4 A Theory of Remote Scientific Collaboration

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In the past fifteen years, a great deal has been learned about the particular challenges of distant collaboration. Overall, we have learned that even when advanced technologies are available, distance still matters (Olson and Olson 2000). In addition, a recent seminal study of sixty-two projects sponsored by the National Science Foundation (NSF) showed that the major indicator of lower success was the number of institutions involved (Cummings and Kiesler 2005; chapter 5, this volume). The greater the number of institutions involved, the less well coordinated a project was and the fewer the positive outcomes.

There are a number of reasons for these challenges. For one, distance threatens context and common ground (Cramton 2001). Second, trust is more difficult to establish and maintain when the collaborators are separated from each other (Shrum, Chompalov, and Genuth 2001; Kramer and Tyler 1995). Third, poorly designed incentive systems can inhibit collaborations and prevent the adoption of new collaboration technology (Orlikowski 1992; Grudin 1988). Finally, organizational structures and governance systems, along with the nature of the work, can either contribute to or inhibit collaboration (Larson et al. 2002; Mazur and Boyko 1981; Hesse et al. 1993; Sonnenwald 2007). This chapter describes our attempt to synthesize these findings and enumerate those factors that we (and others) believe are important in determining the success of remote collaboration in science. In working toward a theory of remote scientific collaboration (TORSC), we have drawn from data collected as part of the Science of Collaboratories (SOC) project, studies in the sociology of science, and investigations of distance collaboration in general.

The Developing Theory

Success

We begin by discussing what we might mean by success in remote collaboration, since in the literature it can vary from revolutionary new thinking in the science to simply having some new software used. Different sets of factors may lead to different kinds of success. These outputs include effects on the science itself, science careers, learning and science education, funding and public perception, and inspiration to develop new collaboratories and new collaborative tools. The details are listed in short form in table 4.1.

Effects on the Science Itself Early goals for collaboratories included that they would increase productivity and the number of participants, and democratize science through improved access to elite researchers (Finholt and Olson 1997; Hesse et al. 1993; Walsh and Bayma 1996). Similar assumptions were made with regard to interdisciplinary research (Steele and Stier 2000). These goals have to date not been tested. Today, scholars, policymakers, and scientists no longer take these assumptions for granted. Increasingly, they recognize that to define and evaluate the success of distributed and large-scale scientific collaborations is a complex task.

Traditional measures of success in science are geared toward the individual, and include metrics such as productivity (e.g., counts of publications, presentations, patents, and graduate students mentored), awards and honors, and the impact of the work as determined by the prestige of the publication outlet or the number of times other researchers cite an individual scientist's papers (Merton 1988; Prpic 1996; Shrum, Chompalov, and Genuth 2001). Some of these measures can be used to evaluate the outcomes of large-scale, interdisciplinary, distributed collaborations, but most of them are inadequate to assess the full spectrum of goals of many current projects. Findings from the SOC project show that collaboratory participants and funding agency personnel frequently describe success in terms of the transformations to scientific practice along with the scale, scope, and complexity of the questions that can be answered. Both scientists and policymakers acknowledge that these outcomes take a long time to achieve and are difficult to assess using traditional measures.

Social scientists have made some attempts to identify appropriate success measures and then evaluate collaborative science projects against these criteria. Methods based on the scientific outcomes of collaboration are the most common means to define and assess success. In the case of cross-disciplinary collaborations, the degree of intellectual integration, innovation (e.g., the generation of new ideas, tools, and infrastructure), and training are used as success measures (Cummings and Kiesler 2005; chapter 5, this volume; Jeffrey 2003; Stokols et al. 2003, 2005). Bradford Hesse and his colleagues (1993) used three scientific outcomes—publication, professional recognition, and social integration—to measure success among oceanographers who used computer networks to communicate with other researchers and access shared resources.

We believe that both more scientists working on a common problem and the diversity among scientists working in a collaboratory can lead to bigger discoveries as well as breakthroughs, such as new ways of working, more revolutionary science, conceptual revolutions, and new models of science emerging. These are the highest-level goals.

Table 4.1
Kinds of outcomes that would count as "success"

Effects on the science itself
New and bigger discoveries are made and are made more quickly
New ways of working are demonstrated, and then sustained
There is a change in the mix of normal vs. revolutionary science
A conceptual revolution is enabled
New models of science emerge (e.g., microparticipation)
There is more high-quality research
Existing collaborations work more easily
More and new collaborations are formed
Collaborations have a wide geographic and disciplinary spread
More jointly authored papers are written and are written more quickly
More papers are published and patents are issued
Greater willingness to share early ideas
Findings are shared more quickly among more people
Artifacts that are shared are richer
Theoretical discussions are accelerated and enriched
Less undesirable duplication
Fewer disruptive activities
Greater success in competitive arenas
Science careers
Greater diversity of scientists
Participation reaches beyond U.S. R1 universities
Stronger tenure cases because young faculty are known through their collaborations
Improved quality of life and higher satisfaction of researchers
Learning and science education
New (diverse) scientists are attracted to the field (capacity building)
More students are mentored
Extended reach of seminars
Material is used in a classroom setting
New distance-learning paradigms emerge
Inspiration to others
New collaboratories are developed as a result
Other software is built inspired by it
Funding and public perception
A particular collaboratory is re-funded
Public become more interested and literacy increases
Public participates more (e.g., microcontributions)
Congress becomes more interested
New funding initiatives appear for science and collaboratories
Tool use
New software is built
Builder demos the tools working
Users use the software and complain when it is taken away
New users try it and continue to use it
Tools move from research prototypes to production quality
Tools are reused elsewhere

For instance, the goal of the high-energy physics community (chapter 8, this volume) and the Alliance for Cellular Signaling (AfCS) (chapter 11, this volume) are to do research on a scale that has not been attempted previously. In the AfCS, for example, the work is centered around the identification of all the proteins that comprise the various signaling systems, the assessment of time-dependent information flow through the systems in both normal and pathological states, and the reduction of the mass of detailed data into a set of interacting theoretical models that describe cellular signaling. This type of success cannot be achieved without a large coordinated effort.

Another type of success could be an increase in the productivity of existing projects, in that they overcome the barrier of distance more easily. Researchers who use the large instruments like Pacific Northwest National Laboratory's nuclear magnetic resonance instruments (chapter 6, this volume) or Keck Observatory telescopes (Kibrick, Conrad, and Perala 1998; see also chapter 3, this volume) without traveling are clearly experiencing an opportunity for more productivity. They can gain access without the time and effort involved in a trip, and furthermore can take advantage of securing time on the instrument when someone else releases it unexpectedly. And when scientists discover people of like mind and goals, new collaborations can ensue, including those with people from distant geography.

Even earlier indicators of success are that there are more jointly authored papers, more papers published overall, and a greater willingness to share early ideas. Although these factors do not define ultimate success in and of themselves, they are often thought to be precursors to scientific breakthroughs. The technology adopted is intended to help people share richer artifacts than allowed by text alone, sharing computational analyses, programs, and visualizations. This should lead to better, richer theoretical discussions. If the tools are indeed off-loading some of the tedious work to technology, then it can be expected that scientists are doing more high-level cognitive work and less of the routine work (such as cleaning data or preparing samples). With higher communication comes less duplication of effort. By allowing people to participate from their home locations, less time is wasted in travel and the disruptions to one's daily life are fewer.

If indeed the higher productivity is evident early on, then various collaboratories would have greater success in competing for funding than those that do not collaborate as well. This pours more research dollars into successful collaborations, creating a measure of desired productivity.

Effects on Science Careers Because long-distance work is possible, we can expect a more diverse set of people working in the field, leading to the desired diversity and possibility for conceptual revolutions. For example, before the Upper Atmospheric Research Collaboratory/Space Physics and Aeronomy Research Collaboratory (UARC/SPARC), going to the sites of the upper atmospheric radar, incoherent scatter radar, imaging riometer, all-sky camera, and Fabry-Perot interferometer often required flights on military transport as well as stays of two weeks or more in unfavorable and uncomfortable conditions (chapter 9, this volume). Only those scientists willing to tolerate such extreme sacrifices for their science are attracted to the field. Now that the same data and some control can be accessed anywhere, a much broader set of people (especially women) could be attracted to the field.

Collaboratories can also build capacity in areas outside the highest-level research (R1) universities, extending to smaller colleges, those with underrepresented minorities, and research institutes and universities in developing countries (chapter 20, this volume), thus broadening the pool of talent working on important problems. For instance, one of the major goals in the International AIDS Research Collaboratory was to build capacity in South Africa to do the data collection and analysis for AIDS research (chapter 19, this volume). This not only speeds the science in general but also allows people to develop the skills to work on problems in science.

In addition, participation in collaboratories can define a cohort of similarly minded scientists, who would otherwise not be known to each other. Although not hugely successful in itself, the Learning through Collaborative Visualization, a five-year project ending in 1998, brought together a cohort of interdisciplinary people who still interact (Gomez, Fishman, and Pea 1998).

Effects on Learning and Science Education Many collaboratories give graduate students opportunities for hands-on experience. Some are even mentored by remote senior scientists. Students, who often cannot afford to travel, can attend seminars. The Ecological Circuitry Collaboratory and the VaNTH Education Research Center were collaboratories that made specialized training more available at the graduate level, contributing to a new distance-learning paradigm (see also chapter 3, this volume).

Some collaboratories have educational outreach as one of their goals. If the collaboratory has outreach to public schools, it may inspire students to follow a science career. The Beckman Center at the University of Illinois, for example, offered two such outreaches: Chickscope and Bugscope. Chickscope allowed children to view a chicken embryo through an MRI machine from their classrooms (Bruce et al. 1997). Similarly, for Bugscope, time on an electron microscope was devoted to classroom use where students could send in sample insects and then view them from afar through the microscope's magnification. The goal was to inspire students to enter careers in science.

There is, additionally, the possibility of a different kind of distance learning. Instead of lectures from remote researchers, technology can afford remote mentoring and observation along with participation in the science itself. UARC/SPARC witnessed remote mentoring; Bugscope and Chickscope allowed remote participation in the science.

Collaboratories can also increase the visibility of scientific disciplines. Visibility can lead younger students to be inspired by such work. The same kind of visibility and outreach can motivate scientists in related fields to become involved. Also, visibility of details of the ongoing work can reduce a duplication of effort.

Effects by Inspiring Others Occasionally, there is a collaboratory effort, like UARC/SPARC, that is not transformative of its own science but serves as an example of what others can do. UARC/SPARC, described earlier, was an inspiration to the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) (chapter 18, this volume), and the Diesel Combustion Collaboratory influenced the Collaboratory for Multi-Scale Chemical Sciences. Key personnel are involved in these pairs. People in the Geosciences Network (GEON) (chapter 17, this volume) helped others in the Linked Environments for Atmospheric Discovery early in their project conception. The Cochrane Collaboration inspired the Campbell Collaboration, the first in evidence-based medicine and the second in social interventions.

Effects on Funding and Public Perception Science requires funding to succeed. The re-funding of a collaboratory is one measure of perceived success. InterPARES1 was funded again under InterPARES2, and the funding for the Biomedical Informatics Research Network (BIRN) was renewed (chapter 12, this volume). If through the collaboratory the public becomes more aware of science, this can in turn influence Congress and funding agencies. New funding initiatives appear, such as those managed by NSF's Office of Cyberinfrastructure. The more funding and the greater the efficiency, the greater is the likelihood of scientific breakthroughs.

Public policy outcomes are another way that success has been defined and measured, although it sometimes takes decades to assess (Stokols et al. 2003, 2005).

Effects by Measuring the Levels of New Tool Use For those collaboratories that create new tools or infrastructure, success may be measured by the degree of technology adoption within the collaboratory and elsewhere. Some projects are able only to demonstrate a new capability, which though not affecting the science itself, may inspire others to try things in their fields. Some of the new powerful visualization techniques, for instance, are demonstrated and then picked up in other fields.

If the tools are designed well, not only to fit the work at hand and for the ease of use, then it is likely that the tools will be utilized. The greater the ease of learning and use, the less is required of local support. If the tool is a recognized aid to productivity, it is likely that others will begin to use it. If research technologies are useful but unreliable, as many are, the clamor for reliability may cause funds to be devoted to making tools "production quality." And better yet, tools may be reused elsewhere. For example, NEES used the Electronic Notebook from the Environmental Molecular Science Laboratory; GEON and the Scientific Environment for Ecological Knowledge both use Kepler, a visual modeling language; and the AfCS and Lipids Metabolites and Pathways

Strategy are both using the Laboratory Information Management System, made available from the National Institutes of Health (NIH), with the modifications that AfCS made.

Factors That Lead to Success

Five major clusters of components are important to success, as shown in detail in table 4.2: the nature of the work, the amount of common ground among participants, participants' readiness to collaborate, participants' management style and leadership, and technology readiness.

The major categories, with the exception of the management issues, were first described in Olson and Olson (2000). We have since identified the key management and decision-making practices that are crucial as well as detailed the significant components within these clusters.

The Nature of the Work

One of the keys to success is dividing the work of the team so that it can get done without a lot of communication across distance. The more modularized the work at the different locations, the more likely is success. Sometimes work requires participants to continually define and refine their understanding of what to do as well as how to do it because it is new, somewhat ambiguous, or highly interdependent, requiring what has been called "tight coupling" (Olson et al. 2002) or what James Thompson (1967) referred to as reciprocal interdependence. We have seen a number of projects fail because the tightly coupled work spanned people in different locations. For example, a software development team located in two places, the United States and Mexico, attempted to build a system to assess the manufacturability of an engineering design. Even though there were regular videoconferencing meetings and a lot of e-mail exchange, the project suffered. After a period of struggle, the team redistributed the tightly coupled work to people who were collocated—giving the algorithm design to one site and the task of populating the database to the other (Olson and Olson 2000). In other cases, ambiguous, highly interdependent work was done at one location with others traveling to meet face-to-face, or the work was more modularized, so that tight interdependencies did not cross distance or institutional boundaries. Distance creates significant barriers to the frequency and richness of communication, which makes it difficult to reconcile ambiguities and keep in synch on many interdependencies (Birnholtz 2005; Chompalov, Genuth, and Shrum 2002).

Common Ground

In order to make collective progress, people engaged in a collaboration need to have mutual knowledge, beliefs, and/or assumptions, and know that they have this (Clark

Table 4.2
Factors that lead to success in collaboratories

The nature of the work

Participants can work somewhat independently from one another

The work is unambiguous

Common ground

Previous collaboration with these people was successful

Participants share a common vocabulary

If not, there is a dictionary

Participants share a common management or working style

Collaboration readiness

The culture is naturally collaborative

The goals are aligned in each subcommunity

Participants have a motivation to work together that includes mix of skills required, greater productivity, they like working together, there is something in it for everyone, not a mandate from the funder, the only way to get the money, asymmetries in value, etc.

Participants trust each other to be reliable, produce with high quality, and have their best interests at heart

Participants have a sense of collective efficacy (able to complete tasks in spite of barriers)

Management, planning, and decision making

The principals have time to do this work

The distributed players can communicate with each other in real time more than four hours a day

There is critical mass at each location

There is a point person at each location

A management plan is in place

The project manager is:
Respected
Has real project management experience
Exhibits strong leadership qualities

A communication plan is in place

The plan has room for reflection and redirection

No legal issues remain (e.g., IP)

No financial issues remain (e.g., money is distributed to fit the work, not politics)

A knowledge management system is in place

Decision making is free of favoritism

Decisions are based on fair and open criteria

Everyone has an opportunity to influence or challenge decisions

Leadership sets culture, management plan, and makes the collaboratory visible

Technology readiness

Collaboration technologies provide the right functionality and are easy to use

If technologies need to be built, user-centered practices are in place

Participants are comfortable with the collaboration technologies

Technologies give benefit to the participants

Technologies are reliable

Agreement exists among participants as to what platform to use

Networking supports the work that needs to be done

Technical support resides at each location

An overall technical coordinator is in place

Special issues:
If data sharing is one of the goals, de facto standards are in place and shared by all participants, and a plan for archiving is in place

If instrument sharing is part of the collaboration, a plan to certify remote users is in place

1996; Clark and Brennan 1991). Collaborations can be hindered if one or more of these aspects of common ground are absent. The ability to work toward common ground is more difficult when the collaborators are geographically distributed.

Mutual Knowledge If people have worked successfully together in the past, they are likely to have achieved common ground, which will improve their chance of success in subsequent collaborations. If they are from different disciplinary backgrounds, however, they are unlikely to share a common vocabulary; misunderstandings are likely to ensue. Time and attention must be paid to the activity of developing a common vocabulary. For example, Mouse BIRN is a collaboratory that joins different kinds of scientists all focusing on multiple levels of the mouse brain, from its molecular structure to its morphometry (chapter 12, this volume). The collaborators recognized early on that they did not all speak the same language, particularly when it came to referencing the anatomy of the mouse brain. In response, they jointly built an ''atlas'' that like the Rosetta stone, shows the relationship between the terms. The interface to the database is a simple spatial layout, with scientists able to point to the areas of interest, without having to specify the terms. In this way, the search engine can find all the data and views relevant to this area, even though the different scientists label that area differently. GEON, likewise, developed an ontology as a way to deal with some of the semantic differences in classification systems used by state geologic survey offices.

Beliefs and Assumptions in Management Interestingly, it also helps if the participants have a common management style, so that their interactions and expectations are aligned. For example, those used to a hierarchical management style with specified deliverables and reports at various intervals will likely not function well with those used to a more open and informal style of management. In the UARC/SPARC collaboratory, for instance, the designers of the interface were used to a software development method that included explicit user requirements followed by a coordinated design of the multitude of features. In contrast, the developers themselves were following a more open and informal style, using a rapid-prototyping development method that sought explicit input from the users, not the user-interface designers, and rapidly changed the interface to suit requests.

Collaboration Readiness

Understanding what motivates people to collaborate, whether they trust each other, how well their goals are aligned, and how empowered they feel are all important to success—a concept we collectively call collaboration readiness. These factors can be related to work or personal and social dimensions, as detailed below.

Work-Related Dimensions Some domains in science are naturally collaborative. High-energy physics, for example, and space physics have long histories of large collaborations. Theoretical computer science does not. The AIDS collaboratories experienced some competition among postdocs (to stand out in order to be chosen for regular faculty positions) and among the lead researchers themselves, competing for recognition and maybe even the Nobel Prize. It is easier to have a successful collaboratory if the scientists themselves are already collaborative.

The goals of the subgroups need to be aligned (Birnholtz 2005; Chompalov, Genuth, and Shrum 2002). For instance, collaborations in which domain scientists (e.g., physics, biochemistry, etc.) and computer scientists work together to develop scientific software (e.g., UARC) are often plagued by competing goals. The computer scientists see the computer system as an object of research, and want the freedom to experiment and make changes with the software. Their goal is to publish novel ideas. The domain scientists, on the other hand, see the system as a research tool, and need it to be hardened and reliable (Weedman 1998). The computer scientists do not want to take time away from their research to continuously improve and support previous projects. Some more recent projects (e.g., BIRN) do not include computer science researchers as much as high-quality developers, whose goal is to make the software work for the users and work reliably overall.

In some cases, people recognize that others have reciprocally needed skills. That is, some collaboratories exist to share the equipment or unique skill sets of various laboratories. At the Great Lakes Center for AIDS Research, for example, the collaborators had complementary skills, making them natural collaborators (see also chapter 13, this volume).

Social Dimensions We have noted that when people *like* working together there is sufficient motivation to succeed. We also have seen that the collaboration is more likely to succeed when there is some benefit for all participants (Grudin 1988). On the other hand, we have seen difficulties when there are asymmetries in value to the participants. For example, a funder mandate to include non-R1 universities in a collaboratory often embodies unequal benefits, with the R1 universities feeling that they have more to give than receive. Additionally, a collaboration frequently fails when the prime motivation for it is driven by funding agency requirements (i.e., in order to get funded, you must collaborate). The Great Lakes Center for AIDS Research mentioned above, where the institutions were mandated to work together to secure funding, continued only until the funding source that mandated the collaboration ran out.

In a similar vein, it is important that people trust each other. If they do not, they must take time and attention to create contracts and sanctions for noncompliance (Shrum, Chompalov, and Genuth 2001). The three major aspects of trust are that (Rousseau et al. 1998):

- Others will keep their promises, called "confident expectations"
- They will produce with high quality
- One will not take advantage of the other's vulnerability

A group that feels empowered has a higher chance of succeeding than a group that does not—a concept called "collective efficacy" (Carroll, Rosson, and Zhou 2005). Building on the personal self-efficacy work of Bandura (1977), John Carroll and his colleagues developed a set of questions assessing how well the members of a team think that the *team* can overcome things like a shortage of funding or unforeseen events. Carroll and his colleagues have shown that groups that have high collective efficacy in the beginning are more likely to succeed in the end.

Management, Planning, and Decision Making

The way in which the work of a distributed collaboration is organized and carried out is critical to its success. The skills that leaders possess and the time they have to devote to running the collaboration, the effectiveness and timeliness of communication, the mechanisms for decision making, and the clarity of institutional and individual roles as well as responsibilities are all critical aspects of management. The larger the collaboration, the more significant these elements become (Cummings and Kiesler 2005; chapter 5, this volume).

Time and Attention It is important that scientists have time and resources to commit to a collaborative project. In science, it is common to have multiple projects going at the same time. A researcher proposes different research plans to a number of funding agencies, and with some probability each gets funded. It is possible, therefore, to have too many commitments to spend sufficient time on one or more of them to succeed. We have found that participants' overcommitments can be a serious problem for collaboratories. Recent research has shown that when working on multiple projects, some with people collocated and others with people who are remote, the collocated people get the time and attention, even though the projects are of equal importance (Bos et al. 2004; Fussell et al. 2004).

In collaboratories that span many time zones, it is difficult to find times in the normal working day when real-time conversations can take place. For example, one international AIDS collaboratory includes researchers from the United States, the United Kingdom, and South Africa (chapter 19, this volume), and a high-energy physics collaboratory we studied spans researchers from one hundred countries. Both have to schedule their meetings during the small workday overlap. With less overlap in the working day, participants have fewer opportunities to clarify information, develop common ground, align goals, and so on. All of these activities are necessary for difficult work to succeed, especially at the beginning of a project, before things have a chance of becoming less ambiguous and more routine. A key feature of science, to be sure, is that it is rarely routine. In addition, when participants are working in different time zones, their ''body clocks'' are set locally. When conversations exclude any cues as to the real time of day in the remote location, misunderstandings can occur. In a study of transatlantic collaboration among automotive engineers, we saw engineers in Detroit on a Friday late morning carry on a conversation too long, insensitive to the fact that their French counterparts were increasingly irritated because they were being kept from going home.

When people are remote and isolated, they are often ignored. Having a critical mass of people at each location ameliorates some of this. When people feel isolated, they feel less motivated to contribute, not owning the problem and not being asked to contribute in any way as frequently as those who are visible to each other and ''at hand.'' Projects should designate a point person at each location who will be responsible for making sure that all participants there are informed and contributing. One business strategy that may work in collaboratories is including a ''rotator'' at each location, someone from the other location(s) to serve as the eyes and ears for the remote people (Olson and Olson 2000).

Management A number of key factors leading to success in large collaboratories have to do with management. First, if there is not a critical mass at each location, the larger sites dominate. The smaller sites are likely to be ''out of sight, out of mind.'' When multiple institutions and/or different departments (disciplines) within the same university are involved, it is crucial to know who is serving in what role. It is particularly important to have a point person—one person to whom outsiders can go to in order to find out who can help in a specific situation (Sonnenwald 2003). Those projects left loose suffer when the participants' directions begin to diverge; if they have not assigned someone to take leadership to get the group back on track, or have not bought in to that person having that authority, failure is likely. Most funding agencies now require a management plan as part of the proposal. For example, the National Institute for General Medical Sciences, one of twenty specialized institutes within the NIH, requires applicants to its ''glue grant'' program to provide detailed descriptions of project management and organizational structure (chapter 11, this volume). The more seriously the scientists take that plan, working out exactly who will do what as well as what the dependencies are among the players and tasks (and assuring that few tightly coupled tasks cross organizational boundaries), the more likely the success.

We have found on numerous occasions that having someone with good project management experience is essential. Few scientists have been trained in project management, a set of known skills to ensure that roles are clear, planning is grounded in reality, and someone monitors the progress and helps resolve problems arising from unexpected events. Some collaboratories find that having a scientist serve as project manager helps to create respect and trust that decisions are made to further the science. Attendees at the NIH's Catalyzing Team Science (2003) workshop reported that having a postdoctoral fellow in a managerial role was an important benefit to distributed projects, and a major recommendation of that workshop was to create career paths for those who provide infrastructure to teams. Certainly understanding the scientific domain is critical, but in some cases it is wise to have a nonscientist project manager so that the scientists are relieved from administrative duties (Mazur and Boyko 1981). Some later collaboratories (e.g., BIRN) have made a case for hiring a project manager who is not a key scientist but has the skills to keep things on track. Ultimate decision authority resides in the principal investigators, but the day-to-day planning and monitoring is in the hands of the project manager. Funders and some scientists themselves balk at spending money on project managers instead of additional scientists, yet when the key to success involves the coordination of a large number of people, such skill has been found to be essential.

Strong leaders not only manage the collaboration well internally but are also effective externally, making the project visible. Visibility has several important effects: it can inspire other scientists to attempt such collaborations, and through public awareness can both increase science literacy and influence Congress to fund more research, as it did post–World War II.

Communication and Possibilities for Redirection We have also found that collaboratories do well to have a communication plan in place—one that clarifies expectations about when meetings will take place, who is expected to attend, how often e-mail will be answered, how to reach everyone, and who is responsible for what. The BIRN yearly meetings are "all-hands" events, with everyone expected to attend. This is a common practice in many of the collaboratories we have studied. Additionally, the more complex and interdependent the project, the more complex and frequent the communication has to be (Maznevski and Chudoba 2000).

Occasionally, a collaboratory discovers something that is unexpected, making the original plan of work no longer appropriate. For example, a large cellular biology collaboratory found that after two years of work, it needed to change its target molecules. Changing the directions of large projects in midcourse can be difficult, but this collaboratory had a strong decision-making process and management structure in place, thereby allowing the change to occur. Similarly, because of issues of trust or motivation, not all parties may turn out to participate as expected, yet funds are locked in for multiple years. Good management facilitates reflection, redirection, and a reallocation of resources. Successful collaboratories should do this as well. Many collaboratories have oversight committees or advisory boards that can provide this function; the NIH glue grants require them.

Institutional Issues Even when all of the scientists are ready to proceed, collaboratories can run into institutional-related problems, especially legal issues that cannot be resolved (Sonnenwald 2007; Stokols et al. 2003, 2005). A number of potential collaboratories have been stymied by their institutions' rigid policies about intellectual property. Some universities want to own or control what their professors discover or invent, especially in the highly commercial areas of biomedicine. Collaboratories that succeed have found ways to share the intellectual property and cooperate on other legal matters as well.

Similarly, financial issues can be barriers. In the international AIDS research collaboratory mentioned previously, a South African university required that the money be in hand before anything could be purchased, whereas the U.S. funder would issue a check only after the purchase had been made. This impasse was finally resolved after the U.S. and South African financial officers met in person (a trust-building move) and together worked out a compromise that fit both systems. They managed to arrange a local South African loan to allow the scientists there to purchase what they needed and the U.S. funder to reimburse them once the appropriate paperwork was in place, essentially paying off the loan.

Knowledge Management We have also noted that those collaboratories without good knowledge management plans often discover too late that data or records are lost. It is common for people to set up informal schemes for keeping records (e.g., minutes of meetings) only to find them inadequate when someone later tries to query the past. This is particularly important when the collaboratory includes people from a number of institutions and is active over a number of years, with key people rotating in and out of the project.

A critical part of today's knowledge management systems is a plan to migrate data when information technology becomes obsolete. For example, today's MRIs are born digital. The whole purpose of BIRN is to collect large enough samples of people with various kinds of schizophrenia and other mental disorders like Alzheimer's to make progress in diagnosis and cure (chapter 12, this volume). One of the challenges they will have to face is how to migrate the data to new technologies as they emerge so that the data are still accessible, say, twenty years from now. Digital preservation is an underappreciated problem that can have costly repercussions. The Protein Data Bank, established in 1971, is a good example of successful migration. It began with punched cards, but now has migrated to servers to hold its results of crystal structural analysis (Berman, Bourne, and Westbrook 2004).

Decision Making and Leadership Carl Larson and his colleagues (LaFasto and Larson 2001; Larson et al. 2002), in their study of six thousand team members and six hundred managers, found that certain aspects of collaborative decision making were important to the success of various projects. Decision making needs to be free of favoritism, and have fair and open criteria. Everyone has to have an opportunity to influence or challenge decisions. These are the seeds of trust, referred to in the organizational behavior literature as ''procedural justice'' (Kurland and Egan 1999).

All of the above management factors imply that an effective leader is heading up the collaboratory. An effective leader establishes the collaborative culture, ensures that the plans are in place, and sets the tone of inclusiveness. Collaboratory leaders also must be external spokespersons, keeping the projects visible and managing public impressions. The early visibility of UARC led to the re-funding of a modified project in SPARC. The NEES project was also aware of UARC/SPARC in its early deliberations in forming.

Technology Readiness

Virtually all collaboratories connect people via technology for both communication and core work. Many collaboratories use generic or commercially available tools like e-mail, instant messaging, data or videoconferencing (like WebEx or Centra Symposium), and basic file servers. Others use specially designed and built software, like the Environmental Molecular Science Laboratory's online laboratory notebook (chapter 6, this volume). The adoption of any technology, whether off the shelf or custom designed, is driven by its fit to the work (providing the right functionality) and ease of use (Olson et al. 2000).

The key is to understand the real needs of the end users, not to push ''cool'' technologies on people. The more user centered the development process, the more likely the technology will be used. The significance of the design process being user centered instead of technology centered cannot be overestimated (Beyer and Holtzblatt 1998). One of the issues with the slow uptake of the grid is the technology push rather than the users' pull (Daniel Atkins, personal communication to authors, 2005).

Similarly, scientists must feel comfortable using the technology. For instance, scientists who are just learning to make efficient use of e-mail will find it challenging to use desktop videoconferencing. It is too big a leap. Interestingly, the early versions of SPARC interfaces mimicked the physical instrument displays (looking the same as the original meters and dials) while the scientists got used to working online. When the scientists later became more comfortable with other online tools, they asked for—and the developers designed—more powerful integrated displays that collected information from a variety of sources. People's beliefs in their abilities to use computers correlate highly with their adoption of technology (Compeau, Higgins, and Huff 1999).

It is also important that all essential technologies give benefit to those expected to use them. As Jonathan Grudin (1988) has pointed out, if some users have to put in effort that only benefits others, the technology will not succeed. An early knowledge management system deployed at the National Aeronautics and Space Administration's

Astrobiology Institute was not adopted widely because it was cumbersome and people were uncertain what advantages the tool provided them. Additionally, in many of the community data systems, there is some concern that one will submit one's data only to have others get credit for the analyses, which could not have taken place without the accumulation of data (chapter 14, this volume). Solutions to this have been few but varied. For instance, the high-energy physicists put *everyone* involved in a project as authors, sometimes running in the thousands (Birnholtz 2006). BIRN has developed an authorship policy that acknowledges the BIRN database at a particular moment in time, and one can look up who the contributors were up to that point.

Technology readiness also involves reliability. If the technology is unstable (as some research proof-of-concept prototypes can be), people will be unlikely to use it. One aspect of reliability, interoperability, is an ever-present challenge for collaborative projects. Few applications are truly compatible across different platforms. Browsers, for example, render the same Web site differently, and some Word documents created on a Macintosh cannot be read successfully on a Windows machine. The success in collaboration is greater if the participants agree on a single platform. Notably, the early SPARC software ran on a NeXT machine; part of the grant budget was spent on giving NeXT machines to all participants (chapter 9, this volume). Similarly, BIRN developed and configured the hardware and software centrally, and shipped it off to each participating institution. The Astrobiology Institute attempted to standardize the tools that its members use for synchronous and asynchronous communication. For instance, it adopted and successfully deployed WebEx for its online meetings and seminars (Blumberg 2003).

It is crucial, too, to ensure that networking infrastructure supports the intended technology. For example, high-energy physicists from Morocco participating in ATLAS have serious bandwidth limitations, which in turn prevent them from participating in videoconferences. They are also even more concerned about getting the large amount of data that will be produced once the detector is operational.

Additionally, technical support at each location is important, especially when technologies are complex or there are new users. Remote systems support is inadequate; computers are physical devices that need onsite technical support. A technical coordinator is helpful in overseeing technical issues. BIRN, for example, is a cluster of four collaboratories, and has a "coordinating center" in support of all of them that handles all technical issues for the cluster (chapter 12, this volume).

There are some special technical issues with particular types of collaboratories as well. If data sharing is the goal, standards must be agreed on and adhered to by all participants (Hesse et al. 1993). Also, data archiving must be planned so that as technology becomes obsolete, the data integrity is maintained. If instrument sharing is part of the collaboratory, then there should be a plan to certify the users. In a high-energy physics collaboratory, say, the operators from different countries have different back-

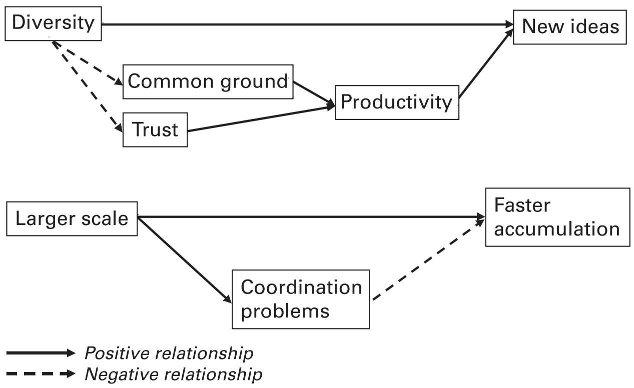

Figure 4.1
The key variables in TORSC showing the inherent benefits and costs of larger-scale efforts and multidisciplinary projects in science and engineering

grounds; in Japan they are technical staff, whereas in the United States they have PhDs in physics. The U.S. operators are having difficulty accepting the fact that the Japanese operators have enough skill for the job.

Discussion

The goals of all collaboratories are to enhance scientific discovery by having more people coordinate their work, use expensive instruments remotely, and engage in more creative activity by allowing people from diverse disciplines and backgrounds to come together. Five factors—the nature of the work, common ground, collaboration readiness, management, and technical readiness—all contribute to the success of a collaboratory.

Two key tensions (see figure 4.1) affecting the achievement of these goals have been identified: the greater the diversity, the less common ground and trust, which together impede the understanding of each other and the production of new ideas; and the larger the scale, the greater the coordination overhead, increasing exponentially rather than linearly (Brooks 1995).

Standards, management, and expectations all play a role in making these tensions as small as possible by finding ways to increase common ground and trust, and addressing the coordination problems by good management and decision making along with trust.

At its core, the theory states that revolutionary science will come about when scientists can work collectively and diverse points of view are brought to bear on a common problem (see figure 4.1). Technology, then, has its effect by allowing more diverse and

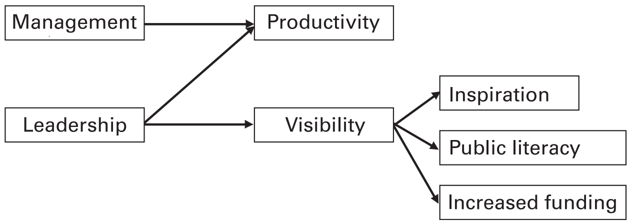

Figure 4.2
Additional key variables showing the importance of good management and leadership

distant groups of scientists to communicate with each other so that their collective work is coordinated (e.g., standards are developed or data are aggregated), and that some aspects of the work can be automated or enhanced (e.g., through visualization and computational aids). But coordinating across diversity and distance offers some particular challenges. As the community of scientists grows, management issues loom large (Kraut et al. 1990). How do we coordinate the various legal and intellectual property issues across the institutions involved? How do we develop standards that satisfy all parties? By the same token, as the diversity of the community grows (e.g., having molecular neuroscientists talking to anatomists to uncover the early signs and perhaps cures of schizophrenia), issues of trust and common ground loom large. How do we assure that we are using the same words in the same way? How do we trust the methods of data collection of others who were not trained in the way we were? TORSC highlights these key trade-offs, and points to areas where particular emphases or new remedial actions are called for. For example, larger and more diverse projects require a more detailed management plan led by experienced project managers, and may call for explicit workshops to engender trust and a common vocabulary.

Good management and leadership not only affect internal productivity but also make the project visible (see figure 4.2). Visibility leads to the possibility of inspiring other scientists to work in new ways, and to borrow tools and lessons learned from earlier efforts. It also can lead to public science literacy, and with pressure on Congress, the possibility of additional funding.

Using TORSC

There is nothing so practical as a good theory.
—Kurt Lewin, "Problems of Research in Social Psychology"

We foresee TORSC as having a number of uses: it can guide the design of high-value technologies; it can provide a framework for conducting evaluations of existing collaborative projects; and it informs strategic planning.

Implications for the Design of High-Value Technologies

TORSC provides guidance to technology designers by highlighting the key social and organizational processes that contribute to the success of collaborations. By identifying those processes that are important for collaboration, TORSC can help developers understand how to design technologies to specifically improve these processes in order to overcome the challenges of relying solely on general-purpose collaborative tools. In particular, TORSC suggests that there are opportunities to improve collaboration support by exploring technologies that create tools targeted to specific social processes as a way to supplement the shortcomings of using general-purpose tools alone, and by searching for abstract representations of information related to critical processes, rather than simply supporting conversations.

In geographically distributed projects, different information and communication technologies are often used in an effort to reproduce (or exceed) the benefits of collocated work (Hollan and Stornetta 1992). While collaboration technologies have yet to completely eliminate the effects of distance, many tools have made strides in helping groups to work well over distance. A common goal of many technologies, including videoconferencing, e-mail, and instant messaging is to enable frequent and ongoing conversation between individuals. This approach to supporting collaboration—emulating the constant conversation that goes on in collocated environments—is extremely widespread and successful.

During the course of the study of collaboratories that led to the development of TORSC, we observed a number of project teams taking a different approach to collaborative tool design. In contrast to technologies that leverage conversation to build trust and awareness, many of these projects were increasing the effectiveness of their collaborations by using technologies that specifically targeted one or more social processes related to collaboration success, using a highly specialized tool to alleviate a particular problem. In all cases, these specialized tools were used alongside general-purpose collaborative tools, but point to an alternate approach to designing collaborative tools based on the specific requirements of antecedents to collaboration success.

One example of these alternate design approaches can be found in the different ways projects have employed technology to support the establishment of common ground. The Mouse BIRN project (discussed above) developed a formal atlas to mediate the different languages of the subdomains involved in the project to support database federation, but scientists have also used it to facilitate cross-domain discussions.

A physical sciences project we studied employed data modeling to build common understandings of subdomains. The formalization of the data model was not nearly as important as the general relationships between concepts, as many data model presentations included the disclaimer "I realize this isn't proper UML, but I think it gets the point across." The value of the modeling language was as a collaboration tool rather than a modeling one. In contrast, a distributed engineering project held weekly technical meetings by videoconference to allow the sites involved in the project to present aspects of their work to other members of the collaboration. These meetings allowed the different sites to build a shared understanding of what was going on at other sites, but were also crucial in reconciling vocabulary misunderstandings and subtle domain differences between sites that represented different scientific fields. Frequent e-mail-list conversation supplemented these meetings.

One commonality in each of these cases is that the projects knew that the creation of a shared understanding was a critical problem facing the collaboration. Once the problem of common ground was well understood and identified, a number of different approaches to design were possible. The distributed engineering group took a mimetic approach, using communication technologies to build and maintain common ground through constant communication, as they would do if collocated. The Mouse BIRN repurposed a technology (the atlas) developed to mediate human-computer communications to support human-human communication. The physical sciences project adapted a methodology intended for another purpose, benefiting from the flexibility of using it incorrectly, rather than limiting its value but following all of the rules.

A Framework for Conducting Evaluations

In scientific research, evaluation is most frequently associated with summative evaluation that measures the outcomes of a scientific project. These outcomes often focus on the quantity and impact of the publications produced, the effectiveness of clinical trials, or the development of technologies that can be adapted for public use. Unfortunately, the true value of a project's output is usually not known until long after the project is finished. To supplement summative evaluations, we need to know more about what processes tend to produce high-value science. TORSC provides an opportunity for distributed projects to identify process and outcome metrics that can be observed early and often in projects, allowing evaluation to become a valuable tool for monitoring project progress and correcting problems along the way.

Formative evaluation is a method used widely in the field of human-computer interaction to understand the requirements of systems, and evaluate existing systems or initial prototypes in order to guide further system design. Formative evaluation frequently employs a variety of analytic methods (e.g., checklists, modeling, or heuristic evaluations) used by experts to predict potential problems or system performance. TORSC can be used as a framework for these kinds of analytic evaluations early in projects to provide administrators or technical coordinators with an understanding of where collaboration problems are likely to arise, and how investments in process changes or technologies might preempt those problems. The identification of key factors can be adapted for checklists or heuristic evaluations. By paying special attention to these processes, we believe distributed projects are much more likely to identify, understand,

Table 4.3
A portion of a script that could be used as a diagnostic tool in an ongoing collaboration

Interviewer: First, let's talk a little bit about your work in general.
1. To begin, tell me a little bit about the type of work you do, who you work with, where they are located, and your relationship with them.
2. For each of the remote workers, how dependent are you on their day-to-day activities? Do you have to coordinate often?
3. How routine is the work that you do? Does everyone know what they're doing? Are you following a standard practice, or are you making it up as you go?

and resolve process breakdowns as they occur, rather than leaving them unaddressed and out of control.

For example, one could imagine building a diagnostic script that asks various questions such as that in table 4.3, which is a portion of an interview script focusing on our first concept: the nature of the work.

The answers to a set of questions such as this would highlight the areas where management might want to put some attention and effort to ensure that the collaboration has the greatest chance of success. And where questions indicate some trouble—for example, a lack of trust—management consultants might recommend various remedies—say, trust-building activities or the use of contractual arrangements.

In providing an understanding of what factors contribute to collaboration success, TORSC helps make the collaboration process measurable and understandable, enabling new kinds of evaluation for distributed scientific projects. By embracing formative and ongoing evaluations, evaluation becomes a tool for maximizing project success rather than simply measuring it after a project is complete.

A Tool for Strategic Planning

In much the same way that TORSC can be used as a framework for ongoing evaluation within a project, the theory can be used as a strategic planning tool. It can help collaboratories decide what kind of geographically distributed projects to participate in and inform how they build capacity in key areas in order to improve their ability to succeed. By providing a set of criteria for comparing different organizations, TORSC offers some insight into the size and nature of the challenges that two organizations are likely to face in trying to work with each other. By understanding the magnitude and likelihood of these challenges before committing to a joint project, organizations can work to develop projects that are likely to match their capabilities. Similarly, organizations that wish to take on more ambitious joint projects can work to build up capacity in key areas. They can build common ground with a particular field, for instance, by hiring candidates with some background in that area or improving documentation practices to make the work more transparent to outsiders. As a strategic planning tool, TORSC offers a way to help organizations systematically improve their ability to collaborate across all projects in addition to within the context of a single project.

Summary

In TORSC, we have gathered the major factors that appear to be important in producing success in science and engineering collaboratories. Research is needed to illuminate the logical connections between the factors, and identify which factors are the most significant and under what circumstances they are operative.

We acknowledge that success can come in a number of forms, from encouraging the use of new tools, to changing the pool of people who become scientists, to enhancing the careers of those in the field, and ultimately, to providing revolutionary breakthroughs in both the conduct and outcome of science. These come about mainly through the judicious design and use of technology, and are enabled by social factors such as the development of common ground, trust, explicit management structures across sites, and the partitioning of work appropriately across sites. The major tensions come from the goal of having larger and more diverse sets of scientists working together, and the tendency in such large and diverse groups to have less common ground, lower degrees of trust, and the need for stricter coordination and management. By facing these tensions and finding remedies in a new focus on key factors, we expect to see an increase of successful collaboratories in the future.

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