An Emerging View of Scientific Collaboration: Scientists' Perspectives on Collaboration and Factors that Impact Collaboration

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Collaboration is often a critical aspect of scientific research, which is dominated by complex problems, rapidly changing technology, dynamic growth of knowledge, and highly specialized areas of expertise. An individual scientist can seldom provide all of the expertise and resources necessary to address complex research problems. This paper describes collaboration among a group of scientists, and considers how their experiences are socially shaped. The scientists were members of a newly formed distributed, multi-disciplinary academic research center that was organized into four multi-disciplinary research groups. Each group had 14 to 34 members, including faculty, postdoctoral fellows and students, at four geographically dispersed universities. To investigate challenges that emerge in establishing scientific collaboration, data were collected about members' previous and current collaborative experiences, perceptions regarding collaboration, and work practices during the center's first year of operation. The data for the study includes interviews with members of the center, observations of videoconferences and meetings, and a center-wide sociometric survey. Data analysis has led to the development of a framework that identifies forms of collaboration that emerged among scientists (e.g., complementary and integrative collaboration) and associated factors, which influenced collaboration including personal compatibility, work connections, incentives, and infrastructure. These results may inform the specification of social and organizational practices, which are needed to establish collaboration in distributed, multi-disciplinary research centers.

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1. Introduction

> Natural sciences have a subjective element to them that's not purely objective, and the personalities involved. . .the way things get published and the way work gets done, there's definitely a human side to it.

This scientist, who was interviewed as part of this study, expresses the viewpoint that scientific research is not purely rational, but is influenced by social factors. This view is in line with others who have studied scientific advances. For instance, Hess (1995) supports this view in his framework, which emphasizes the social constitution of scientific discoveries, in science and technology. As this social view goes against the grain of the prevailing view of science as an objective process, it is the purpose of this research to explore the social dimension of scientific work in order to identify factors, which facilitate or impede collaboration from the point of view of scientists. This is done in the context of collaboration among a group of scientists who are engaged in scientific collaboration. Scientific collaboration may be different from other varieties of collaboration as it is shaped by social norms of practice, the structure of knowledge, and the technological infrastructure of the scientific discipline. The research, thus, considers how scientific work is shaped by social and technical factors related to the collaboration. We do this by giving voice to members of one administratively constructed "team," where collaboration was sparse, in contrast to the other three "teams," where collaboration was abundant. That is, rather than rely on previous conceptions and theory-like statements, we wanted to see what our participants would say in a semi-structured conversation about the nature of collaboration in their research life—not necessarily as part of this focal team.

You might ask why we focused on a negative case. Initially, we were intrigued with the question of why collaborative relationships developed in three situations and not the fourth. Rather than to directly confront this issue, we thought that we would learn more if we opened with a broad question concerning an example of a general collaboration. This led to the insight that collaboration was a regular part of the modus operandi of members of this focal team and that collaboration within the focal team did not develop for good reasons. That is, the members of this team collaborated with others, but infrequently with members of this administratively constructed team. We subsequently interviewed participants in other teams and found that the insights gained from the negative case carried over to the others. This research approach, which is outlined above, is becoming increasingly common in the information field. The work by Lucy Suchman (1996) to articulate collaborative work is one influential basis for this study. Thus, our theoretical lens is methodological and focuses on discovery of what collaboration is to people in the research context. This approach was taken to address the criticism of Sandstrom and Sandstrom (1995) of intensive studies, which mix insider (emic) and outsider (etic) points of view in interpreting research data.

Collaboration is often a critical component of research in the world of 'big science' (Galison & Hevly, 1992; Weinberg, 1961), which involves large-scale projects dominated by complex problems, rapidly changing technology, dynamic growth of knowledge, and highly specialized expertise. The historical trend toward specialization in science has brought a need for multidisciplinary collaboration to bring together the knowledge, skills, and abilities required for the advancement of research (Stevens & Campion, 1994). No individual scientist can possess all of the knowledge, skills or time required to make theoretical or applied contributions in more than a very narrow area of research. For example, researchers often benefit from collaborating to share resources and knowledge (e.g., Kraut, Egido, & Galegher, 1990; Finholt, 1999; Kling & McKim, 2000). Engineers work together collaboratively to develop new products (e.g., Tushman, 1978; Mintzberg, Jorgensen, Dougherty, & Westley, 1996; Sonnenwald, 1996). Students collaborate to solve problems or achieve more effective learning through cooperation (e.g., Johnson & Johnson, 1998; Slavin, 1983). Consequently, there has been an increased emphasis on collaboration as a tool of science, and the need for the development of collaboration know-how (Simonin, 1997). This research explores collaboration among a group of scientists within a newly established academic research center and discusses how their collaborative experiences socially shape their scientific work.

1.1. Definitions of Collaboration

Although many researchers have demonstrated the importance of collaboration, few researchers have paid close attention to the definition of collaboration. In many cases the term, "collaboration," is used intuitively and interchangeably with other terms such as "cooperation" and "coordination." Bruner, Kunesh & Knuth (1992) argue that the development of clear definitions and operational languages can be critical to research on collaboration. Thus, it is important to consider existing definitions or conceptions of collaboration presently used in research and practice.

Focusing on collaboration among organizations, Mattessich and Monsey (1992) define collaboration as "a mutually beneficial and well-defined relationship entered into by two or more organizations to achieve common goals" (p. 7). They characterized the collaborative relationship as a durable and pervasive one, which aims to accomplish common goals (e.g., success and rewards) through a jointly structured and shared responsibility. Kagan (1991) also defines collaboration through organizational and interorganizational structures where resources, power and authority are shared. People are brought together to achieve common goals, which could not be accomplished by a single individual or an independent organization. These two definitions are commonly used in the field of business and management, particularly in the management of joint ventures and strategic alliances among firms.

Focusing on collaboration among individuals, Schrage (1995) defines collaboration as "the process of shared creation: two or more individuals with complementary skills interacting to create a shared understanding that none had previously possessed or could have come to on their own" (p. 33). Iivonen and Sonnenwald (2000) also define collaboration as "human behavior that facilitates the sharing of meaning and completion of activities with respect to a mutually shared superordinate goal and which takes place in a particular social, or work, setting" (p. 79).

In reviewing these definitions of collaboration, two common elements emerge: working together for a common goal and sharing of knowledge. Unfortunately, working together is not a simple task, nor is the development of a common goal or vision. Sharing meaning, knowledge, resources, responsibility and/or power often involves building social capital and taking risks and trusting others, which can be difficult to do when careers, reputations or other valued assets are at stake (Lin, 2001; Dirks & Ferrin, 2001). In short, collaboration is neither easily achieved nor guaranteed to succeed even though the nature of scientific work requires working together for a common goal and sharing of knowledge.

Examining the complex interaction in collaboration, Sonnenwald introduces the concept of "contested collaboration" (1995) to characterize the communication among team members. Different patterns of work activities, expectations, personal beliefs, specialized language and individual goals make it difficult for participants to collaborate, explore, and share one another's specialized knowledge. These differences can cause team members to contest or challenge one another's contributions, although these differences may also enrich collaboration. Allen-Mearres and Pugach (1982) also identify common barriers to collaboration in educational environments. According to them, philosophical differences, educational preparation, organizational/institutional practices and small group dynamics are common impediments to successful collaboration. Cooley (1994) suggests that interdisciplinary teams experience problems related to group interaction because of a lack of organizational procedures, miscommunication, misunderstanding and inadequate commitment. Montoya-Weiss, Massey, & Song (2001) found that coordinating mechanisms helped virtual teams overcome temporal coordination problems. Synthesizing a variety of studies on collaboration, Olson and Olson (2001) discuss the additional challenges that emerge when collaborating across distances.

1.2. A Conceptual Elaboration of Collaboration

Increasingly, research centers are being established to bring together the needed expertise and resources to address important complex research problems. These centers typically span several multiple, geographically distributed institutions and include scientists, undergraduate and graduate students, postdoctoral fellows and visiting scientists, from several disciplines. Some scientists may have never met or worked together. Given the complexity of collaboration as discussed in the literature, how do scientists in such newly formed centers perceive collaboration and what factors facilitate and/or impede their collaboration?

We investigated these questions in the context of such a scientific research center with the aim of developing empirically-based conceptualizations of the nature of collaboration in such a complex, geographically dispersed research center. Using intensive research methods including interviews, observations, and surveys, we identified several connected themes, through our analysis of the data, relating to the social influences of collaboration on scientific work. We present these themes in the following (i.e., collaboration as a rite of passage, collaboration as a continuum of connections, collaboration as influenced by a variety of factors, and barriers to collaboration) and use them to propose a framework, which expresses the voices of the study participants, for considering scientific collaboration. The framework includes a typology of collaboration (e.g., complementary and integrative collaboration), and factors such as personal compatibility, work connections, external and internal incentives and infrastructure, which impact each type of collaboration in this environment. The framework helps to clarify the forms that scientific collaboration may take and the social or human dimensions of collaboration.

2. Research Approach

We are conducting an ongoing study of collaboration in a multi-disciplinary, geographically distributed research center that spans four universities. We are employing an intensive research approach, studying in detail a small number of cases.[1] We use mixed methods (Tashakkori & Teddlie, 1998) to obtain qualitative and quantitative data, which helps us to understand the nature of collaboration in the research setting in a deep and detailed way.

2.1. Research Setting

This study took place in a research center primarily funded by the federal government with matching funds from participating universities, industry and a philanthropic organization. The center connects chemistry and chemical engineering researchers[2] at four universities; three are located within an hour's driving distance in the same state, and one is located in a state in a different time zone. Three of the universities are Carnegie Research I universities, and one is a Master's I university, which emphasizes teaching. There are approximately 100 center members; approximately one-third of the members are faculty and the rest are undergraduate students, graduate students, postdoctoral fellows and research associates. Each center participant was assigned to at least one of four research groups. Most faculty members had one group affiliation, although several had two or more.[3] The students and postdoctoral researchers were assigned to two research groups, a primary and a secondary. These research groups were formed to bring together researchers with related interests so that participants would become aware of possible connections across research projects through various structures including videoconferences and principle investigator meetings.

During the period of this study when interviews were conducted, the center had been in operation for approximately 9 months and was organized into four research areas. When the survey data were collected, the center had been in operation for approximately 7 months.

2.2. Communication and Collaboration Mechanisms in the Center

In addition to e-mail, phone conversations and other interactions initiated by individual center members, the center holds weekly group videoconference meetings to promote awareness and interaction among the center participants. During the videoconferences center-wide issues are presented and discussed, and students and postdoctoral researchers present their research. Usually research presentations were from students and postdoctoral researchers in the same group. All center members were encouraged to attend these videoconferences. Students and postdoctoral researchers were "required" to attend those videoconferences where members of their primary and secondary groups were presenting; however, this requirement was not strictly en-

[1] As contrasted with extensive studies that aim to make generalizations based on surveys of a large sample from a population, an intensive study focuses on small number of respondents in order to discover empirically extant patterns of behavior. Thus, it is not the intent of an intensive study to generalize. Rather, the intent is to describe, define, identify, etc. patterns of behavior that might lead to theory, concept, or framework development. *MIS Quarterly* has run a series of articles beginning in September 2000, which are representative of those utilizing intensive methods.

[2] The center also includes a small number of members who primarily focus on science education outreach to children in kindergarten through 12^{th} grade, and social scientists who study innovation and collaboration. These efforts are outside the scope of this paper.

[3] Five faculty members were assigned to two research areas, and the director of the center was assigned to three areas.

forced. Local group meetings were also held. These were largely organized by individual faculty members and included faculty, students and postdoctoral researchers working on closely related topics. Occasionally, telephone or videoconference meetings that included only faculty in a specific group were held. At these meetings, faculty discussed their research plans and common interests. Weekly management team meetings were also held. These meetings included the director, co-director, executive director, administrative assistant, accounts specialist, information technologist, coordinators from each university, a natural science research coordinator and two social scientists whose areas of expertise are innovation and collaboration.

The center also developed web pages that provide information about center members and their activities, as well as the center's goals, objectives and organizational structure. The web pages also provide links to related research and activities. E-mail lists were created so that center members could more easily send e-mail to everyone in the center, everyone in a specific group, or everyone at a specific location.

The directors of the center enthusiastically encouraged collaboration among center members. For example, collaboration is included in the center's mission statement, faculty members are required to report their collaborative research endeavors annually, periodic meetings are held to identify potential collaboration among faculty, and funding mechanisms were instituted within the center to allow faculty to jointly fund and supervise students and postdoctoral researchers working on collaborative projects.

2.3. Data Collection

We used two primary data collection techniques: sociometric surveys and interviews, but also collected data through, for instance, observation of videoconferences and meetings. A sociometric survey was conducted during the seventh month of the center's operation. The survey asked participants to identify who they interacted with, what they interacted about, how they communicated (via email, phone, face-to-face, video conferencing), and how long they had been interacting. 60.6% of the center members (54/89) at the time completed this survey.

Semi-structured interviews were conducted with members of the center. Questions regarding their background, daily work and collaborative research within the research center were asked (see Appendix A for the interview guide). As noted earlier, the interviews did not follow the interview guide in a structured way. Rather, we wanted the interview to feel like an informal conversation about collaboration and its characteristics. We began the interviews with a relatively broad question, which encouraged the participants to tell us their stories. We filled in the gaps in our interview schedule with follow-up questions. Thus, we developed the interview guide not to reflect a particular theoretical framework, but based the questions on the data, which we had already collected and the questions that this data raised for us. We

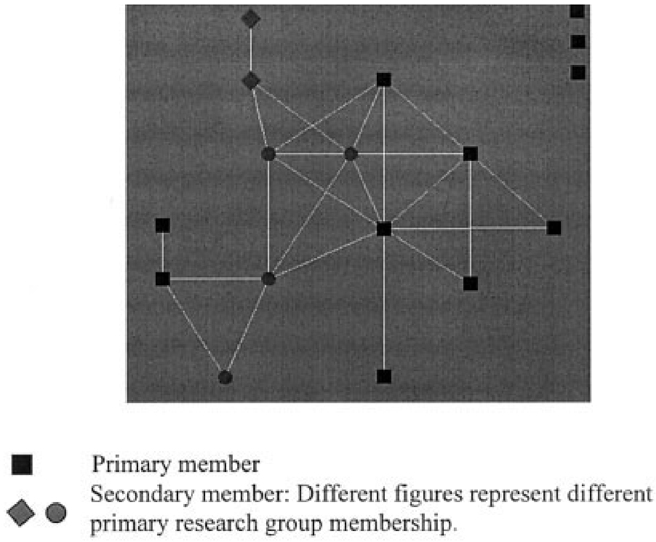

FIG. 1. Links among members of the research group that was interviewed.

recommend this approach of starting off an interview of discovery with a broad question as this approach led to insights, which we would not have otherwise gained.

These interviews lasted from 45 to 75 minutes. The interviews were usually conducted at the informants' offices. All the interviews, with one exception,[4] were tape-recorded and later transcribed. Notes were also taken during each interview to provide some backup in the case of recorder failure and to record the issues that emerged during the interview.

2.4. Study Participants

All center members were asked to respond to the sociometric survey, and all members of one research group were asked to participate in interviews. This group was selected because approximately ten months after the center was established, this group had not developed the synergy that was present in the other research groups. That is, the sociometric survey and resulting sociogram showed that members of this group did not report direct collaborations with other people within their group, though there were some interactions with people outside their group. Figure 1 presents a social network of the people who were affiliated with this research group. This network is very different from those present in the other 3 groups (see Figure 2 for an example of another group). For example, the ties among the group members in Figure 1 are not as strong as in Figure 2. Rather, the group members shown in Figure 1 are often

[4] One study participant did not wish to have the interview recorded. Respecting this preference, notes were taken while the informant was answering questions and the notes were shared with the informant to make sure that there was no misunderstanding. These notes were extensive in nature and closely reflected the comments of the interviewee.

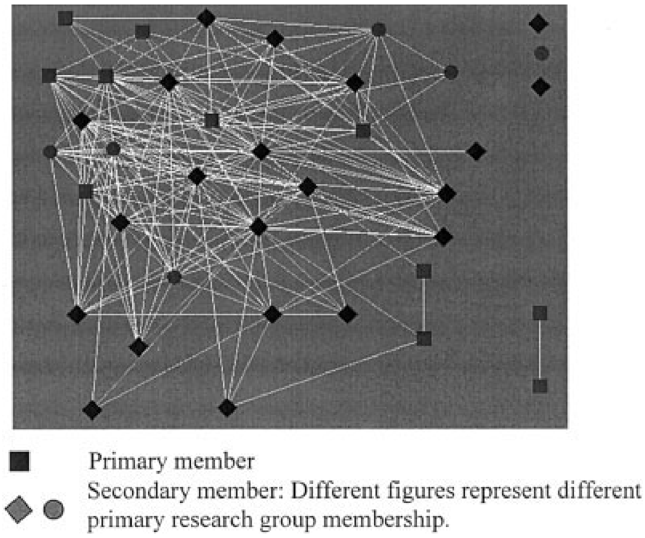

FIG. 2. Links among members of another research group.

connected through secondary group members.[5] Therefore, we decided to focus on this particular group as a starting point in order to understand what was different about this research group in relation to the others.

The research group under study consisted of 14 members (see Table 1). All but one group member participated in an interview. Among the participants, eight were faculty members with 17 to 38 years of experience; one was a research associate with 6 years of experience; one was a post doctoral researcher with less than a year of experience; and three were graduate students in their first to second year of graduate school at the time of interviews. Eleven were males and three were females. There were three Asians, one African American, nine Caucasians, and one Hispanic.

This focus on a negative case may seem inappropriate. For us it was a natural starting point as we were initially interested in understanding why collaboration was not taking place in this "team." Our approach of not directly focusing on why collaboration was not taking place and instead asking for an example of a successful collaboration led us to understand how and why these people collaborated as well as why collaboration was not evident in the focal team. We subsequently checked our findings through interviews with members of other teams as well as other techniques for establishing the trustworthiness of our data (e.g., member checks) (Guba & Lincoln, 1985). Consequently, our findings are robust for the situation under study.

2.5. Data Analysis

Social network analysis (Wasserman & Faust, 1994) was performed on the sociometric survey data. Links indicated for center members were captured and input into UCINET IV for analysis including measures of centrality, reciprocity, connectivity, and into Krackplot, Version 3.01, for further graphical analysis.

Analysis of the interview data was an iterative process. Interview transcripts and notes were read. Comments relating to collaboration or the context of collaboration were marked and categories were developed to identify different types of collaboration, as well as factors present in the data that seemed to facilitate or impede collaboration. Occurrences of particular categories and their interaction with other categories were viewed across the various data

[5] Our purpose in providing these hints at the sociometric data and analysis is to show the wide disparity between interactions within the research groups. It is beyond the scope of this paper to go into this further as this fascinating subject must wait for collection of additional sociometric data and a paper sometime in the future.

TABLE 1. Demographics of study participants who were interviewed.[1]

Study participant	University	Status	Years of professional experience or graduate education	Gender	Ethnicity
Kent	Research I (University A)	Professor	19	M	C
Harris	Master's I University	Professor	18	M	A
Smith	Research I (University A)	Professor	33	M	C
Davis	Research I (University A)	Professor	31	M	C
Murphy	Research I (University B)	Professor	21	M	C
Peterson	Research I (University B)	Professor	17	M	C
Adams[2]	Research I (University C)	Professor	28	F	C
Edwards	Research I (University C)	Professor	38	M	C
Nelson	Research I (University B)	Professor/Director	10	M	C
Brown	Research I (University B)	Postdoc	>1	M	C
Turner	Research I (University C)	Research associate	6	F	H
Fisher	Master's I University	Graduate student	1	M	A
Clark	Research I (University A)	Graduate student	1	M	B
White	Research I (University C)	Graduate student	>1	F	A

Note: M—male, F—female, A—Asian, B—Black/African American, C—Caucasian, H—Hispanic
[1] The names given in Table 1 are pseudonyms. The study received human subjects approval.
[2] Adams preferred not to be recorded; the extensive notes taken during the interview were used in the analysis.

sources (Silverman, 1994). We also had available to us interviews with members of the other 3 groups, which focused on collaboration as well as other issues (e.g., the nature of scientific work). We used these to test the applicability of our findings beyond the group where collaboration was sparse to those where it was prevalent.

We came together to discuss our individual interpretations of the data as instantiated by our categorizations and visual representations (Coffey & Atkinson, 1996) at weekly meetings. As a result of these discussions, each researcher further analyzed the data to identify and clarify the emerging themes and refine the framework that synthesizes the themes found in the data. Thus, different types of collaboration and the factors influencing collaboration in this emerging collaboratory were mapped to create a visual representation of the findings. We went through several iterations of the mapping of the data. The themes and framework were also presented to the informants, and their feedback was obtained and incorporated into the framework presented here. Thus, the analysis was triangulated by the several data collection approaches, the varied viewpoints of the several researchers, and the feedback of informants (Silverman, 1994; Stake, 1995; Lincoln & Guba, 1985).

3. Collaboration as a Rite of Passage[6]

Our respondents suggested that collaboration appears to play a unique role in science and science education today. Our respondents typically considered acceptance as a scientist and intrinsic recognition that one's knowledge is valued as prerequisites for collaboration. For students and postdoctoral researchers, newcomers to science, collaborating with scientists is one indication of achievement and acceptance, and in this sense, is a rite of passage. Undergraduate students and beginning graduate students are seldom viewed as potential collaborators and have limited exposure to and/or participation in collaborative research. These students are taking courses, and their main tasks are to learn about science and scientific practice from coursework, literature reviews, and seminar attendance. They also are expected to learn about their faculty advisor's research as well as the scientific equipment and procedures in their advisor's lab. We found that as students develop and demonstrate substantive domain knowledge and become socialized to normative practice in the science, they may be offered opportunities to work with others in their advisor's lab and others in the R&D center. For some faculty/scientists, working with students (and postdoctoral researchers) does not imply collaboration unless the student is exceptional. As one scientist explained:

> Usually I don't think of working with a student as a collaboration. . .I just think that there is a much bigger role of education where I am teaching than there is where they are bringing anything other than hands to the project to start. There [is] . . . occasionally a student who is so exceptional that it really is a collaboration, but this is quite rare. . .[This] doesn't mean [students] are not important, but I just don't view it as collaborative. Even [working with] a postdoc I don't normally think of as a collaboration in the sense that they bring some skills to the project that are important but if they weren't there you would have another postdoc and you would still get the project done.

This comment represents the perspective that students and postdoctoral researchers are working for scientists, but not working with them. If the scientist could find another student, he could easily replace the student with someone else. This respondent emphasized that he was providing learning opportunities for the students and postdoctoral researchers. Thus, for this scientist, collaboration requires sufficient and unique scientific expertise that students and postdoctoral researchers typically acquire through years of education.

This process of gradually learning how to become a scientist can be explained in terms of the communities of practice concept (Brown & Duguid, 2000; Hara, 2000; Lave & Wenger, 1991; Wenger, 1998). Lave and Wenger (1991) originally coined the term and described the phenomena. Those who are new to a profession learn their ways by peripherally participating in the activities in a professional community. They progressively learn to become full members of the community. The first and second year graduate students are relative novices in a community of scientists. Courses provide domain knowledge and some practice but students primarily learn what it takes to be a scientist through activities, which include hands-on experiences as well as observations of and conversations with more senior students, postdoctoral researchers, their advisors and other scientists.

The involvement of students in faculty projects is an important part of both scientific training, which emphasizes apprenticeship, and the advancement of science, as researchers with students and postdoctoral researchers working in their labs can move their research along faster than if they were working alone (see also Traweek, 1988). Having the support of learners at whatever level, thus, contributes to the mission and objectives of an R&D center. This contribution is enhanced as students move from novice to expert. For example, by the time students were in their fourth and fifth years of graduate study, they were able to articulate connections with other projects in their lab and R&D center. Although this tendency varied individually, students with less academic experience did not report such connections.

For postdoctoral researchers, individuals who have achieved some status in the scientific community through the completion of their Ph.D. degree and possibly publications and/or presentations, collaboration was found to be more prevalent. These researchers usually have had some collaborative experience by the time they began their postdoctoral appointments. One mentioned his experience of

[6] We have chosen to integrate the results and discussion. We prefer this approach as it results in a more compact presentation as it reduces duplication. The ideas of others are indicated by reference to their works.

collaborating with a faculty member during his doctoral program:

> This is from my Ph.D. days. The aim of my Ph.D. was attempting to model a particular type of liquid crystal, which did not happen with the model we originally derived. I met a faculty member from a different institution at a conference who was working toward the same goals and we modified our model slightly with her ideas and we eventually managed to succeed.

Postdoctoral researchers learn to become full standing members of the scientific community by attending professional conferences, having discussions with senior researchers, and supervising graduate students.

Our data suggest there are two kinds of collaboration that arise among graduate students (or postdoctoral researchers) and their advisors: collaboration with students and collaboration through students. Collaboration with students includes advising and mentoring, i.e., providing information about science and scientific practice. For example, during videoconferencing sessions, we observed that faculty members sometimes provided a student presenter a list of references for additional information. Furthermore, collaboration with students includes problem solving, planning, and information creation and dissemination. For instance, one scientist reported:

> You advise [graduate students], but also, they're your collaborators. . . .I treat my students and post-docs as collaborators. . .What's the typical collaboration? For me it's having a seminar together and discussing a problem and pointing out what has to be done next. And deciding who is doing what. That's the best. Collaboration means. . .your paper is signed by two, three people.

The other type of collaboration that involves students is described as collaboration through students. A scientist defined this form of collaboration as follows:

> If I collaborate with another professor, what it usually means is that we have a student who is working with both of us. For example, a student might be doing experimental work, and he's being guided by one of my colleagues, and I'm doing simulation work, and he also does simulations, and I got his work in the simulation area, so collaboration usually means that there's a student who is interacting with both professors.

Collaboration becomes possible with the student who bridges the work of two professors. Of course, it is possible to replace this student with another, but the success of this kind of collaboration depends on the students who are working with both faculty members and provide a channel for information transfer between researchers. One scientist in the center mentioned that "the students are the key" for successful collaborations. Students working with and be-

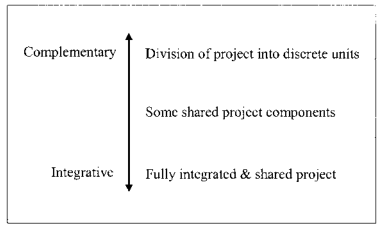

FIG. 3. Typology of collaboration (adapted from Sonnenwald, 1999).

tween two faculty members appear to enable collaboration among faculty.

As discussed previously, students' knowledge about science and the scientific process is also critical to collaboration between two faculty members. A faculty member mentioned that if a student was not capable, collaboration might fail. He listed several elements that would lead to unsuccessful collaboration. The first element was communication. If the student does not communicate well between the two professors or the professors do not communicate well with the student, the project could fall apart. The second element was the student's ability to become "a very good ambassador" and bring faculty members' ideas together. One professor claimed that it usually takes higher quality students to make a successful collaboration and sometimes it is hard to find one who understands the different cultures in separate labs. The third element was unclear ownership of the research project. If students from two different labs collaborate and are not sure who will get the primary credit, the project tends not to be successful.

4. Types of Collaboration: A Continuum of Connections

In addition to being a rite of passage, collaboration manifests itself in different forms of interaction among scientists. A typology of collaboration emerged from our analysis of interview data. Our research participants discussed collaboration as a continuum of different types, or levels of teamwork, ranging from complementary to integrative (see Fig. 3) both of which are based on awareness of common goals and sharing of knowledge or expertise.

For example, a faculty member in the teaching university suggested that the collaboration that exists at the top to the middle part of the continuum is called a "mild collaboration" or "connection" if we use his words, and the one at the lower part of the collaboration continuum expressed in Figure 3 is called a "true collaboration." He clarified what he meant by mild collaboration:

> [When] somebody needs some data or thermodynamics of certain CO2 systems they approach me and see if I can provide that. That's more of a connection than collaboration—whatever you want to call it. It's a smaller level of collaboration. But that can easily happen. I mean, that doesn't require a whole bunch of other factors—like you don't have to be buddies and you don't have to have

> chemistry or so forth. Because you're going to still do your own work, but what you produce will be useful to somebody else.

These comments indicate the need for both an awareness of other participant's distinctive knowledge/skills and the complementary fit of those knowledge/skills with the ongoing aspect of research. This type of collaboration requires awareness and complementarity rather than personality compatibilities; thus, it can be easier to establish. Much of the collaboration mentioned by center members falls into this category. Walsh and Bayma (1996) found a similar trend in collaboration in the fields of chemistry and biology. These scientists are looking for a complementary or sequential fit with their research. They may work on the same project, but not necessarily work closely with each other. They are responsible for their own pieces of the research process, contributing to the project by providing their particular inputs. The whole, or end result, is bigger than what any members could accomplish by themselves. For example, Kent explained the details of a collaborative project with Nelson (working at a different physical location) that shows this complementary division of work:

> We did one [project] with Nelson where we looked at, with light scattering, at stability of colloids and super-critical fluids and he provided the stabilizers that made these colloids possible. He provided expertise in colloid chemistry to study the stability of these colloids with light scattering. . .. Nelson's surfactants allowed novel colloids. . .exist. So he discovered new colloids. Then our understanding of the . . . surfactants by the super-critical fluids allowed us to understand how to control the stability of the colloid.

This quote indicates that this project could not be accomplished without each scientist's knowledge and contributions. Nelson's research group created surfactants, which they provided to Kent's group, and then Kent's group analyzed the surfactants. Thompson (1967) refers this kind of working relationship as sequential interdependence. In this situation, both parties have very complementary expertise. Additionally, this type of collaboration appears less likely to lead to conflicts over responsibility and contribution.

Integrative collaboration requires individuals to work closely together throughout the research process in order to develop ideas, and challenge each other's assumptions while respecting/trusting each other on both personal and professional levels. One faculty member described his experience within an integrative collaboration as follows:

> The most amazing thing about Kent and I is that if you ask either one of us independently about some chemical problem, what makes this interesting or important, we almost always come up with the same point.

In this type of collaboration, both parties are involved in developing research problems, refining ideas, and analyzing results through reporting the results. They fully participate in the whole process together and share responsibilities in all the components.

Types of Collaboration	Factors: Compatibility	Work Connections	Incentives	Socio-Technical Infrastructure
Complementary	Work style Priority	Work interests Expertise	External, e.g., funding & publication	Awareness Communication mechanisms Organizational culture & structure
↕	↓ Management style ↓	↓	↓	↓
Integrative	Approach to science Personality		Internal	Unlimited access to collaborator(s)

FIG. 4. Factors influencing the different types of collaboration.

5. Factors Impacting Collaboration

What makes collaboration work or not? This section presents the insights that we gained on this question through our data analysis. In particular, we identify four key factors that impacted collaboration in the context of the research setting: personal compatibility, research work connections, incentives, and socio-technical infrastructure. Figure 4 arrays these factors along the collaboration continuum introduced in the previous section. That is, different aspects of each factor appear to impact each type, or category, of collaboration.

5.1. Compatibility

When scientists employ a complementary type of collaboration, personal compatibility with respect to work style, writing style, and priority appear to be important. When collaboration becomes more integrative, management style appears to become an important factor. Fully integrative collaboration appears to also require compatibility in approach to science and compatibility of personality, often including personal friendship and the trust that comes with friendship.

5.1.1. Work style

A scientist's work style appears to influence collaboration in several ways. For example, when Murphy was asked about ways to facilitate collaboration with others, he answered:

> I think that the experimentalists should just talk to [theorists]. . .and see. That's what we have. And actually that happened. Some of the people from Nelson's group talked to me about something they can have an interest in.

In fact, the conversation between Murphy's and Nelson's groups led to a concrete collaborative project; Murphy wrote a proposal for the next year that involves the particular student who contacted him. Alternatively, it is apparent that he did not initiate action to start the collaboration. He is open to collaborations, yet his style of work is not likely to lead to proactively seeking collaborative projects. A student in this research group had comments similar to Murphy's:

> Somebody in [another group] came and said, Clark, we need you tomorrow on this diffusion problem for us because we don't want to do any modeling ourselves. Could you do it for us? I would say, yes, that would be real collaboration . . . . Um, and I actually think that's one of the big benefits of [our group] is that we can do a lot of modeling for experimentalists if they need it.

Again, the passiveness in his words is evident. This is an interesting mixture because the willingness to help and passiveness of waiting to be asked to help are both present. He is excited to provide the tools for other group members, but he is waiting until someone approaches him regarding those tools.

5.1.2. Writing style

Smith, a scientist, describes the importance of writing style and approach to science when collaborating with one of his colleagues, Kent:

> When we write, the writing style is the same; the focus is the same. We can write two halves of a review article and put them together and they fit because we have the same way we like to look at things physically. It's quite unusual. I have not had that experience before where the writing style and the focus was never an issue. . .if he and I sit down, just the two of us, for an hour we can get a weeks worth of work done because we think so much similarly about science even if we do different things in the laboratory.

Harris, a faculty member, mentioned an unsuccessful collaboration. He explained that one of the reasons why it did not work was because he and his potential collaborators had different working styles and approaches to science. He went on: "And that's what I mean by [personal] chemistry—chemistry is the same philosophy in research."

5.1.3. Work priority

Another scientist, Edwards, discussed the importance of the priority scientists give to their collaborative project:

> [It's] really important is that both sides are really seriously interested in this project. You know, they give it high priority . . . we have done some simulation model and we think we've discovered something new, some new phenomenon, and then we go to them, and they will immediately go in their lab and do some experiment, and try to validate to test this, and vice versa. So because we both have this intense interest in understanding this set of phenomena associated with freezing in porous media, we've discovered a lot. We've had a lot of really good joint papers and our proposals get very excellent reviews, and it's been a big success.

Edwards further mentioned that many times collaborations fail because of this element, although other requirements were satisfied.

5.1.4. Other forms of compatibility

In addition to compatible work and writing styles, and priority, another scientist, commented that in order for integrative collaboration to happen:

> You've got to have the right chemistry, the two people have to be buddies and they've got to be close friends, basically.

Peterson, a faculty member who is a theorist in the center, has collaborated with an experimentalist for over ten years. They have co-authored more than 20 papers and still continue to collaborate. This example is classified as one of the higher-level integrative collaboration in our analysis. When he was asked what made it continue, he explained:

> I think we had very complementary backgrounds . . . he was very well trained in experiments, but he understood theory. And I was trained in theory, but I was interested in experiments, and so we complemented each other. And then from there, we learned and studied together to develop a common language. We worked very [closely]—our offices were next to each other in the lab, and so it was a geographical closeness. . . . I guess we have grown, as scientists together, like kids who grow together helps friendship, so this was like a friendship, really. It started there, this was our first full-time job, and then we stayed the same time at the company. . .worked 10 years and ended . . . about the same time.

In that interview, he indicated a number of aspects of the successful collaboration: complementary expertise, interests and value in each other's work, awareness and access, and development of a professional relationship as well as a friendship. The first point was that their expertise was complementary. Peterson had expertise in theory and his collaborator had expertise in experiments. However, the significant element that made them work together was that they both had an appreciation of each other's work. According to him and other informants, this complementarity in their expertise is one of the major reasons for scientists to collaborate. The second point was awareness and access fostered by geographic closeness that made them aware of what each other was doing and also provided easy access to one another. Awareness and access are in fact proposed as factors in the socio-technical infrastructure category in Figure 4. Peterson and his collaborator were initially co-located. That situation increased their chances to interact with each other and aided the development of their friendship, although they relocated to different places after ten years. The third point was that they both started working at the same time. These circumstances helped to foster camaraderie and develop trust. Similar phenomena have also been found in other settings, such as in a police academy (Van Maanen, 1973). Van Maanen noted that the people who went through the same experience about the same as they start their professional careers develop strong ties.

"Collaboration is like a marriage." This metaphor was used by several informants. The analogy includes various meanings such as trust, "chemistry," personal friendship, good communication, and mutual efforts to make things work. Similarly, Kanter (1994) indicates that her informants used romances as an analogy for collaboration. Kanter also lists three key criteria that are often employed when companies look for alliances: self-analysis, chemistry, and compatibility. Self-analysis indicates that these companies are fully aware of their own companies and industry. Chemistry refers to personal relationships between chief executives. Finally, compatibility in Kanter's term includes "compatibility on broad historical, philosophical, and strategic grounds: common experiences, values and principles, and hopes for the future" (p. 101). That is, they had complementary approaches to business. This seems to parallel what emerged from our analysis of successful collaboration among scientists.

5.2. Work Connections

When the scientists collaborate, they look for correspondence in work interests and skills, expertise, and perspectives, regardless of collaboration levels. One of the faculty, Edwards, noted that a match of interests is a critical factor for successful collaboration. Regarding interests, he notes:

> One [critical factor] is that there's a very good match of interests, I mean we're experts in simulations; they're experts in . . . several kinds of experiments that are really excellent for testing and validating our models, and so on. So there's a very good match of interests. And they're complementary. And so because we work in quite different but complementary areas. . .one experiment, one modeling, when we talk to each other we learn a lot,. . .I mean I didn't understand anything about these experiments when I started but now I understand . . . clearly what information they can give me. And so that is one feature I think that's necessary.

In this comment, his term, "a good match of interests" indicated three things. One is that collaborators should be interested in investigating the same phenomena that the other is interested in though possibly from different perspectives. The second element is complementarity of knowledge, skills, abilities, and interests. The third component is that one party can provide a learning experience for the other. This is related to the second point, complementarity, but it also requires both parties to be interested in the others' work. That is, both sides are willing to learn from each other.

As suggested earlier, it appears that the scientists studied tend to connect with others who are in different research groups. One of the explanations of this phenomenon is that this research group consists of theorists who are looking to collaborate with experimentalists in other groups. This suggestion is supported by the comments of Brown, a student in this research group who described how important it is to compare the results of computer simulations with experiments because computer calculations should be grounded in reality. He gave an illustration of how computer simulations bridge experiments and theory:

> You have [an] experiment, and then you have theory and the computer simulation sits in the middle between the two. . . . A theoretician will take experimental results and construct a theory for it and with computer simulation . . . we can solve a theory exactly and compare it back to the experiment and so it acts as a test of the theory.

In the above comments, Brown explained why it is important for both experimentalists and theorists to work together and how computer simulations help both sides by "sitting in the middle." Therefore, computer simulations make problems simpler and easier to solve if they are based on theories. Afterwards, the experimentalists need to check if the theories and simulations match the reality. Theorists, simulators, and experimentalists have complementary expertise and skills embedded in their individual areas.

Peterson, a faculty member who does theoretical research in this group and who is eager to collaborate with experimentalists, described how experimentalists and theorists work together:

> Well, the way I was doing it in the past is I had polymers made by people in [the Nelson group] . . . and then had coordinated different experiments, like scattering or surface tension, or some other experiments, and then to try to do the calculations. For example, [Susan] was calculating a phase diagram of micelles, the size of the micelles, the mixed micelle association, things like that. And then experiments were measuring these properties at the same time.. . .If you have materials made, properties measured, and modeled for the same system, then you have a working collaboration. If the results of models agree with experiments, you can study more complex systems. If they do not agree, you ask to do additional experiments to test the assumptions of the model, or to do computer simulations and modify the theoretical model. That is what I call a successful [collaboration].

The implication is that it is more important for theorists and computer simulators to work with experimentalists than other theorists or simulators. This theme also came up several times during the interviews with other members of this research group. Peterson was also asked whether it was more important to collaborate with other research groups than with other theorists. He replied:

> I think both are important, but at this point, I would say, yes, I think at this point, it would be more important to people in

> this research group to collaborate with other [research groups]. And then, later stage, or at the same time, to collaborate within themselves, because that's the nature of theory. You have to connect with experiments; otherwise, you become too abstract.

As noted earlier, other researchers in this group also echoed Peterson's comment: this complementarity in their expertise is one of the major reasons for the scientists to collaborate. In fact, Edwards, one of the researchers in this group, invited a postdoctoral researcher who has expertise in experiments and interests in simulations to give a talk to his group. Edwards mentioned that the talk was very informative and expressed his interest in collaborating with this postdoctoral researcher in the future. In sum, the work of theorists, simulators, and experimentalists is enhanced when one (e.g., a theorist) extends or tests the results of work (e.g., a theory) through the others (e.g., testing the theory experimentally or through computer simulation).

Fujimura's (1987) study of basic cancer research led to a framework that describes how scientists develop "do-able" research problems. In the framework, a problem is do-able when scientific tasks are aligned to three levels of work organization—experiment, laboratory, and social world. Her findings suggest that the problems have to be interesting and do-able and that these problems have to be articulated before researchers go through the full series of problem solving stages. Her findings seem to complement our findings on work connections. The do-ability of problems should be discussed during an early stage of a period, though there is likely to be some evolution as the research collaboration unfolds. Atkinson, Batchelor, and Parsons (1998) also acknowledge that the scientific collaboration that occurred during medical discoveries evolved over the course of the research.

In addition to promoting the work connections, there is another possible factor that encourages collaboration. If expertise is different, specification of ownership is less of a problem because it is clearer to readers how the research tasks were divided and who worked on which part of the research or resulting article(s). Therefore, two people with different orientations, such as theory and experimentation, have less to worry about with regard to attribution of credit. This may contribute to their motivations to take a chance and collaborate. There is another side to this. When one collaborator does not follow through and do what is expected, further collaboration is not likely as the expectation of trust is not confirmed and trust turns to distrust (Sztrompka, 1999).

5.3. Incentives

Incentives, or motivation, to collaborate exist externally (e.g., prestige, funding, and publications), and internally (e.g., personal motivation). Edwards, who has primarily participated in complementary collaborations, explained:

> A. . .feature that's necessary, of course, is that the people are good in their respective areas. Meaning, you want to have people that have good reputations in the scientific world. Working with eminent colleagues may increase the chances of getting projects funded and articles accepted by journals.

Smith also reported:

> [Working with Kent is] very important in raising funds and so on too. Because one of the things that is important to someone who is evaluating a program is this money that should be spent—whether it is going to solve problems. If you have a well-known experimentalist and a well-known theorist working together to solve a problem, [it is] a very good [situation] and will get some [results], because of all the knowledge involved.

As mentioned earlier when discussing collaboration as a rite of passage, perceptions of prestige may impact collaboration. Brown reported that experimentalists are not interested in working with simulators due to perceptions of prestige:

> A general problem with computer simulation. . .[is that] experimentalists don't value on the whole computer simulation results, because it's a relatively new field. It's only been around about 30 years. You see it in every conference I've been to—there's a computer simulation afternoon and a lot of the experimentalists leave. But without the experimentalists knowing what we can do, what we can predict, they don't give us any feedback to what they would like us to look at. . .And then if the experimentalists don't turn up [at our group] meetings then they don't know what we can do. Then there's half of the equation missing.

A consequence of this issue of lack of prestige of simulation studies is that potential cooperators are unaware of collaboration possibilities and our data strongly suggests that awareness is a necessary precursor of collaboration.

Some subfields or methodological approaches have higher status than others. Other scientists' understanding of the role of computer simulation as a method of research in chemistry and chemical engineering is apparently lacking. Since the days of the Greek philosophers of science in the sixth and fifth centuries B.C., pure science has been considered to have superiority over applied science (Stokes, 1997). Traweek (1988) describes the hierarchy of the sub-fields in physics in a similar way. According to her observations, physicists believe that basic research, such as that which leads to theory, has higher status than applied research. While similar perceptions emerged from our data, there appear to be some disciplinary influences with chemists favoring theoretical and experimental approaches and chemical engineers valuing methods, which lead to solutions to problems.

Sonnert's study (1995) found that the existence of single-authored publications and graduate school prestige of authors are likely to influence peer evaluation in biology. Atkinson, Batchelor, & Paterson (1998) also report that the success of obtaining research grants is mostly determined by previous research and publications. This tendency encourages eminent scientists to work together, but lessens the possibility of inviting less established scientists into the circle. In fact, the isolation of faculty members and students at the teaching university is one of the issues within the research center.

External incentives, such as funding, publications, and prestige, are more important at the complementary level of collaboration. They are fundamental factors, which encourage collaboration. However, these external incentives do not automatically lead people to eventually establish integrative collaboration. Integrative collaboration requires the availability of internal incentives, such as solving interesting research problems and personal compatibility.

5.4. Socio-Technical Infrastructure

The socio-technical infrastructure embedded in research organizations is another factor that influences collaboration. Traditionally, scientists tend to work in their own individual labs in an organization, especially in such fields as biology and chemistry (Walsh & Bayma, 1996). As they possess their own separate labs, they seldom communicate with others (Finholt, 1999; National Research Council, 1993). Therefore, it is natural to find that this tendency remains among the scientists we studied. Furthermore, because the center has over 100 participants, it can be difficult to know what others are doing and to find the right people to work with. One of the students—Brown—mentioned that one of the benefits of being a part of the center is having access to experimentalists who might want to collaborate with him: "It will give us access to experimentalists and the collaboration with other simulators as well." Thus awareness of each other's work and the possibility of communication with others are important. As discussed earlier, awareness is traditionally facilitated by geographic proximity.

Where spatial dispersion is the rule, the use of communication tools may help compensate for the lack of physical proximity. The weekly videoconferences are intended to provide awareness of collaborative opportunities within the center. Some faculty and students actively seek collaborative opportunities during videoconferences and initiate contact with others. For example, Turner and a graduate student found that they were working on the same problem, but using different approaches. After they saw each other's presentations during videoconferencing sessions, they started to work together, and Turner considered it a successful collaboration.

> [It's] really moving quickly because she has already done this experiment. I have my program working. And we are putting together a report of results. We are obtaining a good result. And it's very good. Because I can test my model with this experiment, and she can test. . .her experiment with the model. And we are both happy because we can use our results.

The above excerpt is an example of working separately on a same problem, but eventually starting to collaborate to complement each other' work because they found the opportunity during a videoconference. Therefore, videoconferencing appears to be useful in developing an awareness of collaboration opportunities. The videoconferences are an integral part of the center; participation is mandatory for students and postdoctoral researchers, and, in general, strongly encouraged for faculty. (Faculty are requested to attend specific videoconference meetings.) Furthermore, a specialized social protocol and format has evolved for the videoconferences to help compensate for limitations inherent in the technology and to meet the needs of the members (see Sonnenwald, Solomon, Hara, Bolliger, Cox, 2002). On the other hand, once scientists establish a project, they often prefer to use other communication mechanisms, including face-to-face interactions, phone calls, and e-mail to communicate with each other. Thus, a variety of communication mechanisms appear to be necessary to support collaboration.

A challenge found in this study, within this particular research group, was its changeable organizational structure, including its changing leadership. Group members and even the group leaders themselves often did not know who the group leaders were. The leaders of this group changed several times, whereas leaders in other groups were more stable. Because of this changing leadership, the meetings among participating faculty were postponed several times. However, when all faculty in this research group met together, they found that the conversations within this group were productive. This suggests the importance of structural mechanisms of organization as a stimulus for seeing connections that lead to both complementarity and integrative levels of collaboration (cf., Dirks & Ferrin, 2001).

6. Conclusions

This paper provides a framework, which is grounded in the experience of an emerging science collaboratory involving the multidisciplinary interaction of chemists and chemical engineers and physical dispersion of participants across the campuses of four universities. This framework articulates various types of collaboration among scientists and identifies factors that influence collaboration. These factors include four categories: compatibility, work connections, incentive, and socio-technical infrastructure. The data suggests that there is an interaction between factors and types of collaboration. In some cases these factors facilitate collaboration; in others they present barriers.

During the start-up period of a research center, new opportunities for collaboration may emerge because the center can provide 1) access to experts in complementary research areas, 2) learning opportunities through colleagues who provide different perspectives regarding research and teaching, and 3) social and technical infrastructure to support communication across distances. Especially critical in this start-up phase is providing mechanisms that encourage awareness of colleagues' research and possible connections across the various research projects both within and across institutions. Complementary types of collaboration, in particular, seem to rapidly flow from such awareness mechanisms.

This study also illustrates the challenges that individuals encountered because the new way of working in the center did not correspond with the traditional work styles of the participants. As Walsh and Bayma (1996) noted, collaboration and the use of technologies differ in different disciplines. Both Walsh & Bayma (1996) and Solomon (1997) argue that communicative events are shaped by (and, in turn, shape) organizational and social structures and resulting actions, and that we should take them into consideration when introducing new practices and technologies. Furthermore, integrative collaboration may not readily emerge in a newly formed research center because people who are asked to work together may not have established the needed scientific or professional compatibility, interpersonal relationship or trust, which is a necessary foundation. Integrative collaboration relies on the coincidence of people making personal connections. If these connections do not initially exist, it is possible that they will develop, but this may take time as well as infrastructure that promotes awareness of research capacities (e.g., video conferences, faculty meetings) and facilitates broad, or unlimited, access to colleagues. Frequently, integrative collaboration is something that occurs quickly as people find that they enjoy working together and the synergy resulting from working together produces something that would not occur if those involved were working alone—the whole is greater than the sum of its parts.

One of the raison d'être of the research center under study is to enhance collaboration among the members, as a means of achieving a level of research output that is greater than would have been achieved by working alone. As mentioned earlier, the science community increasingly celebrates collaboration (e.g., National Research Council, 1993), yet successful collaboration is not easily found among the scientists that we studied, with some notable exceptions. We hope that this research will inform general research in this field as well as encourage the center members and members of similar research centers to consider the role of collaboration in their research practices.

A next step of research is to gain an in-depth understanding of scientists' daily work practices and to examine whether and how integrative scientific collaboration may be facilitated, perhaps through supporting technologies. Ultimately, it is hoped that the results of this study will serve as a foundation to help inform similar organizations of the factors, which at times facilitate and at other times inhibit collaboration in distributed, multidisciplinary research centers.

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Appendix A. Interview Guide

Perceptions Regarding Collaboration in General

- Could you share with me an example of a successful collaboration that you participated in?
- What made it successful?
- Could you describe an example of a collaboration that was not successful?
- What made it unsuccessful?

Collaboration in the Research Group and Center

- Do you know the other researchers and students in your research group?
- Are you collaborating with anyone else in your research group and/or the center currently? [What are you doing? How it is going? Etc. . .]
- Would you like to collaborate with others in your research group/the center? Why or why not? Or: what do you expect the benefits of collaboration with your research group/center members might be?
- Are there problems that you have encountered in your past work—or anticipate in this project—that might be aided by collaborations with others (in your research group)? Or in the center?
- Do you see opportunities for collaborating?
- Have you had any problems with collaborating with others in your research group/the center? If so, could you tell me about them?
- What do you think is needed to facilitate collaboration among members of your group? Between your research group and other groups in the center? In the center in general?
- In the past have you collaborated with others who are in your group/the center? Could you please give an example?

Organizational Context of Collaboration

- How is collaboration perceived by your department/organizational unit?
- How is collaboration perceived by your students?
- How is collaboration perceived within the center?
- What potential obstacles do you see arising with respect to collaboration in center projects?