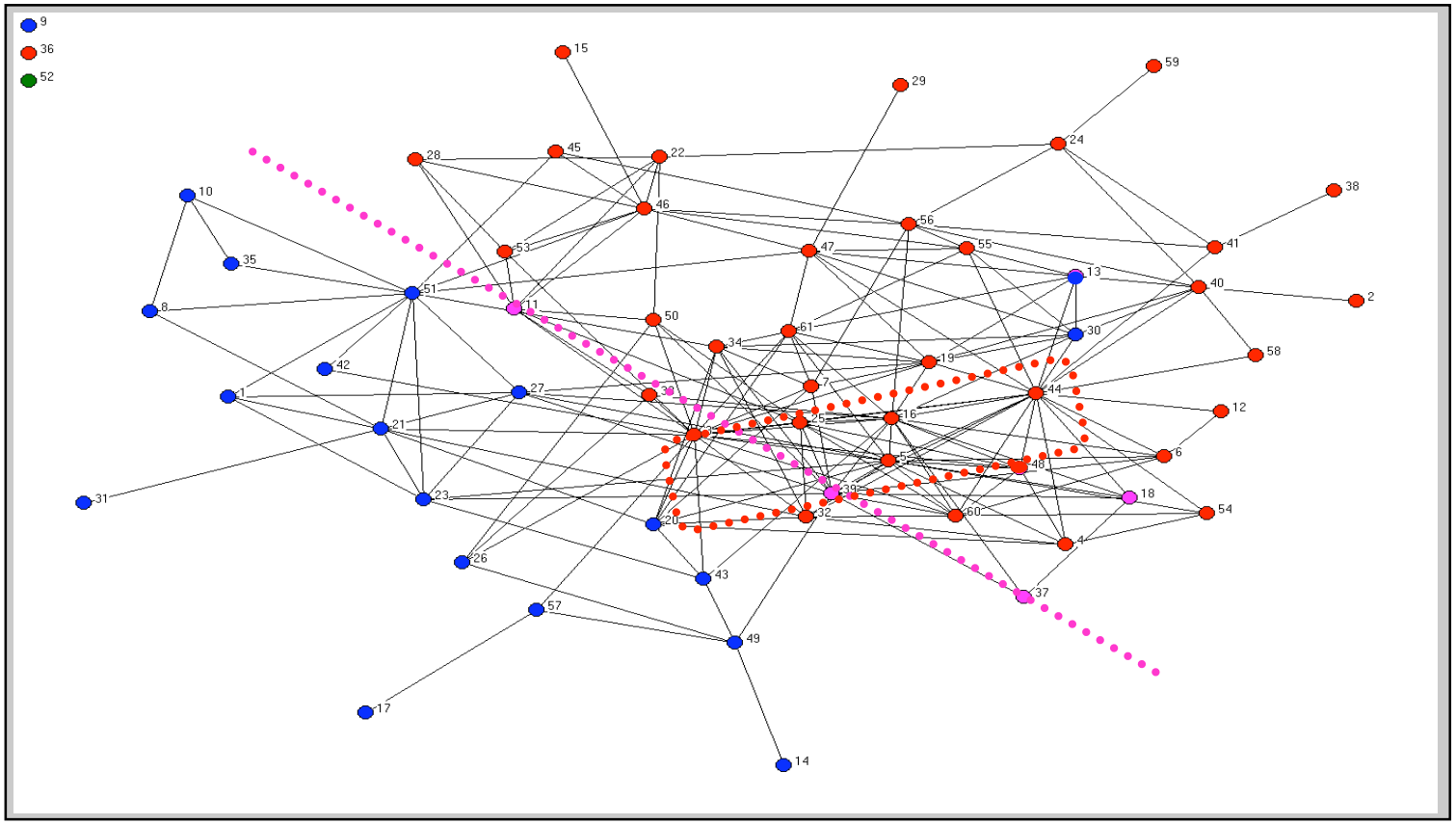
Discipline
- = Analytical Chemistry
- = General Chemistry
- = Inorganic Chemistry
- = Chemical Engineering
- = Civil/Enviro Engineering
- = Mechanical Engineering
- = Agricultural Engineering
- = Bioengineering
- = Atmospheric Chemistry
- = (Bio)Geochemistry
- = Hydrology
- = Mineralogy
- = Soil Science
- = Fisheries Science
- = Biochemistry
- = Microbiology
- = Applied Mathematics
- = Radio Chemistry

Network Measures
Density = 10%
Cohesion = 2.6
Ave. Centrality = 6

CENTER 4 CRN-T: diagram shows all "close" connections by DISCIPLINE/FIELD based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram V

At the level of science, we can see that all the clusters from Sociogram U are single science subgroups in the engineering sciences or physical sciences. In fact, there is a noticeable split in the entire network between the engineers and the physical scientists, with the life scientists as the interface between the two groups (pink line). (Note: The two physical scientists in the engineering area of the network are housed in the engineering department)**.**



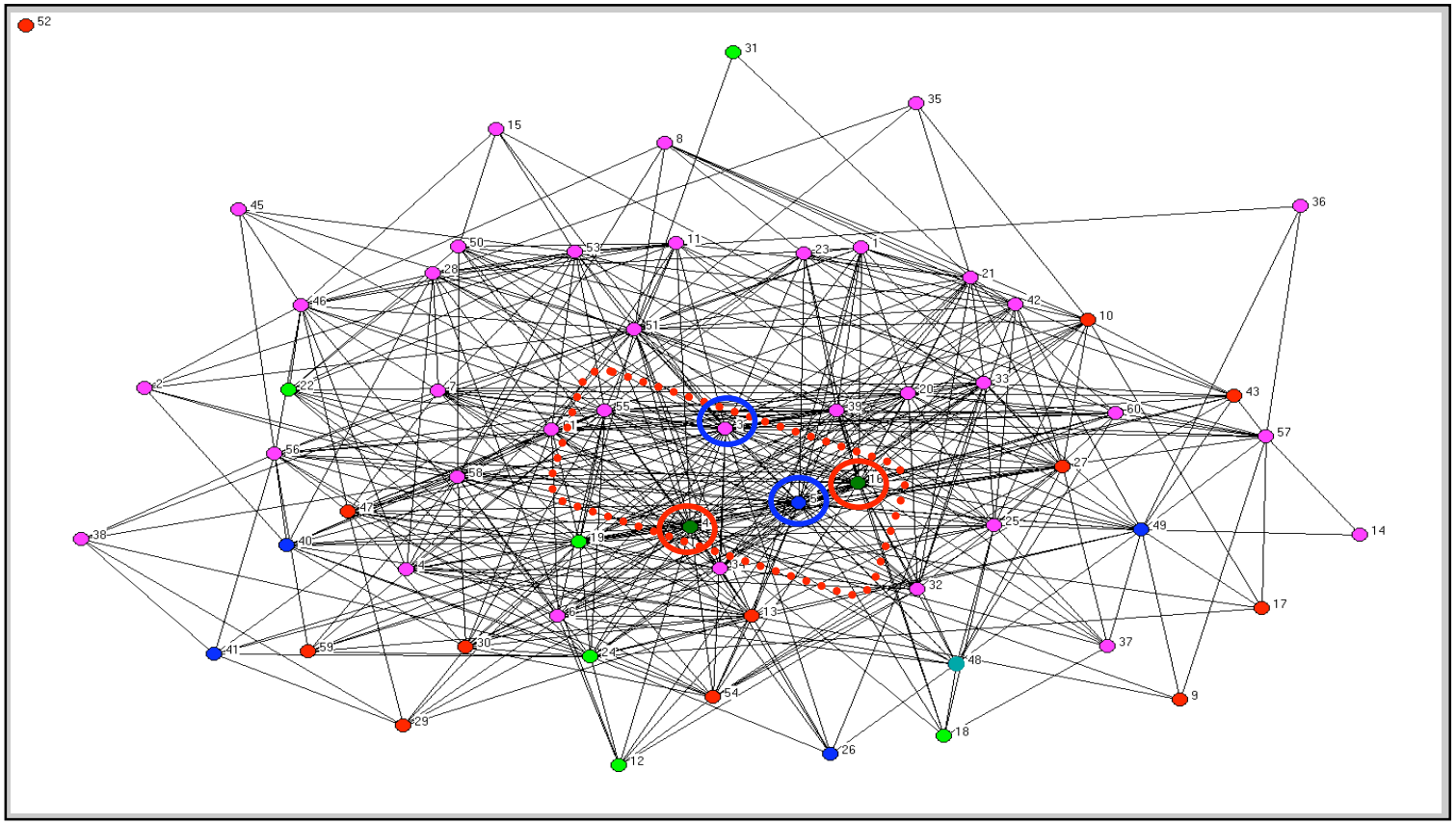
Science Field
= Engineering
= Physical Sciences
= Life Sciences
= Social Sciences
= Comp & Math Sciences
= Environmental Sci Eng
= Environmental Soc Sci
= Arts & Humanities

Network Measures
Density = 10%
Cohesion = 2.6
Ave. Centrality = 6

CENTER 4 CRN-T: diagram shows all "close" connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram W

There are four "hubs" in the close and collegial network -- two center directors (past and present), one assistant professor (original center founder), and a graduate student. Graduate researchers dominate the network of close and collegial relations both in number and centrality. Except for three identified above and a second original center founder, senior and junior faculty are on the periphery.



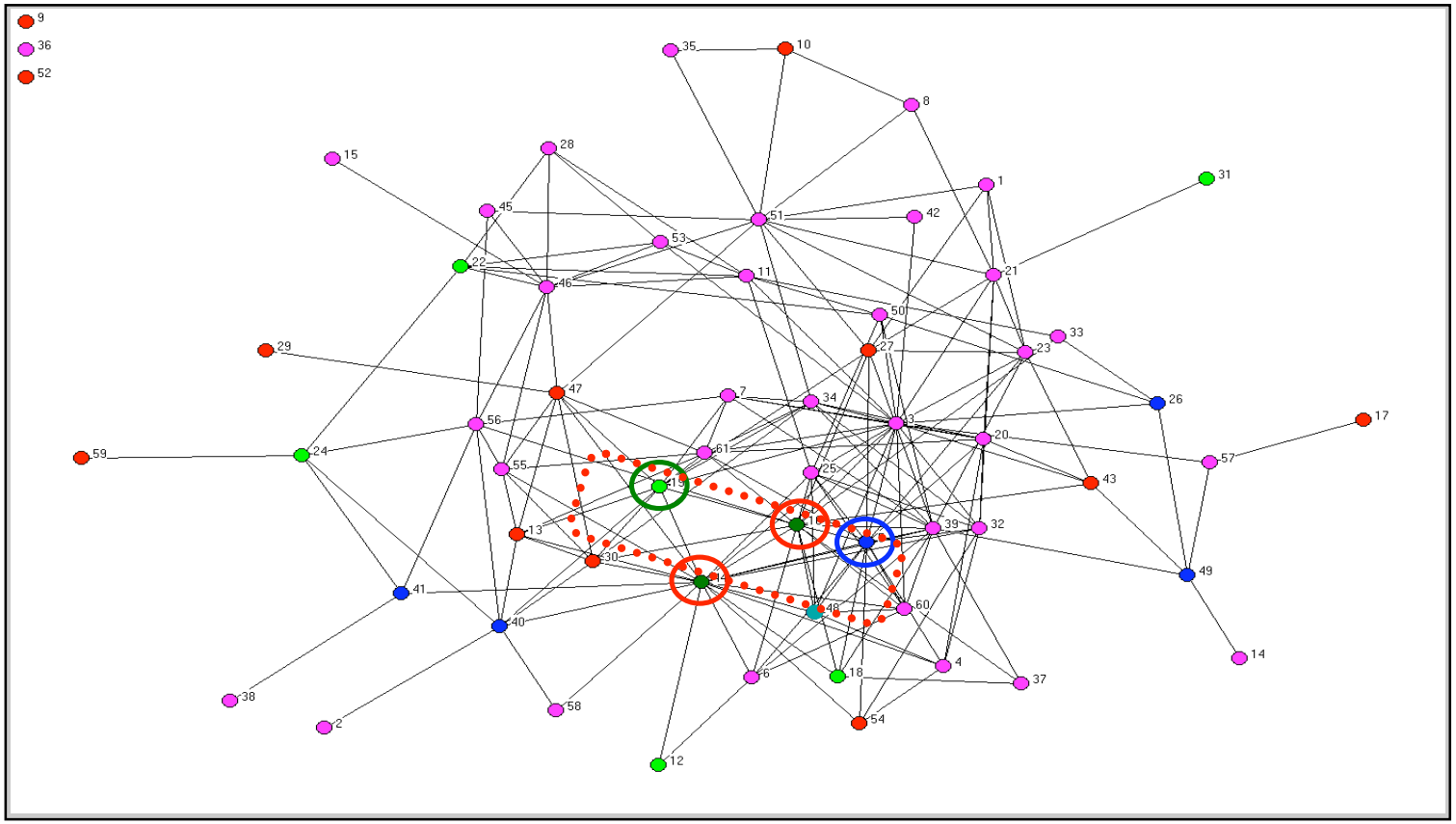
Position
- = Professor
- = Associate Professor
- = Assistant Professor
- = Post Doc
- = Graduate Researcher
- = Researcher
- = Center Director

Network Measures
Density = 26%
Cohesion = 1.8
Ave. Centrality = 15

CENTER 4 CRN-T: diagram shows all "close"and "collegial" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram X

In the close network, there are four "hubs" as in the close and collegial network. Three of the four are the same. There are the two center directors, the same assistant professor (one of center founders), and an associate professor (also one of the original center founders).



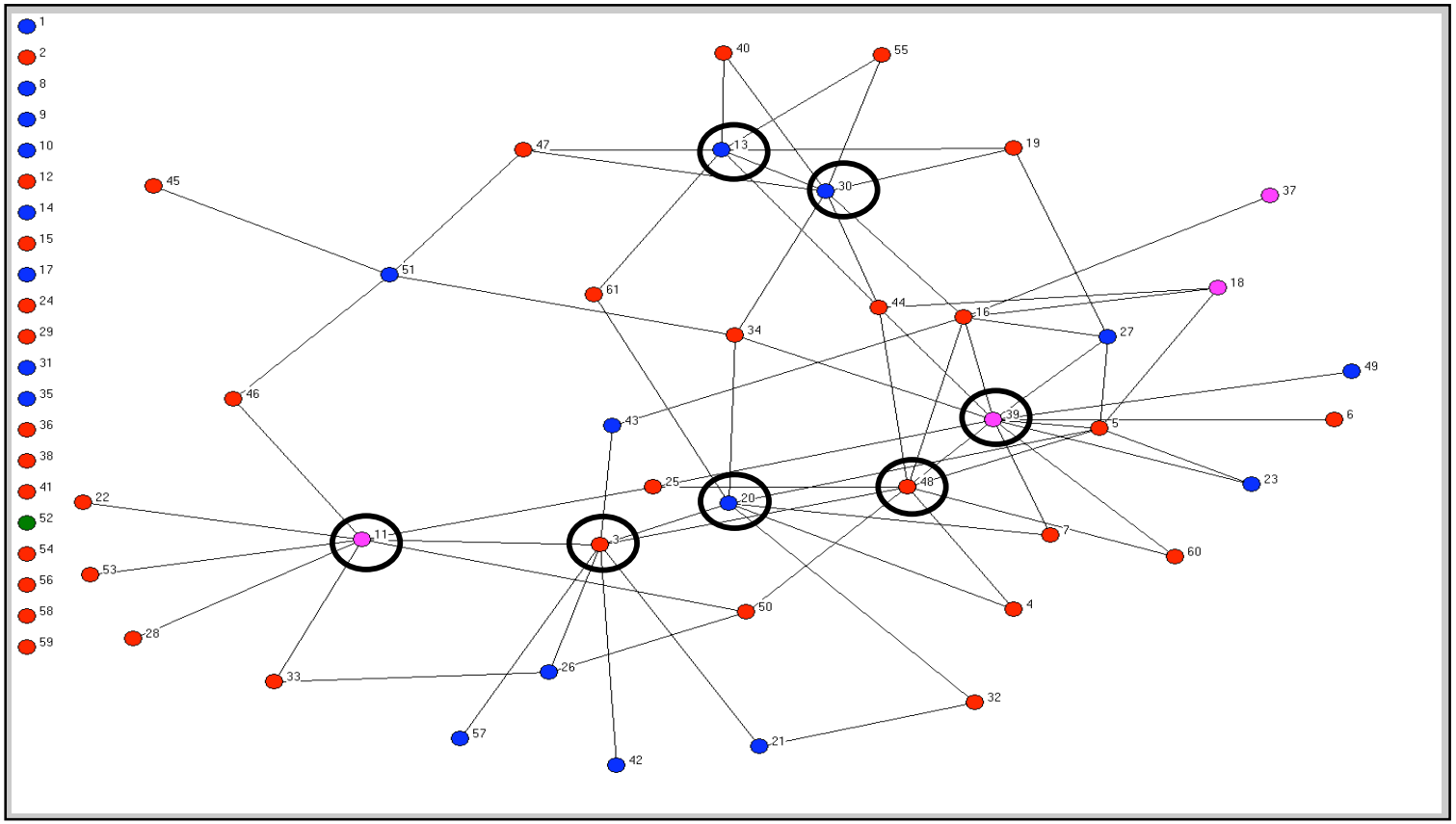
Position
= Professor
= Associate Professor
= Assistant Professor
= Post Doc
= Graduate Researcher
= Researcher
= Center Director

Network Measures
Density = 10%
Cohesion = 2.6
Ave. Centrality = 6

CENTER 4 CRN-T: diagram shows all "close"and "collegial" connections by POSITION based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram Y

Center 4 researchers have on average 2 close interdisciplinary ties. There are seven "bridges" in the network. Two are physical science professors who are housed in the engineering department. . The other five "bridges" are current or very recent graduate students who (a) have transferred from life sciences into the engineering or physical sciences or (b) are in life sciences working on projects at the interface of the physical or engineering sciences.



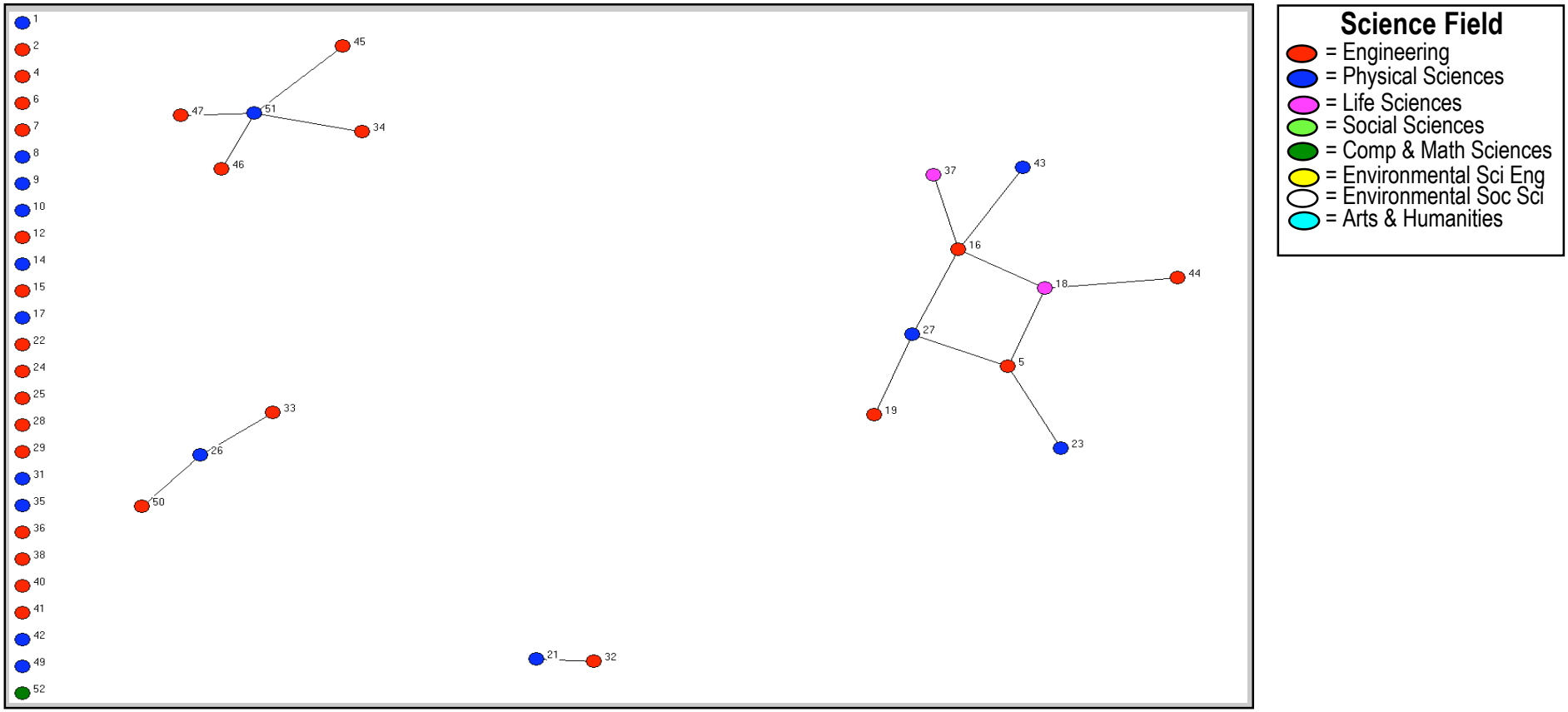
Science Field
= Engineering
= Physical Sciences
= Life Sciences
= Social Sciences
= Comp & Math Sciences
= Environmental Sci Eng
= Environmental Soc Sci
= Arts & Humanities

Network Measures
Density = 4%
Cohesion = n/a
Ave. Centrality = 2

CENTER 4 CRN-I: diagram shows all "close" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."

Sociogram Z

When the seven interdisciplinary hubs are removed, only 19 and 16 relations remain.



CENTER 4 CRN-I: diagram shows all "close" interdisciplinary connections by SCIENCE based on responses to:
"Please indicate the strength of your relationship with other center affiliates."