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Abstract

Scientific and engineering research increasingly involves multidisciplinary collaboration, sometimes across multiple organizations. Technological advances have made such cross-boundary projects possible, yet they can carry high coordination costs. This study investigated scientific collaboration across disciplinary and university boundaries to understand the need for coordination in these collaborations and how different levels of coordination predicted success. We conducted a study of 62 scientific collaborations supported by a program of the United States National Science Foundation in 1998 and 1999. Projects with principal investigators (PIs) in more disciplines reported as many positive outcomes as did projects involving fewer disciplines. By contrast, multi-university, rather than multidisciplinary, projects were problematic. Projects with PIs from more universities were significantly less well coordinated and reported fewer positive outcomes than projects with PIs from fewer universities. Coordination mechanisms that brought distant researchers together physically slightly reduced the negative impact of collaborations involving multiple universities. We discuss implications for theory, practice, and policy.

Collaborative Research Across Disciplinary and Organizational Boundaries

Scientists have collaborated with one another for centuries (Finholt & Olson, 1997).

Recently, policy makers have begun to encourage and support two or more disciplines working

together in applied and basic science – multidisciplinary collaboration (Grinter, Herbsleb, &

Perry, 1999; Teasley & Wolinsky, 2001; Chin et al. 2002). Important fields such as

oceanography and cognitive science have developed out of multidisciplinary collaborations

(Hesse et al. 1993; Schunn et al. 2002). Because the formal organization of science and

engineering in universities and industrial laboratories usually follows disciplinary boundaries,

multidisciplinary collaboration often requires crossing organizational boundaries as well. The

geologist who collaborates with a computer scientist often works in another department or

university as well as in a different field.

In the past, dispersed forms of collaboration would have been made difficult by physical

distance between scientists, which not only reduced the likelihood of collaboration, but also had

a negative impact on success (Allen, 1977; Kiesler & Cummings, 2002; Kraut et al. 1990).

Today, dispersed collaborations are more feasible because communication technologies allow

scientists to exchange news, data, reports, equipment, instruments, and other resources (Finholt,

2002; Hesse et al. 1993; Kouzes et al. 1996). Fields such as particle physics and mathematics

have relied on computer-mediated communication for several decades (Walsh & Bayma, 1996).

A recent explosion in dispersed collaboration has been spawned by funding agencies, such as the

National Science Foundation (NSF) in the United States and the Framework Programmes in the

European Union, which aim for diverse organizational representation.

Recent research suggests that, even with some signs of progress (Sonnenwald, 2003),

technology has not yet conquered distance (Cramton, 2001; Herbsleb et al. 2000; Hinds &

Bailey, 2003; Mark et al. 1999). A major challenge for dispersed scientific collaborations is coordinating work so that scientists can effectively use 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 project structure, for example, by creating clear lines of authority and division 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 (Malone & Crowston, 1994; Kraut & Streeter, 1995).

Multidisciplinary collaborations also must manage interpersonal relationships within the project. Scientists from different disciplines have usually trained in different departments, have had different advisors, publish in different journals, and attend different conferences. Their social bonds are likely to be comparatively weak (Granovetter, 1973), increasing the difficulty of developing trust and effective interdependence.

Innovation in Multidisciplinary Collaborations

An important claim favoring multidisciplinary collaborations is that they promote innovation. We define innovation 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 & Clark, 1990; O'Connor & Rice, 2001; Utterback, 1994). Multidisciplinary projects should increase the likelihood of innovation due to their juxtaposition of ideas, tools, and people from different domains. As the Internet and other forms of computing have enhanced the potential for this 'distributed intelligence', policy makers in science and engineering expect greater innovation from such projects (Zare, 1997).

There is tension between the benefits to innovation of working across disciplinary and organizational boundaries versus the risks that arise from the costs of coordination and relationship development in these collaborations. Dispersed science and engineering projects are forms of innovation systems that are meant to create, diffuse, and use diverse sources of knowledge (Carlsson et al. 2002). How researchers managing such projects and organize work to be productive has been the subject of much discussion over the years (Hagstrom, 1964). Some authors distinguish between the amount of bureaucracy versus participation in the scientific collaboration (Chompalov et al. 2002), whereas others focus on the extent to which work is project-based (Hobday, 2000). The existing literature provides no clear guidelines to managing coordination and relationship development in multidisciplinary collaborations.

Multidisciplinary projects may require new approaches to coordination to get the work done and to foster trust. When working with other disciplines requires working across organizational boundaries, as when a biologist at one university collaborates with a computer scientist at another university, the need for coordination increases due to field differences and to geographic dispersion. The research question we pose in this paper is how collaborations involving multidisciplinary and multi-organizational relationships achieve successful coordination.

Methods

The authors studied a research program created by the Computer and Information Science and Engineering Directorate (CISE) of the United States National Science Foundation (NSF). The program 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

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scales'. The program was highly competitive. It supported only 40 awards out of 697 proposals in 1998, and 31 awards out of 554 pre-proposals and 163 full proposals in 1999. These projects were supported at $1.5 Million (US) each over three years. We report analyses of 62 of the 71 projects awarded this funding.

In the fall of 2001, NSF asked the authors to organize a workshop of research grantees to assess what had happened in the KDI research projects. NSF invited the principal investigator (PI) and one co-PI from each of the 71 KDI projects to the workshop. Researchers from 52 research projects attended the workshop, held in late April 2002. At this workshop we asked researchers, organized into small randomly-assigned groups, to discuss with one another how their research projects were organized and managed, the kinds of outcomes they generated, and the ways in which their research experience could inform future program evaluation. During three mornings of group discussion, note takers as well as participants compiled lists of experiences, outcomes, and suggestions. We asked the participants to send us copies of reports they had written and links to their websites.

During the workshop and when 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 project objectives. For example, one PI, whose university ran on the semester system, ran into difficulty finding times to meet with his co-PIs, whose university ran on the quarter system. Another PI spoke of how he had to negotiate budgets, contract language, intellectual property, indirect costs, and human subjects procedures across universities. Still another discussed how students at different universities had been trained with different statistical software, an obstacle to sharing analyses until everyone could agree on a common approach. Many PIs discussed distance as a barrier to meeting, and recounted how their

early enthusiasm for travel to one another's sites was dampened over the course of the project. To overcome these obstacles, project PIs or co-PIs employed traditional approaches to coordination, such as weekly 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 project.

We observed considerable variation in the number and types of outcomes of these projects. Some of the projects mainly produced computer-based tools or resources, such as shared data repositories that could be used in other scientific projects. In other projects, PIs' publications, presentations, and workshops opened up an entirely new field of endeavor. Others were effective in training graduate students who later went on to fill top research jobs, or they gave undergraduates the experience they needed to earn places in graduate programs. Others worked with community groups, for example, by creating museum exhibits, elementary school classroom materials, or websites designed for public use.

Post-Workshop Survey

From the workshop notes and documentation from PIs' websites and reports, we created an online survey 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 the most frequent coordination mechanisms and project outcomes mentioned in the workshop. In Fall 2002, we surveyed all KDI PIs and co-PIs and a random sample of students and staff in each project. We asked this entire sample whether or not their project had used each mechanism or had produced that outcome. Our questionnaire included the following items designed to measure coordination: direct supervision of work; use of special events, such as workshops, to get people together in the same place; travel in order to work together or meet; and

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regular use of face-to-face meetings, email, and telephone. If respondents checked an item, they were asked to describe how they used the respective mechanism in their project. They also could add items that were not otherwise listed, though no single item was mentioned often enough to warrant inclusion in our analysis. The items measuring project outcomes were grouped into categories corresponding to the National Science Foundation's goals: generation of new ideas and knowledge (e.g., publications, patents, grants), generation of tools and infrastructure for research (e.g., software applications, databases), training of scientists and engineers (e.g., Ph.D. students, undergraduates), and outreach and public understanding and use of science and engineering (e.g., school and community projects, links with industry). Respondents checked whether their project had achieved outcomes within each of these categories; and if so, they were asked to describe these outcomes.

Results

We report results for 62 (87%) of the 71 research projects in which at least one PI or co-PI answered the survey and provided documentation of project outcomes. 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, when the PI did not respond, the co-PI (n = 25). Preliminary analyses show that the reports by PIs and co-PIs were equivalent. For example, PIs and co-PIs were equally likely to report positive outcomes, regardless of their projects' size, or of the number of disciplines or universities involved in their projects. We used data available from the web, NSF reports, and other NSF data to verify factual information such as project size, disciplines, and universities.

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 and co-PIs represented 40 disciplines, including computer science (16%), electrical engineering (13%), other engineering disciplines (12%), psychology (12%), physics (9%), mathematics (9%), and biology (8%). These PIs and co-PIs were employed by nearly 100 organizations. All but five of these organizations were universities. Henceforth, in this article, we refer to the PI organizations as "universities," in that these were 95% of the sample. Twenty-six of the research projects were at a single university and 36, a majority, were collaborations of multiple universities, up to 6 (see Figure 1). A greater number of universities was particularly characteristic of those projects involving more disciplines (correlation $r = .29$; see Figure 2). This finding supports our argument that multidisciplinary projects are likely to require coordination across organizations and over distance.
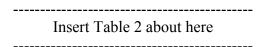

Insert Figures 1 and 2 about here

The mechanisms used for coordination across projects varied in popularity. At least 20% of the projects used the coordination mechanisms reported in Table 1. A few projects used communication technologies other than regular telephone and email at least once a month, such as conference calls (13%), video conferencing (8%), instant messaging (3%), and online forum discussions (8%). However, these were too few to include in the subsequent analyses.

Insert Table 1 About Here

Respondents reported many different project outcomes and products, ranging from an algorithm for large scale predictive species distribution to a blood flow simulation for prosthetic heart valves, a system to support manual manipulation of virtual objects, an undergraduate thesis published in a top journal, and a partnership with a major corporation. We ran a confirmatory
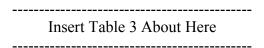
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factor analysis, which showed that the items were clustered into four independent categories of outcomes that mapped onto the four NSF goals we had previously specified: ideas and knowledge (Ideas), tools and infrastructure (Tools), student training (Training), and outreach (Outreach). For subsequent analyses, we used items from the four factors that loaded together at least at the .4 level on each factor. Every project received a score for each of four categories, Ideas (Chronbach's Alpha = .55), Tools (Chronbach's Alpha = .51), Training (Chronbach's Alpha = .54), and Outreach (Chronbach's Alpha = .28), depending on the number of items to which the PI or co-PI responded "yes." For instance, in the Ideas category, a project could receive up to 4 points if the PI or co-PI reported that his or her project started a new field or area of research, came up with new grants or spin-off projects, developed new methodologies, and was recognized with an award for contributions to the field. Projects' average score in this category was 2 points. Respondents who answered "yes" to any item had to document their answer by describing the specific outcome, giving a citation, naming the student, and so forth. We intended this requirement to discourage gratuitous entries.

Insert Table 2 about here

Effects of Multiple Disciplines and Multiple Universities on Project Coordination

We argued that more disciplines and/or universities involved in a research project might impair project coordination. We performed statistical tests, using ordinary least squares regression, to examine the simultaneous effects of the main predictor variables, number of PI disciplines and number of PI universities, on their projects' use of each of the coordination mechanisms. The regression analyses statistically control for year the project started, size of the project in budget and people, and level of R&D in the main PI's university. Table 3 shows these analyses. The findings were that, to a statistically significant degree, more PI universities

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involved in a project predicted fewer coordination mechanisms used in that project. More PI universities on a project predicted a lower level of faculty, post-doc, and graduate student direct supervision, a reduced likelihood of having created a project-related course, seminar, or invited speakers, and a much lower likelihood of having at least monthly project meetings. The results also show that, with more universities involved, the pattern of coordination mechanisms changed. PIs were more likely to hold a conference or workshop and to work on the project at a conference or a workshop. (Holding a conference or workshop, however, was less likely when the PIs were from different disciplines.) The analyses taken as a whole suggest that distance and organizational boundaries interfered with those coordination mechanisms that involve frequent, spontaneous conversation and problem solving (direct supervision, face-to-face meetings, seminars, courses). Distance and organizational boundaries impelled researchers to use other means of getting together, such as putting together a workshop to which all the collaborators could travel. Our data do not show that PIs from multiple universities used technology or travel more than PIs who were collocated.

Insert Table 3 About Here

Effects of Multiple Disciplines and Multiple Universities on Project Outcomes

Table 4 (Model 1) shows the results from regression analyses of the impact of number of PI disciplines and number of PI universities on project outcomes. The number of disciplines and control variables had little impact, except that more disciplines in the project tended to be less beneficial for student training. The strongest statistical effects derived from the number of universities. Having more PI universities on a project was significantly negatively associated with the generation of new ideas and knowledge, and it was also negatively associated with

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student training and project outreach, though this association did not reach statistical significance.

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Mediation Analysis

We conducted an analysis to examine how coordination mechanisms were related to outcomes. We found that, controlling for the number of universities, coordination mechanisms predicted the outcomes of projects. The most effective coordination mechanism overall was direct supervision, especially by faculty and graduate students; this mechanism was used more by single university projects. Face-to-face mechanisms such as holding a seminar, inviting outside speakers, and having face-to-face lab meetings were especially important in student training. The mechanisms used in multiple university projects such as holding a workshop or conference, and travel, were somewhat effective in helping the project generate new ideas.

To test whether coordination mechanisms partly caused the negative relationship between number of universities and project outcomes, we conducted a mediation analysis (Baron & Kenny, 1986). We compared a model using only the number of PI universities and disciplines (plus controls) to predict project outcomes (Model 1 in Table 4), with a model adding in all the coordination variables (Model 2). If negative beta coefficients for number of PI universities is smaller or reversed in Model 2 as compared with Model 1, that difference suggests coordination mechanisms could account for the lower degree of success of projects with more PI universities. The beta for number of PI universities in Model 2 versus Model 1 is indeed smaller in predicting Ideas outcomes (-.33 vs. -40), Training outcomes (.27 vs. -.22), and Outreach outcomes (-.17 vs. -.26), showing some support for the idea that a lack of coordination was associated with poorer outcomes of these types. Note that the opposite occurred in predicting outcomes in the Tools

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category. That is, the beta for number of PI universities becomes significant and positive when coordination is added to the model. This finding suggests that, controlling for coordination effects (which are all positively associated with good outcomes, as in the other models), more PI universities contributed to better Tools outcomes. The finding suggests that that research to produce computer-based tools might be qualitatively different from other kinds of research.

In sum, the results show more PI universities rather than more PI disciplines was problematic for collaborations, and that using more coordination mechanisms could reduce the negative impact somewhat. Unfortunately, having PI universities involved in a project significantly reduced the likelihood that PIs would actually employ sufficient coordination mechanisms.

Discussion

Despite widespread excitement about dispersed collaboration reflected in terms like 'virtual team', 'eScience', and 'cyberinfrastructure', there appear to remain a number of challenges that scientists encounter when they work across organizational boundaries. The multi-university projects we studied were less successful, on average, than projects located at a single university. We show these trends in Figure 3. The overall trend in Figure 3 is a downward slope from single university to multiple universities. Also, Figure 3 indicates a marginally significant overall interaction effect, suggesting that multidisciplinary projects can be highly successful in producing new ideas and knowledge, and outreach, when they are carried out within one university. Projects with many disciplines involved excelled when they were carried out within one university. We also found that when projects used more coordination mechanisms, they were more successful, but projects involving more universities used fewer coordination mechanisms than did projects involving fewer universities. Using more coordination mechanisms partly made

up for distance and organizational boundaries, but even controlling for the number of coordination mechanisms used, projects involving more universities were less successful.

Insert Figure 3 About Here

Our findings are open to alternative explanations that need to be examined before drawing strong inferences. One problem is that the projects investigated here represent only 6% of all the proposals sent to the program. We do not know what forms of selection bias operated. For example, did peer reviewers give higher scores to multi-university projects because they liked the number of organizations and regions represented? If reviewers gave multi-university proposals extra points for including many organizations, and if doing so is independent of scientific merit, then the poorer outcomes of multi-university projects could be explained by a difference in intrinsic merit. To check on this possibility, it will be necessary to examine the peer review process.

Another problem is that our analysis represents a case study of one funding agency's program and, especially, the beginning of this agency's attempts to support interdisciplinary research on a grander scale. The research program had a number of distinctive attributes that might have influenced the results: for example, that funding was provided for only three years, probably insufficient time to create effective coordination for the multi-university projects.

Implications for Theory

Research on innovation and social networks suggests that multidisciplinary collaborations should generate innovations in science and engineering. Multidisciplinary collaborations can bring new ideas 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

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our data, the pattern of coordination in multi-university projects was indeed different than in single university projects.

In managing their projects, the PIs of multi-university projects were less able to supervise all 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 participants in 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, piece of equipment, or database. These mechanisms were sometimes successful, particularly if they were sustained. Monthly phone calls, and regular email 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 easier to work on their own tasks, rather than try to work together. These behaviors suggest that technology did not overcome distance. In multi-university collaborations, leaders and members had to figure out how to keep communication going to create successful projects.

Theories of innovation and social networks have not yet addressed this problem. Social network research mainly focuses on the importance of strong ties for achieving deep exchanges of knowledge and effective learning, and such research is only beginning to address how groups with comparatively weak ties can achieve innovative outcomes (Hansen, 1999). Research on innovation has examined mainly single organization projects in which ties are comparatively

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strong (Clark & Wheelwright, 1992). Our study suggests that theories of innovation and social

networks could benefit from further investigations of how weak ties change into strong ties

during the collaboration process. Longitudinal data with measures taken at multiple time periods

would be required for such analysis, and cannot be addressed with our cross-sectional data.

Currently we have no theory of the 'ideal' level of collaboration in science, especially in

interdisciplinary science. Our results suggest that student training benefits from less

collaboration across disciplines or universities (see Figure 3). The most successful training

outcomes were in one university with fewer disciplines involved in the project. In future

research, we should examine how different kinds of science use different forms of coordination,

and how the use of those mechanisms change the nature of the collaboration. It may be the case

that some mechanisms are more effective than others for tightly coupled, as compared with

loosely coupled, projects (Weick, 1979). For example, the data in Figure 3 suggest that work on

tools and infrastructure (especially software projects) is not at all impeded by multiple

disciplines or universities. This is work that can be decomposed, managed, and evaluated across

distance and organizational boundaries, as is indicated by the success of many open source

projects (e.g., Linux, Mozilla).

Implications for Practice

Our findings should stimulate discussion about the organization and management of

funding agencies' multidisciplinary programs and large-scale initiatives, and also about

approaches that researchers themselves can use to manage multidisciplinary projects. Given the

importance of face-to-face supervision and coordination, which is apparent in our data, perhaps

more project-related conferences, workshops, sabbaticals, and travel to other sites would

improve the opportunity for supervision in multi-university collaborations. Additional research is

needed to identify the incentives that would encourage multi-organizational collaborations to explicitly use coordination mechanisms in their projects.

The use of communication technology (email, IM, phone conferences, and videoconferences) did not give principal investigators at multiple universities an added advantage, at least as far as we could determine. Websites were common, though they were rarely used for ongoing work. Our impression from the workshop was that email was used a great deal but that it failed to help people coordinate project work across many investigators located at different places. Using email 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

It is likely that these suggestions apply not only to the comparatively small multi-university collaborations we studied, but also to bigger projects focused on large-scale data analysis and visualization, such as Biomedical Informatics Research Network (BIRN), Network for Earthquake Engineering Simulation (NEES), and Grid Physics Network (GriPhyN).

Implications for Policy

Policy makers in the research establishment must understand the difficulties of projects that cross distance and organizational boundaries, and decide if they are willing to invest in their

extra coordination costs to make them successful. What really accounts for the difficulties associated with such projects? Are they inherently more difficult? Does it simply take more time and effort to get them started? Or, do investigators simply have too little skill or time to manage distributed work arrangements? At the KDI workshop, a litany of issues was raised ranging from the difficulty of arranging meetings and joint courses, when different universities have different teaching calendars, to the difficulty of meeting expectations of different researchers in different departments. Some university departments, believing that they were on the periphery of the problem, did not reward 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. It is not difficult to imagine that the problems become even more severe when national and language boundaries are introduced, as in case of the European Union Framework Programmes.

The experiences expressed at the workshop and analyzed by our survey, suggest that funding agencies should consider a number of changes to meet the challenges of multi-organizational collaborations. Changes were made in some programs: for instance, longer-term funding to build infrastructure and relationships and collaborative grant mechanisms instituted in NSF's Information Technology Research program. Further changes that funding agencies should make include, for example, budgets to support an infrastructure for multi-university collaborations and PI salary support. In addition, the practice of encouraging a funding target and then cutting budgets has caused needless stress and resentment by researchers who developed proposals while 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 1000 researchers wrote full applications for KDI research funding and did not receive awards. These proposals were required to be innovative and interdisciplinary, but it seems likely that many involved work that the investigators would have done anyway. If, under a conservative estimate, it took each group only 3 weeks to write its proposal, then the aggregate effort represents 3,000 weeks of wasted scientific labor. Because funding agencies do not currently study unfunded proposals and unsuccessful applicants, we cannot answer this question.

Conclusion

The question of how to promote collaboration across disciplines and organizations applies to innovation systems beyond science. Hence the tradeoff we have characterized here – innovation opportunities versus coordination costs – is a general question. We show that the dilemma is serious. There may be organizational and technological ways to alleviate it.

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Table 1. Coordination mechanisms used by projects. (N = 62 projects)

Coordination Mechanism Items (0 : no - 1 : yes)	Percent of Projects
Faculty supervised tasks	84%
Post-doc supervised tasks	44%
Graduate student supervised tasks	34%
Held seminar or invited speakers	60%
At least monthly face-to- face project meetings	55%
At least monthly phone or email on project	84%
Held conference or workshop	55%
Worked on project during conference or workshop	52%
Sabbatical to work with collaborators	21%
Traveled by airplane to work with collaborators	52%

Table 2. Project outcomes (N = 62 projects)

Project Outcome Items (Yes/No)	Percent of Projects Saying "Yes"
Ideas	
Started new field or area of research	58%
Created new grants or spin-off projects	58%
Developed new methodologies	66%
Recognized with award for contribution to field	19%
Tools	
Created new software	71%
Created new hardware	13%
Generated new datasets	47%
Submitted patent application	15%
Training	
Undergrad/graduate student finished thesis or dissertation	76%
Undergrad/graduate/postdoc got academic job	48%
Undergrad/graduate/postdoc got industry job	42%
Outreach	
Formed partnership with industry	27%
Formed community relationships through research	27%
Formed collaborations with different researchers	65%

Note.   The items above loaded above .4 on four separate factors, as categorized above. Each project could have zero to 4 points in the Ideas and Tools category, and zero to 3 points in the Training and Outreach category.

Table 3. Regression analyses predicting the amount of project coordination from the number of PI disciplines and number of PI universities in the project. (N = 62 projects)
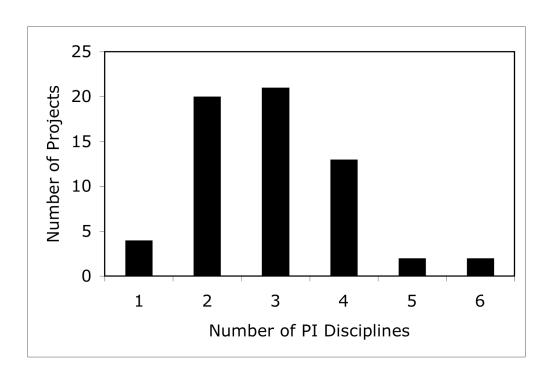
	Coordination Mechanisms Used in Projects									
	Faculty supervised tasks	Post-doc supervised tasks	Graduate student supervised tasks	Held seminar or invited speakers	At least monthly face-to-face project meetings	At least monthly phone or email on project	Held conference or workshop	Worked on project during conference or workshop	Sabbatical to work w. collaborators	Traveled by airplane to work w. collaborators
Predictor Variables										
Number of PI disciplines	-.18	.17	-.01	-0.07	-.07	-.03	-.43 ^{t}	-.29	.67 ^{t}	.08
Number of PI universities	-.22 ^{t}	-.39 ^{t}	-.56*	-0.62**	-.64**	.07	.37*	.38 ^{t}	-.06	.23
Controls										
Year started	1.25**	1.31 **	.44	1.09**	1.41**	.66**	.91*	.77 ^{t}	.86 ^{t}	.43
Budget	-.16	-.26	.04	-.04	-.13	.09	.08	-.14	-.11	-.23
University R&D	-.05	-.14	.05	-.08	-.04	.12	.00	.05	.00	.10
Number of PIs	.19	-.18	.49	.36	.17	.05	-.18	-.04	-.85*	.02
Number of post-docs	.09	.39**	.20	.25*	.11	.00	.27*	.14	-.09	.03
Number of graduate students	-.02	-.18	0.	-.1	-.17	-.01	-.18	-.07	-.04	.21
R Square	**.86**	**.56**	**.44**	**.71**	**.66**	**.85**	**.65**	**.56**	**.31**	**.57**

Note. Values in table are beta coefficients. Statistical significance is indicated by, ^{t}p < .10,*p < .05,**p < .01. Positive beta values indicate that a higher value of the predictor (or control) variable predicts a higher likelihood that the coordination mechanism was used in a project. Negative beta values indicate that a higher value of the predictor (or control) variable predicts a lower likelihood that the coordination mechanism was used in a project. For instance, the significant negative beta (-.64**) for number of universities predicting monthly face-to-face project meetings means that when more PI universities were involved in a project, the project team was less likely to have held at least monthly face to face project meetings.

Table 4. Regression analyses testing the effects of number of PI disciplines, number of PI universities, and number of coordination mechanisms on project outcomes (N = 62 projects.)

	Ideas		Tools		Training		Outreach	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Controls (not shown)								
Predictor Variables								
Number of PI disciplines	-.08	.09	.25	.16	.00	.01	.25	.25
Number of PI universities	-.40**	-.33 [t]	.00	.39 [t]	-.22	.27	-.26	-.17
Coordination Mechanisms								
Faculty supervised tasks		.35*		.42 [t]		.38*		.26
Post-doc supervised tasks		.01		.02		-.13		.00
Grad student supervised tasks		.13		.24*		.17*		.05
Held seminar or invited speaker		-.07		.08		.31*		-.10
At least monthly face-to-face project meetings		.17		.12		.24*		.17
At least monthly phone or email on project		.03		-.19		-.23		.12
Held conference or workshop		.13		-.05		-.11		-.03
Worked on project during conference or workshop		.11		-.07		.01		.06
Sabbatical to work with collaborators		-.04		.19*		.08		.08
Traveled by airplane to work with collaborators		.24*		.16		.17 [t]		.13
R Square	**.87**	**.77**	**.78**	**.68**	**.87**	**.77**	**.73**	**.68**

Note. Values in table are beta coefficients. Statistical significance is indicated by, [t] p < .10,*p < .05,**p < .01. Mode shows the effects of number of PI disciplines and number of PI universities on project outcomes. A positive beta ind that the predictor is associated with more outcomes in each category shown. A negative beta indicates that the predi associated with fewer outcomes in each category shown. Model 2 shows the combined effects of number of PI disci number of PI universities, and number of coordination mechanisms on outcomes. The comparison is a mediation an (Baron & Kenny, 1986). If the beta for number of disciplines or universities is lower in Model 2 than in Model 1, or infer that coordination mechanisms are partly mediating (causing) the effect of the predictor on outcomes.
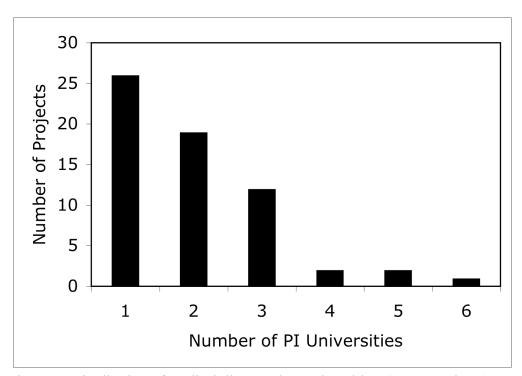
Figure 1. Distribution of PI disciplines and PI universities. (N=62 projects)
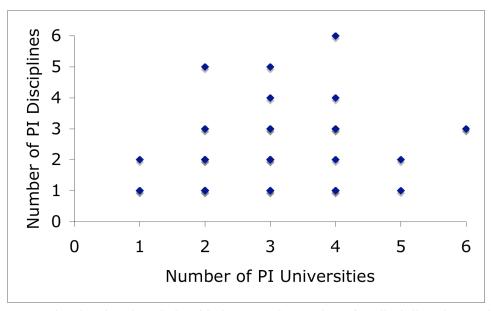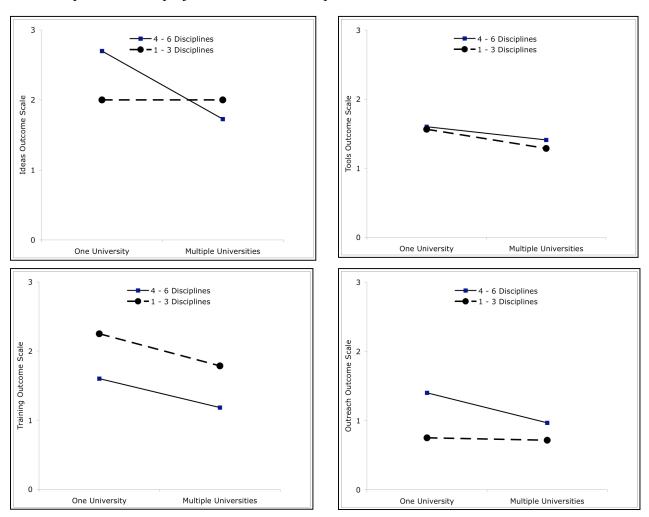
Figure 2. Scatter plot showing the relationship between the number of PI disciplines in a project and the number of PI universities in a project. The correlation is *r* = .29.

Figure 3. Project outcomes in single university and multi-university projects (N=62 projects)

Note: The unit of measurement on the y-axis is the number of items checked on the post-workshop survey for each outcome. Based on a median split, there were 30 projects with 1-3 PI disciplines and 32 projects with 4-6 PI disciplines.

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