71

Information Technology Research

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In the first decade of the twenty-first century, firefighters in the wilderness abandoned their old tools of handwritten reports and fire hoses and adopted new ones such as wireless Internet relays and airborne fire-retardant drops. These changes were made possible by research that brought researchers together across the chasms that traditionally separate disciplines such as computer science and biology. Increasingly, policy makers have recognized that many great advances have been the products of interdisciplinary work: the discovery of DNA structure, magnetic resonance imaging, laser eye surgery, radar, and the green revolution are a few examples. Interdisciplinary work has spawned new fields and areas of investigation such as cognitive science, oceanography, nanotechnology, genomics and proteomics, bioinformatics, human-computer interaction, and neuroscience. Nonetheless, interdisciplinary research, to the extent it departs from normal science, is risky for researchers and the organizations that support this work financially.

How, then, does interdisciplinary research happen? A groundbreaking initiative at the National Science Foundation (NSF), called Information Technology Research (ITR), provides a window on this process. ITR started in the year 2000 and spanned all the divisions of NSF. This chapter describes ITR's history, the kinds of work it supported, how it was administered, the experiences of the researchers themselves, some of the problems encountered along the way and how NSF, universities, and investigators responded. The chapter ends with a discussion of what we can learn from this pioneering program of research and what more we need to learn. As scientific research increasingly occurs in teams (Wuchty, Jones, and Uzzi 2007) and virtual organizations that cross boundaries of intellect and culture (Finholt and Olson 1997), we face important new problems in leveraging these changes.

Brief History

The ITR program emerged in a context of concern for the status of U.S. science in the world. Leaders in science, industry, and politics increasingly recognized the tremendous role of technology and science research in advancing society and lives. Many of today's most innovative businesses (Genzyme, Google, IBM, Novartis, Red Hat, and Twitter, to name a few) began with scientific research and technological innovation. Growth in the economy and our standard of living depends on research, whether this be research into rice crops, computer logic, or the causes of chronic disease. In a parallel trend, the development of complex computer-based methods and tools has increasingly necessitated the interaction and fusion of different technical expertise and disciplines (Gibbons et al. 1994). These changes have caused a rise in the significance of interdisciplinarity and collaboration. For instance, advances in computational biology depend on collaborations in computer modeling, statistics, and genetics. Finally, the need to share expensive research resources, to manage huge amounts of information, and to overcome disciplinary silos to solve social problems, has pushed science policy toward externally generated priorities (for example, Insel et al. 2004). Those goals have led to a tighter meshing of research with societal missions, and a closer relationship between basic research and industrial application (Llerena and Meyer-Krahmer 2003).

To meet these priorities, agencies in the United States, Europe, and Asia have sponsored a wide range of large research projects such as the European Large Hadron Collider to investigate particle physics, the multinational Antarctic drilling project to investigate climate change, and the Human Genome Project to investigate human DNA (Collins, Morgan, and Patrinos 2003). Networks of relationships still motivate many interpersonal collaborations (Blau and Scott 1962; Tichy 1981), but these new investments, and the increasingly rapid application of science and technology to products and services in agriculture, finance, energy, health care, transportation, communication, and entertainment has increased the size of the science enterprise, its costs, stakeholders, and structural complexity. Policy makers have grappled with the question of how the NSF, the leading institution responsible for the support of scientific disciplines and technology in the United States, can leverage advances in technology by supporting interdisciplinary science across its many divisions.

In 1997, the President's Information Technology Advisory Committee (PITAC) was charged with advising the president on high-performance computing and communications, information technology, and the "next-generation Internet." PITAC's influential 1999 report, "Information Technology Research: Investing in Our Future," proclaimed that information technology created unprecedented possibilities for advancing knowledge across the spectrum of human endeavors, including scientific research, education, engineering design and manufacturing, environmental systems, health care, business, entertainment, and government operations. The report further asserted that the United States was "gravely under-investing" in information technology research. In response to the PITAC report, the NSF created what it called a "priority area" initiative, ITR, to encourage and stimulate interdisciplinary research.

Meanwhile, NSF had already begun a modest initiative known as knowledge and distributed intelligence or KDI. NSF developed KDI as a foundation-wide two-year interdisciplinary research program. The purpose of this program was "to span the scientific and engineering communities . . . to generate, model, and represent more complex and cross-disciplinary scientific data from new sources and at enormously varying scales" (http://www.nsf.gov/cise/kdi). The competition was fierce. NSF supported just 40 awards of 697 proposals in 1998 and 31 awards of 554 preproposals (and 163 full proposals) in 1999. Projects were supported at $1.5 million each, on average, and were to run three or four years.

The PITAC report echoed the arguments for KDI. Science policy makers recognized that the explosive growth in computing power and connectivity was reshaping relationships among people and organizations and transforming the processes of discovery, learning, and communication. These policy makers recognized an unprecedented opportunity to study more complex systems than was hitherto possible and to advance our understanding of living and engineered systems. To achieve these goals, NSF would need to foster more interdisciplinary research, especially projects including the computer sciences and the other sciences and engineering. A KDI goal was to support research that would model and make use of complex and cross-disciplinary scientific data. The research would analyze living and engineered systems in new ways. It would also explore the cognitive, ethical, educational, legal, and social implications of new types of learning, knowledge, and interactivity. It would foster scientists sharing knowledge and working together interactively. In an editorial in *Science*, Richard Zare (1997:1047), chairman of the National Science Board and professor of chemistry at Stanford University, wrote, "This knowledge and distributed intelligence (KDI) initiative [will] promote collaborations that seem long overdue, such as linking the science of learning and cognition with the development of technologies for teaching and learning."

The ITR initiative got started as KDI ended. ITR's official purpose was to encourage innovative, high-risk, and high-return multidisciplinary research that extended the frontiers of information technology, improved understanding of its impacts on society, helped prepare Americans for the information age, reduced the vulnerabilities of society to catastrophic events, whether natural or man-made, and augmented the nation's information technology knowledge base and workforce. ITR was seen as advancing visionary work that could lead to major advances, new and unanticipated technologies, revolutionary applications, and new ways to perform important activities. These were not empty claims. NSF funding for computer sciences was doubled by the ITR initiative, and, especially in its investment in sizable interdisciplinary visionary and socially relevant projects, the ITR represented a major step to advancing interdisciplinary technology research.

The project created two real-world deployments of tracking collars on zebras in central Kenya.

Another highly interdisciplinary project was called "Simulation-Based Medical Planning for Cardiovascular Disease." The project's goal was to transcend the existing paradigm for the treatment of congenital and acquired cardiovascular disease, which relied exclusively on diagnostic imaging to define the present state of the patient. Led by Charles Taylor of Stanford University, the project created a new paradigm for predictive medicine in which the physician uses computational tools to construct and evaluate a combined anatomic/physiologic model to predict differential changes in blood flow for alternative treatment plans for an individual patient. A surgeon using such a system could do if-then predictive planning for surgery to consider possible approaches and effects. The project helped create a new computational medicine subfield that combines models of the human vascular system directly from medical imaging data, and modification of these models to incorporate multiple potential interventional and surgical plans, simulate blood flow in these patient-specific models, and visualize and quantify resulting physiologic information. This approach may revolutionize the cardiovascular interventional and surgery planning process from the present approach that is based solely on diagnostic and empirical methods to one that incorporates predictive simulation-based methods.

A third project, headed by Ali Hurson and called "Integrating Smart Sensing, Data Mining, Pervasive Networking, and Community Computing," had the goal of monitoring, preventing, and recovering from natural and inflicted disasters. Teams from four universities proposed to create a novel technology-enabled security framework, called Pervasively Secure Infrastructures (PSI), making use of such advanced technologies as smart sensors, wireless networks, pervasive computing, mobile agents, data mining, and profile-based learning in an integrated, collaborative, and distributed manner. This multidisciplinary, multi-university project aimed to create efficient data collection and aggregation from heterogeneous sensors and monitors; novel techniques for real-time, secured, authenticated information transmission and sharing; and intelligent situation awareness (e.g., threat detection and security services) through new learning, data mining, and knowledge discovery techniques. The project focused on authentication and secure data transmission in wireless networks that could efficiently handle dynamically changing information, adapt to changing situations, and provide scalability in the number of users, devices, and data sizes.

A fourth example is "HomeNet Too: Motivational, Affective, and Cognitive Antecedents and Consequences of Home Internet Use," headed by Linda Jackson of Michigan State University. This was an interdisciplinary project of social psychology, cognitive science, and information systems faculty to install computers and Internet connections in low-income households and to study the impact over time of using the Internet in these families. The project provided Internet access and help to 120 adults and 140 children in low-income urban neighborhoods in Lansing, Michigan. Most households were African American and female-headed families with incomes less than $15,000 annually. The children averaged 13.8 years. A startling study result was that, controlling statistically for their baseline scores, children who used the Internet more frequently later showed higher grade point averages and higher scores on standardized tests of reading achievement than did children who used the Internet less. This work was the first that demonstrated to policy makers a clear outcome of investment in Internet access in schools and homes. It is possible that the ITR was the only program that could have supported the level of effort required to involve students, adults, and children in low-income communities, schools, and faculty from different disciplines in this important project.

Taken as a whole, the ITR broke new ground in many ways. It addressed compelling national needs that no other program in NSF could meet. No other program was able to support research within computer science while applying this research to one or more other disciplines, or as one principal investigator (PI) reported at a PI meeting, "discipline with the interdisciplinary." Also, no other program was able to support the same level of commitment to outreach—to students, to teachers, to small businesses, to nonprofit groups and foundations, and to online communities.

ITR Administration

In accordance with its goals of significantly expanding the depth and scope of interdisciplinary research, ITR was a five-year NSF-wide priority area, a major NSF initiative, growing from US$90 million in 2000 to US$295 million in 2004. Separate peer-review panels coordinated within the computer science directorate made three kinds of awards:

The ITR initiative was especially difficult administratively because of its success. ITR offered researchers opportunities to create new collaborations and projects, which made it extraordinarily popular in information technology communities around the United States. The number of proposals increased from approximately 2,100 proposals in 2000 for the first year of the program to more than 3,100 proposals by 2004. Its popularity spread to other disciplines, supported by other divisions at NSF. Proposal pressure grew, and as it grew, NSF had to impose a new proposal submission limit, one proposal per PI. Even with increased ITR funds, the program became more competitive over time. In 2000, 30 percent of the medium and large proposals were funded; in 2001 and 2002, 27 percent; in 2003, 24 percent; in 2004, 21 percent. At the same time, proposal project budgets were reduced more in the latter years of the program. In year 2000, medium and large projects received 76 percent of their proposal budget; in year 2001, 68 percent; in years 2002 and 2003, 50 percent, and in year 2004, 49 percent.

Another change occurred in the locus of projects. At the start of ITR, most projects received major funding from the Computer and Information Sciences and Engineering Directorate (CISE), but other divisions pressed for funds, impelling a broader distribution of awards across the foundation and disciplines. Ultimately, more than 70 percent of the projects involved two or more disciplines, with roughly 50 percent of senior researchers from computer science and the remaining senior researchers coming from engineering, physical sciences, and other sciences.

Experiences of Researchers

As the ITR reached programmatic maturity, NSF's Suzanne Iacono asked the authors of this chapter to organize a meeting with ITR PIs. We invited the PI and a co-PI from each of the medium and large projects to the workshop; a total of 379 PIs and co-PIs attended along with 37 NSF officers. At the workshop, the researchers, organized into small groups, discussed with one another how their research projects were organized and managed, the kinds of outcomes they hoped to generate, and the ways in their experience could inform future interdisciplinary research programs.

ITR researchers at the meeting said the initiative had given them license and incentive to pursue interdisciplinary research and education by providing substantial funding for innovative work and that there was no other place to obtain that kind and level of support in a highly competitive funding environment. They said the ITR helped create new communities of interdisciplinary researchers and was a rallying point for vertical collaboration within computer science departments and horizontal collaborations across the sciences and engineering. They named new interdisciplinary courses, new collaborations with industry, and new relationships with the public. They said ITR enabled economies of scale in people, equipment, and data resources. For example, it provided funding for collaborations among statisticians and researchers in artificial intelligence and machine learning to visualize and model huge data sets ranging from photographs of cities to detailed economic data. It enabled people from multiple disciplines to tackle larger problems with new technology—problems ranging from global warming to economic recession. It provided time to cross-train students for new fields and new kinds of positions using technology. One participant said, "it was a humbling experience, discovering how narrow you are."

Despite all this enthusiasm, researchers described strains. Interdisciplinary research can clash with the incentive structure of disciplines and departments. ITR researchers said they had pushed a few computer science and science departments, and some universities, to adapt their formal reward and tenure system to interdisciplinary research. One researcher said, "Our president has created a university-wide review system, independent of departments, to review promotion and tenure cases for faculty who are conducting funded interdisciplinary research. He feels this is the future and we have to adapt to it." These changes were comparatively small, however, and many junior faculty avoided undertaking major ITR project responsibility; 80 percent of listed senior personnel on ITR projects already had tenure.

In addition to the problem of entrenched department cultures, researchers on ITR projects had to learn to work with others unlike themselves. They had to cross-train students, to develop a coordination infrastructure and management team, and to learn and appreciate one another's language and scientific goals in more than a superficial way. Five years, they said, is a minimum number of years; many projects got their first breakthroughs only after three years or even more. ITR researchers were inventive in coming up with new ways to manage and now working and publishing with their ITR partner. Thus, if researchers did not have a productive relationship already, getting funding for a new collaboration within the ITR was fraught with the peril of not accomplishing anything together. NSF responded to these data by requiring, starting in the 2004 funding year, that all project submit a "coordination plan" showing how researchers would organize to collaborate. This step might have forewarned researchers to plan the management of their project, but our later work shows that collaboration across distance and discipline, without prior experience, remained a daunting barrier to research.

Lessons From the ITR

To the regret of many ITR researchers, the ITR initiative ended in 2005 without a comparable successor program. As of 2010, some ITR projects remained active, and others had obtained follow-on funding for work started with ITR funds. New (albeit smaller) crosscutting NSF programs such as Virtual Organizations, Social-Computational Systems, and Cyber-enabled Discovery and Innovation make interdisciplinary awards. Thus, lessons learned from the ITR experience should be valuable for the future.

ITR encouraged risky research. Risky research takes time and incentives to develop, and during this time, researchers need to make progress on their research. There has to be a high payoff to compensate for the high coordination costs in this type of work. One PI recommended that NSF hold a workshop on the management of large-scale projects. "It seems to me that an alternative and equally worthwhile subject or additional training would be management skills. As faculty members and researchers, we have almost no training for running our research operations—often equivalent to a half-million dollar or more per year startup."

Some argued that NSF, and particularly CISE, needs to institutionalize interdisciplinary research and peer review beyond workshops by designating an office and officers whose task is to review and promote interdisciplinary work. This office should have a primary rather than secondary focus on interdisciplinary results and real-world application of information technology. For example, one ITR project experimented with new sensor technology to help in managing and tracking livestock. Although the Department of Agriculture has development projects in this area, for continued work on this topic, NSF research communities could provide more scientific depth and rigor. A staff focused on interdisciplinary work also might have a budget for management support for coordination and for creating panels whose job is interdisciplinary peer review. ITR panels built a community and a culture supportive of interdisciplinary IT research, and a sensitivity to nontraditional outcomes. As one PI put it, "The ITR interdisciplinary program involved a chicken-and-egg challenge to peer review since there were no peers who could evaluate ITR proposals. In other words, it should be recognized that the challenge was about generating a new culture. This successful endeavor should continue. It takes time to establish a culture." Another said, "What's next? So don't pull out the rug. How do we continue, follow-up? Will we put together an interdisciplinary proposal and have it wind up facing single-discipline review?"

Many other ideas came out of the ITR experience, some of which the NSF has adopted. The ITR allowed for support of postdocs, professional programmers, and undergraduates. New interactive applications were developed for K–12 students. Project recruitment efforts focused on diversity, including women and minorities. Funds were available for workshops, which brought together multidisciplinary communities to discuss research, analyze results, and brainstorm future directions.

Outstanding Issues

The ITR has exposed some important fault lines in our knowledge of successful, productive interdisciplinary collaborations. Here are four open research questions for future research and experiments in collaboration and interdisciplinary work.

Large Projects

Predicting an optimal project size remains an important issue. ITR projects were large enough to induce industrial partners to share resources, including source code. They were large enough to build tools not otherwise possible. ITR increased the ability to conduct empirical studies that could inform policy and to produce technologies that could transition to use in government, industry, and education. To achieve these outcomes, interdisciplinary research requires that collaborators behave as peers and that one discipline does not dominate the budget or the intellectual agenda, leaving the other disciplines as token participants. Use of advisory committees and consultants, although helpful in expanding the perspective of some disciplinary projects, is insufficient investment. An interdisciplinary program must provide support for teams of PIs in more than one or two disciplines. Truly innovative work will depend on these projects drawing on substantial rather than token expertise in all the relevant areas. Innovative work also requires resources for administration, oversight, and maintenance of technology that does not have commercial value but does have value for the national and public good.

Conversely, there are real problems entailed in large projects. First, with larger projects, the demand for accountability rises markedly, increasing time spent in site visits, meetings with sponsors, reports, and untimely requirements for progress. Further, it is often expected that the number of investigators must increase in proportion to the project budget. Yet increasing the number of PIs on a project is not necessarily appropriate for the science to be done. In recent retrospective interviews with ITR award recipients, many said they did not know how to reduce the costs of projects with more than a few investigators. Respondents viewed multiple PIs as complicating project structure and reducing the likelihood of successful collaboration.

> I personally think two is a good number and three's okay, but four and above, yeah, it would have to be a really large project with well-managed smaller pieces. I just see that as impractical for the way academia is structured. (Researcher #11)

> I think it would be sort of complicated, tedious or boring, probably not very efficient to have say, you know, a weekly conference call with five people, or with five kinds of senior people and a bunch of students. . . . It's not very productive. (Researcher #38)

Currently, the way some researchers seem to be adapting to the advent of large projects is to collaborate in obtaining these awards whereupon they divide the budgets and continue their own work (see "Integration" later in this chapter). This understandable behavior is one of the real trade-offs entailed in large and multi-investigator projects and collaborations, but the impact is not well understood. The "sweet spot" where we gain the best outcomes from different project sizes in the short and long term are not yet well understood.

Geographic and Institutional Differences

Throughout ITR, its review panels and NSF privileged proposals with PIs at multiple institutions. We know this because we compared a sample of 549 anonymous, unfunded proposals from the first four years of ITR (provided to us by NSF) that were matched with our sample of 549 funded proposals. The matching criteria were the size of their proposed budgets and the research and development (R&D) expenditures of the institutions that submitted the proposal. (R&D expenditures are a proxy for institutional reputation and status.) The resulting statistical model included as predictors the year of the proposal, whether it was a large or medium proposal (each category having its own peer review panel), the number of investigators, and number of universities involved in the proposal. The dependent variable was a bivariate variable: whether the proposal led to an award. Logistic regressions assessed whether the number of universities predicted whether a proposal was awarded a grant. Controlling for other variables in the model, the number of universities was a highly significant predictor of whether an award was made ($\chi^2 = 10.4$, $p < .01$). This analysis supports the claim that peer reviewers and NSF favored proposals when more universities were involved, controlling for the sheer number of investigators (Cummings and Kiesler 2007).

The reason for pointing to this phenomenon is that, unquestionably, more institutions in a project, compounded with disciplinary differences, create higher coordination costs for researchers and reduce their chances of success. Differences in discipline and university raised barriers to forging a successful collaboration (Cummings and Kiesler 2008). In fact, institutional differences were an even bigger barrier to collaboration than were disciplinary differences. Furthermore, an analysis by the authors in 2009 of post-ITR publications of a sample of 2,800 PIs, controlling for their pre-ITR productivity, indicates that a combination of multiple disciplines and institutions represented in a project significantly reduced PI publication output. These results suggest that even as time goes on and collaborators have a chance to get to know one another better, projects may not recoup losses from institutional and disciplinary differences present at the outset of the project.

Integration

The ultimate aim of ITR and interdisciplinary programs today has been to create research teams that can integrate diverse perspectives and expertise into new knowledge, methods, and products. Integration is not the same as collaboration or coordination. Collaboration can occur without coordination or integration, as in an alliance or a project in which PIs work in parallel under the same theme. Coordination supports the smooth functioning of a project and consists of behaviors such as joint meetings, common websites, division of labor, and other such mechanisms to get the work done within budget and deadlines. Integration is a higher goal, a melding of visions, mental models, and intellectual property such that the substantive outcome is a coherent combination of the team's work products. The ITR, ideally, supported integrated outcomes—something beyond what would have occurred if each of the PIs had been funded separately.

Recently, 55 retrospective interviews were conducted with ITR PIs and co-PIs (Balakrishnan et al. 2011), finding examples of integration, as the following quotes suggest:

> We couldn't carve up the tasks very easily. Everyone had to work together on this. (Researcher #6)

> And so in order to do any of the computer vision and machine learning work we needed to have the images. (Researcher #15)

> And so a lot of the code in my group has been written with a computer scientist and an astronomer working side-by, literally, sitting side-by-side at a single keyboard. (Researcher #19)

Nonetheless, the results suggest that only about one-third of the projects achieved significant integration. Many forces caused research teams ultimately to become fractionated into separate individual and subgroup cliques. For instance, during the initiation phase of their ITR project, project progenitors' main priorities were to assemble a team and to create a coherent proposal. Proposal criteria, departmental tenure requirements, departmental faculty make-up, and the location of close ties all affected the composition of a project team. Some PIs found collaborators who had the necessary credibility and expertise to win funding but then a lack of familiarity interfered with team chemistry and encouraged members to work with team members they already knew, usually in the same department. Moreover, researchers often did not have integration as a personal goal.

> And it was like, well, why would I want to build a personal relationship and start work with someone else here when I could work with my buddy? It's more fun. (Researcher #30)

> There was really not much, you know, cross-university research. After it was funded, you were able to do research independently. So, you know, a lot of good research came out. (Researcher #47)

Others agreed with the goals of integration but the realities of the local environment caused them to suborn these goals for more important objectives such as preparing graduate students for the job market.

> And yeah, it's partly driven by the pressures of publication, because it's related to, for graduate students, "Can I get a good job after I graduate?" . . . I mean me and my group and my students, while they are crosscutting, there is a pressure, especially coming from the students, that they want to be able to publish, write papers and publish within their own well-defined communities. (Researcher #45)

The question of integration in interdisciplinary work—whether it is a realistic goal, whether it can be managed or is more a question of mere contact, and how to estimate the probabilities, benefits, and costs—remains important for the future.

Understanding Collaboration

Despite two decades of research on collaboration (e.g., Dourish and Belotti, 1992; Olson and Olson 2000; Hinds and Kiesler 2002), this domain remains more descriptive than theoretical. Lacking theory, it is hard to make predictions for the success and failure of collaboration and to base policy on fundamental principles. One particularly relevant field, that of organization science, which is theoretically driven, has until recently neglected university research and research organizations as a focus of study. Significant progress will come from advances in the theories that address related problems, such as organizational coordination (Malone and Crowston 1994; Crowston 1997), organizational learning (March 1991; Argote 1999, Lakhani and von Hippel 2003), innovation (Cohen and Levinthal 1990), and social networks (Monge and Contractor 2003). As an example of the gap, coordination theory does not address very well the issues of coordination in large scientific teams. In such teams, coordination costs may be exacerbated because division of labor, task specialization, and bureaucratic rules (which aid coordination) may be unsuited for important parts of the work. Science ultimately is a creative activity in which transformative discoveries can require changing goals, collaborators, or tasks midstream, each of which poses coordination challenges. Coordination theory offers a productive lens for studying these challenges in scientific organizations and for advancing theory as well. The theory might help us understand the trade-offs between formal organization, which rationalizes routine workflow and resources, versus creativity, which may not be readily rationalized. At what point do large organized projects, with their many strings that tie people together and coordinate work, sacrifice creative advances in research? Current theory is not yet situated for addressing these kinds of questions.

Conclusion

The ITR initiative was a pathbreaking venture of the National Science Foundation, enabling significant interdisciplinary collaboration between computer science and other scientific fields. ITR's size and scope, diversity of topics, far-reaching ambitious goals changed the way technologists and scientists interacted and made progress. ITR exposed new opportunities and challenges of interdisciplinary technology research. Describing those opportunities and challenges helps clear a path into the future.

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