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Coordination and Success in Multidisciplinary Scientific Collaborations

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COORDINATION AND SUCCESS IN MULTIDISCIPLINARY SCIENTIFIC COLLABORATIONS[1]

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Abstract

The research enterprise increasingly involves multidisciplinary collaboration, sometimes over geographic distance. Technological advances have made these collaborations possible, and the history of past innovations suggests these collaborations are desirable. Yet multidisciplinary projects can carry high coordination costs. This study investigated how collaborations address disciplinary differences and geographic dispersion to coordinate people and tasks to achieve success. We conducted an inductive study of 62 scientific collaborations supported by a program of the U.S. National Science Foundation in 1998 and 1999. Projects with principal investigators in more disciplines did not appear to suffer more coordination losses and reported as many positive outcomes as did projects involving fewer disciplines. By contrast, geographic dispersion, rather than multidisciplinarity, was most problematic. Dispersed projects, with principal investigators from more universities, were significantly less well coordinated and reported fewer positive outcomes than collocated projects. Coordination mechanisms that brought researchers together physically somewhat reduced the negative impact of dispersion. We discuss several implications for theory, practice, and policy.

Keywords: Scientific collaboration, multidisciplinarity, geographic dispersion, technological innovation

Introduction

Scientists have collaborated with one another for centuries (Finholt and Olson 1997). Some of the last century's most remarkable innovations derived from work across disciplines and laboratories. James Watson and Francis Crick, physicists-turned-biologists who discovered DNA structure in 1953, shared the same office in Cambridge, and talked for hours and days on end. But their achievement depended on the work of Rosalind Franklin, a crystallographer, at King's College in London. From such examples, scientists, policy makers, and managers have begun to encourage and support multidisciplinary collaboration in research and development, as well as in applied and basic science (Chin et al. 2002; Grinter et al. 1999; Teasley and Wolinsky 2001). Important fields such as oceanography and cognitive science have developed out of multidisciplinary collaboration (Hesse et al. 1993; Schunn et al. 2002).

Because the formal organization of science and engineering still mainly mirrors fields, multidisciplinary collaboration often requires crossing organizational boundaries. The geologist who collaborates with a computer scientist typically works in a different department or even in a different university. In the past, this dispersed form of collaboration would have been difficult; physical distance among scientists not only reduced the likelihood of collaboration, but also had a negative impact on success (Allen 1977; Kiesler and Cummings 2002; Kraut et al. 1990). The current explosion in dispersed collaboration has occurred, in

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part, because novel tools and technologies allow scientists to share information, data, reports, equipment, instruments, and other resources (Finholt 2002; Hesse et al. 1993; Kouzes et al. 1996). As the Internet and other forms of computing enhance the potential for *distributed intelligence*, policy makers in science and engineering have high expectations for innovation (Zare 1997).

Recent research suggests that technology has not yet conquered distance (Cramton 2001; Herbsleb et al. 2000; Mark et al. 1999). A primary challenge for dispersed scientific collaborations is coordinating work so that scientists can effectively leverage one another's ideas and expertise without frequent face-to-face interaction. Coordination is the integration or linking together of different pieces of a project to accomplish a collective task (Van de Ven et al. 1976). Although some coordination can be accomplished through the structuring of a project, for example, establishing lines of authority and divisions of labor, science is dynamic, and members of the collaboration still must talk out common problems, discuss shared resources, and monitor and review the work to make joint progress (Kraut and Streeter 1995; Malone and Crowston 1994).

Multidisciplinary collaborations also must manage interpersonal relationships within the project. Scientists from different disciplines have usually trained in different departments, have had different advisors, published in different journals, and attended different conferences. Hence, their ties are more likely to be weak than strong (Granovetter 1973), increasing the difficulty of developing trust and effective interdependence. How does the multidisciplinary collaboration turn comparatively weak ties into strong ties, or alternatively, create a virtual community of practice involving weak ties (Wellman et al. 1996)? There is tension between the benefits of working across disciplines and institutions, which should increase opportunities for innovation, and the costs of coordination and relationship development.

This tension is reflected in theoretical work on the social context of innovation (Brown and Duguid 1991). Innovation can be defined as the successful implementation of creative ideas, tasks, or procedures (Amabile 1988). In science and engineering, innovations are technical discoveries or insights, new ways to use existing technologies, or radical approaches to problems (Hargadon 1998; Henderson and Clark 1990; O'Connor and Rice 2001; Utterback 1994). Multidisciplinarity should increase the likelihood of innovation due to the juxtaposition of ideas, tools, and people from different domains. At the same time, multidisciplinarity, especially that involving dispersion, may require new approaches to coordination to get the work done and to foster trust. The research question we pose in this paper is how collaborations involving multidisciplinarity and geographic dispersion achieve the coordination they need to do the work and to be successful.

Methods

We studied a research initiative created by the Computer and Information Science and Engineering Directorate (CISE) of the U.S. National Science Foundation (NSF). The initiative was called "Knowledge and Distributed Intelligence" (KDI). Its purpose was "to span the scientific and engineering communities…to generate, model, and represent more complex and cross-disciplinary scientific data from new sources and at enormously varying scales." The program was highly competitive. It supported just 40 awards out of 697 proposals in 1998, and 31 awards out of 554 preproposals and 163 full proposals in 1999. These projects were supported at $1.5 million each over three years. We report analyses of 62 of the 71 projects awarded this funding.

We developed this study inductively. In the fall of 2001, NSF asked us to organize a workshop of research grantees to assess what had happened in the KDI research projects. We invited the principal investigator (PI) and one co-PI from each of the 71 KDI projects. Researchers from 52 research projects attended the workshop, held in late April, 2002. At this workshop, we used a documented discussion procedure to illuminate how research projects were organized and managed, the kinds of outcomes they generated, and the ways in which the research experience of these investigators could inform future program evaluation. We asked the participants to send us copies of reports they had written and links to their Websites. During three mornings of group discussion, note takers at each table created lists of experiences, outcomes, and suggestions.

During the workshop and in reviewing our notes later, we observed that almost all of the projects faced serious obstacles to collaboration. These obstacles ranged from different teaching schedules to different visions of where the project should go. For example, one PI, whose university ran on the semester system, encountered difficulty finding times to meet with his co-PIs, whose universities ran on the quarter system. Another talked about how he had to negotiate budgets, contract language, intellectual property, indirect costs, and human subjects procedures across universities. To overcome these obstacles, project PIs or co-PIs employed traditional approaches to coordination, such as weekly research lab meetings, as well as mechanisms they invented to maintain communication and keep the project on track. For instance, a few PIs arranged for graduate student exchanges to promote cross-training of students in the projects.

We also observed considerable variation in the number and types of outcomes of these projects. Some of the projects mainly produced new research tools, such as software that could be used in other projects. A few projects published a considerable literature and opened up an entirely new field of endeavor. Still others were successful in training graduate students who went on to good research jobs, or in giving undergraduates the experience they needed to earn places in excellent graduate programs. Others worked with community groups to bring science closer to the public, for example, through museum exhibits, elementary school classroom materials, or Websites designed for public use.

From notes and documentation, we created an online questionnaire to systematically assess the coordination mechanisms and project outcomes that workshop participants had described in connection with their own projects. We created items that represented each of the coordination mechanisms and project outcomes mentioned in the workshop. In the fall of 2002, we surveyed all KDI PIs and co-PIs and a random sample of students and staff in each project, and asked this entire sample whether or not their project had used each mechanism or had experienced that outcome. The items measuring coordination covered direct supervision of work, use of special events, such as workshops, to get people together in the same place, travel to work together or meet, and regular use of face-to-face meetings or e-mail and telephone. If respondents checked an item, they were asked to describe how they used this mechanism in their project. The items measuring project outcomes were grouped into categories corresponding to NSF's goals for research programs: generation of new ideas and knowledge, generation of tools and infrastructure for research, training of scientists and engineers, and public understanding and use of science and engineering. Respondents checked whether their project had achieved outcomes within each of these categories, and if so, they were asked to describe the outcomes as they were represented in their project.

Results

We report results for 62 (87 percent) of the 71 research projects where at least one PI or co-PI answered the survey and provided documentation of the project. PIs or co-PIs usually said they spoke for the entire project, inflating scores for those projects where more than one PI responded to the survey. Therefore, we report data for the most senior respondent on each project, either the PI ($n = 37$) or the co-PI ($n = 25$) when the PI did not respond. Preliminary analyses comparing the reports given by PIs and co-PIs show that these reports were equivalent. For example, PIs and co-PIs were equally likely to report positive outcomes, regardless of their project's size, multidisciplinarity, or dispersion. We used data available from the Web, NSF reports, and other NSF data to verify factual information such as project size, disciplines, and locations.

Each project in the sample of 62 projects had one PI and up to five co-PIs; the average number of co-PIs was three. The PIs on the projects represented nearly 100 universities and 40 disciplines, including computer science (16 percent), electrical engineering (13 percent), other engineering disciplines (12 percent), psychology (12 percent), physics (9 percent), mathematics (9 percent), and biology (8 percent). Twenty-six of the research projects were geographically collocated and 36, a majority, were dispersed over multiple institutions, up to six. Dispersion was particularly characteristic of those projects involving more disciplines (correlation $r = .29$), which supports our argument that multidisciplinary projects are likely to require coordination over institutions and distance.

The mechanisms used for coordination across projects varied in popularity. The following were used by at least 20 percent of the projects:

- Direct supervision of work (e.g., faculty or postdocs supervising tasks and studies)
- Special events to bring people together (e.g., workshop or conference)
- Direct communication (e.g., weekly or monthly face-to-face meetings)

A few projects used other communication technologies at least once a month, such as conferences calls (13 percent), video conferencing (8 percent), Instant Messaging (3 percent), and online forum discussions (8 percent). However, these were too few to include in the subsequent analyses.

Respondents reported many different project outcomes ranging from generating an algorithm for large scale predictive species distribution to creating a blood flow simulation around prosthetic heart valves, inventing a system to support manual manipulation of virtual objects, having an undergraduate thesis published in a top journal, and creating a new partnership with a major corporation. Through factor analysis, these survey responses were converted to four quantitative scales representing new ideas, new tools, student training, and project outreach.

Effects of Multidisciplinarity and Dispersion on Project Coordination

We performed initial tests, using ordinary least squares regression, to examine the direct impact on project coordination of control variables (year the project started, size of the project in budget and people, level of R&D in the project's universities), and the independent variables of multidisciplinarity and dispersion. These tests demonstrated that dispersion, measured as the number of universities in which the PIs worked, was the most powerful force on the coordination mechanisms used in the projects. Other factors, such as the size of the projects, their budgets, and the number of disciplines they represented, had no significant effect on the coordination mechanisms used.

Dispersion across universities affected both the sheer amount of coordination used and the kinds of coordination that PIs used. Greater dispersion reduced the total number of active coordination mechanisms that PIs used. Furthermore, the greater a project's dispersion, the *less* likely that faculty, postdocs, or grad students supervised tasks directly, that the project ran a seminar or invited outside speakers, and that collaborators had at least monthly face-to-face meetings, and the *more* likely that the project held a conference or workshop and worked during a conference or workshop the members attended.

Effects of Multidisciplinarity and Dispersion on Project Outcomes

Next we used regression analyses to examine the impact of the control variables, multidisciplinarity, and dispersion on outcomes. The main results of this analysis are shown in Figure 1. The control variables and multidisciplinarity had marginal overall impact. More disciplines on the project tended to be less good for student training. The strongest statistical effects derived from dispersion. Geographic dispersion was significantly negatively associated with the generation of new ideas and knowledge, and it was also negatively associated with student training and project outreach.

Mediation Analysis

Controlling for dispersion, coordination mechanisms played a critical role in the outcomes of projects. The most effective coordination mechanism overall was direct supervision, especially by faculty and graduate students; recall that this mechanism was used more by collocated projects. Face-to-face mechanisms such as holding a seminar, inviting outside speakers, and meetings were especially important in student training. The mechanisms used in more dispersed projects such as holding a workshop or conference, and travel, were effective in helping the project generate new ideas.

To test whether coordination mechanisms mediated the negative relationship between dispersion and project outcomes, we examined the change in coefficients for dispersion in our analyses of the effects of controls, dispersion, and multidisciplinarity on outcomes. A reduction in the size and/or reversal of direction of the negative coefficients for dispersion would suggest that coordination mechanisms could account for why dispersed projects were less successful, on average, than collocated projects. In two of the outcomes ($B = -.18$ to $B = .31$ for student training and $B = -.16$ to $B = .08$ for student training), it appears as though coordination mechanisms could account for some of the relationship between dispersion and outcomes. However, for new ideas, coordination mechanisms could not account for this significant negative relationship ($B = -.41$ to $B = -.39$). In sum, the results show that dispersion rather than multidisciplinarity was problematic for collaboration, although coordination mechanisms could reduce the negative impact somewhat.

Discussion

Despite widespread excitement about dispersed collaboration reflected in terms like *virtual team*, there still appear to be a number of challenges that scientists encounter when they work across institutions. Even when the dispersed collaborations had faculty or graduate students directly supervise tasks and studies, these collaborations were still less successful on average than collaborations located at a single university using the same coordinating mechanisms. The overall trend in Figure 1 is a downward slope going from collocated to dispersed. Also, Figure 1 suggests a (marginally significant) overall interaction effect suggesting that multidisciplinary projects are less successful for new ideas and knowledge when they are dispersed.
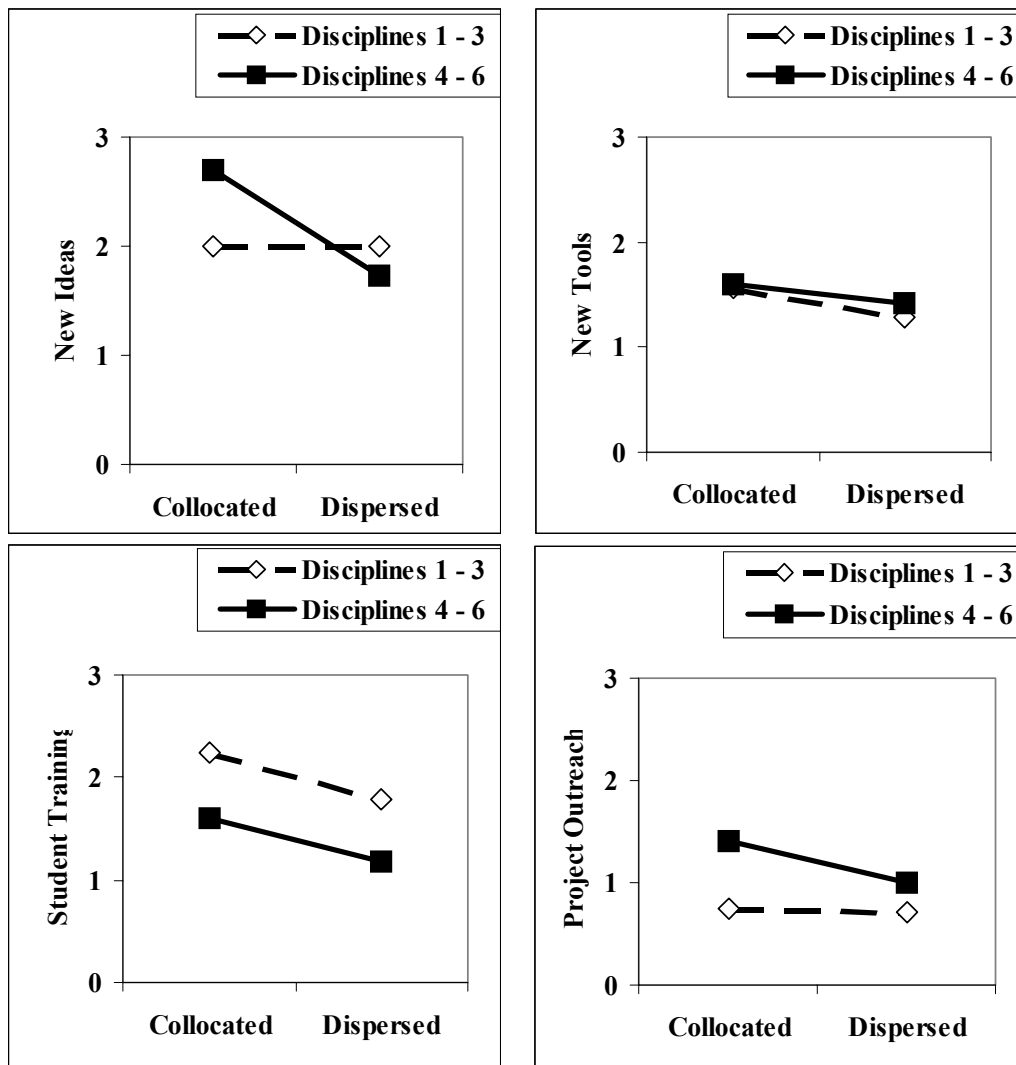
Figure 1. Project Outcomes in Collocated and Dispersed Projects (N = 62 Collaborations)

These findings, of course, are open to alternative explanations that need to be examined further before drawing strong inferences. One problem is that the projects investigated here represent a mere 5 to 6 percent of all the projects that researchers proposed in the research. We do not know what forms of selection bias operated other than merit alone. For example, did reviewers give special consideration to more dispersed projects because they were impressed with the number of universities represented? If collocated projects were intellectually stronger or otherwise more meritorious initially, it would explain their superiority of outcomes. Another problem is that our analysis represents a case study of one funding agency's program. The research program had a number of distinctive attributes that might have influenced the results, for example, that funding was provided for three years, perhaps insufficient time to create effective coordination for the dispersed projects. Because of these limitations, the generality of our findings remains to be tested.

Implications for Theory

Research in innovation and social networks suggests that multidisciplinary collaborations should generate innovations in science and engineering as well as in other domains such as business. Multidisciplinary collaborations can bring new thinking and approaches to a problem. However, the work arrangements that make these collaborations possible require a deliberate strategy

for coordination because the natural forces of propinquity and similarity are absent or reduced. In our study, the pattern of coordination in dispersed projects was indeed different than in collocated projects.

In managing their projects, the PIs of dispersed projects were less able to supervise all of the work directly (and supervision was related strongly to outcomes), to hold regular weekly face-to-face meetings involving the whole group, or to create mechanisms such as co-taught seminars and reading groups that would help the research staff and students share information, learn from one another, and develop professional relationships. They had to travel more and arrange other ways to communicate with people on the project. Some project leaders jump-started their projects by holding a workshop or conference in which they brought everyone together. Others scheduled monthly telephone meetings. Other groups shared an application or piece of equipment or a database. These mechanisms were sometimes successful, particularly if they were sustained. Monthly phone calls and regular e-mail, and workshops improved outcomes. But investigators complained that funding agencies did not recognize the costs incurred, that budgets did not support the extra coordination efforts needed, and that communication tended to fall off as the dispersed investigators discovered it was just easier to work on their own tasks alone than to try working together. These behaviors suggest that, in dispersed projects, weak ties did not turn into strong ties, nor did technology overcome distance. In dispersed collaborations, leaders and members had to figure out how to keep communication going, perhaps through the excuse of special workshops or conferences, to create successful projects.

Theories of innovation and social networks have not yet addressed this problem. Social network research mainly focuses on the use of strong ties to achieve deep exchanges of knowledge and effective learning, and is only beginning to address how groups with comparatively weak ties can achieve innovative outcomes (Hansen 1999). Research on innovation has examined mainly collocated groups in which ties are comparatively strong (Clark and Wheelwright 1992). Our study suggests that theories of innovation and social networks could benefit from further understanding how weak ties change into strong ties during the collaboration process. Longitudinal data with measures taken at multiple time periods would be required for this analysis, and cannot be addressed here with our cross-sectional data.

Implications for Practice

Our findings should stimulate discussion about the organization and management of funding agencies' multidisciplinary programs and large-scale initiatives, and the approaches that researchers themselves can use to manage multidisciplinary projects. Given the importance of face-to-face supervision, which is apparent in our data, perhaps more project-related conferences, workshops, sabbaticals, and other reasons to travel to other sites would improve the opportunity for supervision in dispersed collaborations.

The use of communication technology (e-mail, IM, phone conferences, and videoconferences) did not give principal investigators at multiple universities an added advantage, at least insofar as we could determine. Websites were common, although they were rarely used for ongoing work. Our impression from the workshop was that e-mail, in particular, was used a great deal but that e-mail failed to coordinate project work across many investigators at different places. E-mail sometimes encouraged too much task decomposition and too little intra-project sharing and learning. What kinds of technology might help? Our data, and comments at the workshop, suggest the requirements of such technology would include

- tools to manage and track the trajectory of tasks over time
- tools to reduce information overload
- tools for on-going conversation (perhaps some version of IM for scientists)
- tools for awareness with reasonable interruption for spontaneous talk
- tools to support simultaneous group decision making
- tools to schedule presentations and meetings across distance

Implications for Policy

Policy makers in the research establishment must understand the difficulties of dispersed projects and decide if they are willing to invest in their extra coordination costs to make them successful. What really accounts for the difficulties of dispersed projects? Are they inherently more difficult, or are they merely slower to get started or more effortful, or do investigators have too little skill or time to manage distributed work arrangements? At the workshop, we heard a litany of issues raised by dispersion ranging from the difficulty of arranging meetings and joint courses if different universities have different teaching calendars, to the difficulty of meeting expectations of different researchers in different departments. Some university departments, feeling they

were on the periphery of the problem, did not reward the investigators for their work. Some projects fell apart when their budgets were cut and resources had to be redistributed. (For example, in one project whose budget was cut, one of the co-PIs at a distant university was cut out of the grant entirely.) In some cases, the subcontracting mechanism delayed progress while co-PIs waited for funding.

The experiences related at the workshop and our survey analyses suggest a number of changes funding agencies should consider to meet the challenges of dispersed collaborations. Changes have been made already in some programs—longer-term funding to build infrastructure and relationships and collaborative grant mechanisms instituted in NSF's Information Technology Research program, for instance. The funding agencies would have to make other changes, including budgets to support an infrastructure for dispersed collaborations and PI salary support. Also, the practice of encouraging a funding target and then cutting budgets has caused needless stress and resentment in researchers who built proposals assuming a particular distribution of resources. The entire community should reconsider the costs of "proposal pressure." Researchers, like everyone else, respond to the promise of large-scale funding despite poor chances of funding. Over 1,000 researchers wrote a full application for KDI research funding and did not receive an award. These proposals, because they had to be innovative and interdisciplinary, probably all did not represent work that the investigators would have done anyway. We wonder, if it took each group, very conservatively, only three weeks to write their proposals, if their effort represents 3,000 weeks of wasted scientific labor. Because funding agencies do not study unfunded proposals and investigators, we cannot answer this question.

Conclusion

The issue of how to promote collaboration across disciplines, institutions, and distance applies to many domains beyond science. Competitive pressures have led many firms to increase their pool of expertise through acquisitions, mergers, alliances, and offices opened in new market areas. Hence the tradeoff we have characterized here—innovation opportunities versus coordination costs—is a general question. We show in this paper that the dilemma is serious, but that there may be both organizational and technological ways to alleviate it.

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