IMPLEMENTING A "BOTTOM-UP," MULTI-SECTOR RESEARCH COLLABORATION: The Case of Texas Air Quality Collaboration[1]

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Introduction

Long a topic of interest, inter-institutional and multi-sector research partnerships have received increasing attention of late, not only from economists (e.g. Madhok and Tallman, 1998; Olson and Olson, 2002; Branstetter, and Sakakibara, 2002) but from scholars in a variety of disciplines (see Hagedoorn, Link and Vonortas, 2000, for an a review and synthesis of the academic literature and of public policy initiatives). Indeed, in the U.S. the past three decades could be credibly termed the "era of inter-institutional research collaboration," as U.S. science policy[3] has moved from decentralized support of small, investigator-initiated research projects to more centralized, block grant-based, interdisciplinary research centers (Bozeman and Boardman, 2003).

The study of research collaboration has been hindered to some degree by a conceptual muddle in which too little attention is paid to differences between research collaboration, partnerships, alliances, joint ventures and consortia, to name just a few of the possibilities. We prefer the term "collaboration" because it is neutral, has no obvious strategic connotation, and is encompassing. But the term research partnership is also quite close to our meaning. The Council on Competitiveness (1996, p. 3) defined research partnerships as "cooperative arrangements engaging companies, universities, and government agencies and laboratories in various

[3] In the U.S., a series of technology transfer policies (Bayh-Dole Act, Stevenson-Wydler Act, and Cooperative Research Act) in the 1980s enhanced interaction among researchers throughout R&D organizations. In particular, some technology programs such as Advanced Technology Program (ATP) require inter-organizational collaboration for funding and research. While some of the centers programs (e.g. Engineering Research Centers; Science and Technology Centers, Nanoscience and Technology Centers, Industry/University Cooperative Research Centers) of the National Science Foundation specifically require inter-institutional collaboration, it is an element of almost all their funded centers.

combinations to pool resources in pursuit of a shared R&D objective." While this is quite close to our meaning for research collaboration, we note small differences between this definition of research partnership and our definition of a research collaboration: (1) some of those involved in the collaboration may not view themselves as "research partners," but as, among other possibilities, funding agents, resource providers, or priority users of the knowledge; (2) the Council definition does not explicitly concern itself with the fluidity and dynamism of collaboration. Thus, our reformulated definition of inter-institutional research collaboration is *"cooperative arrangements among the producers of scientific and technical knowledge, research managers, the priority or privileged users of the knowledge, and those providing funding and other support for the joint activity."* This is a more encompassing definition, but one we prefer because the effects of collaborations are not fully explained by focusing only on the producers and first order users of the research. Our case analysis of the Texas Air Quality Study underscores this point.

The Heuristic Value of the Texas Air Quality Study

While we know the vast majority of research collaborations between firms are informal (Link and Bauer, 1989), little research has focused on informal, inter-institutional research collaboration, in part because by their very nature these collaborations are difficult to study systematically (Hagerdoorn et al., 2000). The particular case of research collaboration we examine in this paper, the Texas Air Quality Study, provides a unique opportunity to study this under-examined yet prevalent form of research collaboration.

We consider this opportunity unique for two reasons. First, while informal, the Texas Air Quality Study (hereafter the "Texas Collaboration") constitutes one of the largest environmental research collaborations yet undertaken – a consortium of more than 300 researchers from over 40 universities, private industry groups, federal laboratories, and state regulatory entities. Notably, the Texas Collaboration shows the potential for very large scale "bottom up" collaboration. In an era characterized by politically-envisioned, government-structured science and technology centers and by stable, formalized infrastructures for the conduct of "big science," the Texas Collaboration is an anomaly. The Texas Collaboration produced many of the same categories of results that agency heads, governors and other political leaders seek to induce, but achieved them in a different, more fluid, more informal way.

Another reason to study the Texas Collaboration is that it is a research collaboration occurring not only across institutions but also across sectors. Link and Bauer (1989) have shown that most multi-institution collaborations are within the same sector, chiefly the private sector (Link and Bauer, 1989). Moreover, while managing and implementing large research collaborations is inexorably complex, the complexities multiply when crossing institutional and sector barriers, not to mention disciplinary barriers. Compared to its same-sector counterpart, the multi-sector, multi-institutional research collaboration is generally presumed to have broader public goods implications, is generally more complex in structure, and often consumes enormous resources (Bozeman and Boardman, 2003).

Research Objectives and Theory Context

In this study we demonstrate the ways in which large-scale, inter-institutional collaboration can flow from relationships that are initially informal and person-to-person. While the acorn to oak phenomenon of large projects beginning from personal ties is well recognized, it is not much researched. Our chief objective in examining the Texas Collaboration is to assess the impacts of various characteristics of the Texas Collaboration on the project's outcomes, thereby distilling possible implications for a theory of research collaboration effectiveness, at least within the rather limited domain of large-scale, multi-institutional, multi-sector research collaborations.

We use a model of collaboration effectiveness to guide this analysis, keeping us focused on particular sets of variables. The model, which we term, "A Contingency Model of Research Collaboration Effectiveness" was developed by the authors from the literature on research collaborations as well as from previous case studies developed by researchers at the Research Value Mapping Program (www.rvm.gatech.edu). The model (see Figure One below) focuses on (1) attributes of the collaborating researchers; (2) attributes of the collaborating institutions; and (3) attributes of the research collaboration process and its management. Thus, our underlying interpretive model seeks to examine multiple levels of analysis, not only the interactions of individual scientists but also of structures and institutions. Case studies are particularly well adapted to this type of multi-level analysis.

-Figure One goes here-

Though our study is neither a literature review nor a literature synthesis, we use the literature in the structuring and interpretation of our model of collaboration effectiveness. It is important to understand the positioning of our model and case study in the extensive research collaboration literature. In the first place, there is a wealth of research, most by sociologists and social psychologists, at the individual level of analysis, particularly collaborative patterns among teams of researchers (for review and synthesis of this literature see Beaver and Rosen, 1979a; Melin, 2000; Katz and Martin, 1997; Bozeman and Corley, 2004). Our study is informed by this individual-level research and we examine attributes of individual level collaboration, though our primary focus is on inter-institutional research. The more microscopic research and theory of individual-level collaboration actually employs many of the same variables as the institutional-level analyses but often from the perspective of a different theoretical tradition. Thus, it is worth noting that individual-level studies of researcher collaboration show us that collaboration choices are governed by a wide variety of factors including inter-institutional structures (Landry and Amara, 1998), formal (Wen and Kobayashi, 2001) and informal (Bozeman and Rogers, 2002) research networks, research alliances and covenants (Pisano, 1991; Rogers and Bozeman, 2001), and arrangements for sharing expensive or scarce scientific resources and equipment (Kevles, 1995). When one says “collaboration” it is useful to provide additional information about the type of collaboration and its organizational and institutional framework.

The research in economics and management focuses less on individual scientists' patterns of research collaboration than collaborative relationships among organizations and institutions. Hagedoorn and colleagues (2000) have provided an excellent review of these literatures, one of sufficient depth that there is no need for us to recapitulate (instead, we integrate these literatures into our analysis of our case study findings below).

It is worth noting that the organizational and institutional level studies of research collaboration are very different in one respect from the individual level studies. In the organizational level studies (e.g. Katz, 1996; Sinha and Cusumano, 1991) research collaborations are almost always assumed to be positive in their impacts on productivity or, when empirical tests are provided, the empirical findings (e.g. Link and Bauer, 1987; Scott, 1996; Link 1998) report a positive relationship (for an exception see Becker and Dietz, 2004). In the individual-level studies the findings are much more mixed (see Katz and Martin, 1997 for an overview), with some studies showing productivity benefits from collaboration, others indicating that transactions costs offset the benefits of collaboration, and at least one study (Bozeman and Lee, forthcoming) showing that the particular measures used are vital to understanding impacts. The vital difference in the individual level studies and the institutional level studies is that the former typically use a stable and easily operationalized set of dependent variables related to publication counts and impacts, whereas the latter generally use a diverse set of economic productivity measures.

In their taxonomy of research partnerships, Hagedoorn and colleagues (2000) suggest two particularly important supra-categories, the institutional type of the partners (business, government, university) and the level of formality of the agreements. Case studies are useful in fleshing out various aspects of their typology. In our analysis, we examine that part of the Hagedoorn and colleagues taxonomy that could be labeled "multi-sector, multi-institution" and "informal." As mentioned, we feel this is an unusual type, but one of the advantages of case studies is using idiosyncrasy and distinctiveness to provide empirical findings and theory against which to gauge the typical (Campbell, 1975).

Empirical Evidence and the Case Study

Before developing the case, it is worth noting that our approach to the symposium topic, "Empirical Evidence on Knowledge Flows from Research Collaborations," is different in certain obvious respects from others'. The empirical evidence we examine is based on qualitative data, chiefly telephone interviews. While decidedly "empirical," the data require interpretation.

As is generally the case with case studies, we made no attempt to completely standardize our telephone interview questions; the questions were to a considerable extent tailored to the interviewee. The interview guide is available from the authors upon request. The interviews were conducted in June and July, 2003, as part of a larger study that included other research collaboration cases (for details see Bozeman and Boardman, 2003). For the Texas Collaboration, the authors conducted extended telephone interviews with ten participants, including each of the lead investigators[4], researchers, and government agency personnel either funding or using the research. In addition, one Georgia Tech substantive expert was interviewed in depth, an air quality researcher who was well acquainted with the study and had worked with the Texas Collaboration team on related projects. Other data for the case study included hundreds of pages of official and unofficial documentation, including the original "Science Plan," research reports, contracts, memoranda, and scientific publications provided by the Texas Collaboration participants.

With respect to research collaboration, the use of case study methods has many of the same weaknesses and strengths as identified for other research topics. Often policy evaluators and other social scientists approach case studies with considerable wariness. Perhaps the single

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[4] The Texas Collaboration had six lead investigators: Dr. Peter Daum (Brookhaven National Laboratory), Dr. James Meagher and Dr. Fred Fehsenfeld (National Oceanic and Atmospheric Administration), Dr. James Price (Texas Natural Resource Conservation Commission), and Dr. David Allen (The University of Texas at Austin). Interviews with the lead investigators lasted from forty-five minutes to one and one half hours and were followed up via email.

most important one is the widespread suspicion that case study methods are insufficiently general and theoretical, that case studies are good for explaining the unique, but not up to the task of providing generalizable explanations (Dyer and Wilkins, 1991). However, the chief problems case studies present with respect to theory building flows from one of the method's strengths. Case studies provide rich detail, nuance, and depth. But, as Eisenhardt (1989: 547) notes, one of the more severe problems, that "a hallmark of good theory is parsimony, but given the typically staggering volume of rich data, there is a temptation to build theory which tries to capture everything."

There are two fundamental approaches to dealing with the "staggering volume of rich data" problem. Those doing case studies in a "grounded theory" mode eschew hypotheses and use the case to provide a more holistic understanding or, in some cases, to develop broad hypotheses. Another approach, the one we use here and have used elsewhere (see Bozeman and Klein, 1999; Bozeman and Kingsley, 1997; Kingsley, Bozeman and Coker, 1996) is to develop cases based on a model or tentative theory, determining the extent to which the case(s) aligns with the terms of the model. For more general treatment of the strengths and limitations of case studies in developing and contributing to theory, see Yin (1984; 1989).

In the next section we present the case study of the Texas Collaboration and in subsequent sections analyze the case and its implications, using the components of the Contingency Model of Research Collaboration Effectiveness as an analytical framework.

A Case Study of the Texas Air Quality Research Collaboration

One of the largest environmental research collaborations yet undertaken, the Texas Air Quality Research Collaboration was a consortium of more than 300 researchers from over 40 universities, private industry groups, federal laboratories, and state regulatory entities. Accordingly, the Texas Collaboration constitutes the most comprehensive air quality assessment ever conducted in the United States.

Unlike traditional efforts to control air pollution, the study did not focus on compartmentalized emissions from industrial sources or automobiles; rather the chief aim was to understand better the complex interactions among meteorological phenomena, pollutants such as hydrocarbons, and other variables that contribute to ozone production and fine-particle air pollution in the Houston region and the eastern half of Texas.

Study participants included a number of scientists who cooperatively conducted previous air quality studies under the umbrella of the Southern Oxidants Study, including researchers from the National Oceanic and Atmospheric Administration and the U.S. Department of Energy. Resources for the program included over 60 air quality and meteorological monitoring stations located across the eastern half of Texas and in the neighboring states of Oklahoma, Arkansas, and Louisiana. The study also employed a fleet of six aircraft to take in-flight air quality and meteorological measurements across the region as well as over the Gulf of Mexico.

In sum, the Texas Collaboration is an excellent example of a large-scale, multi-institutional research collaboration with multiple actors pursing very different, though often compatible goals. By most standards, the study was quite successful, as we document in the case study.

Genesis and Development of the Texas Collaboration

The "Texas Air Quality Study 2000," is the most recent field program in a series of oxidant/aerosol studies being conducted under the umbrella of the Southern Oxidants Study (SOS) in affiliation with NARSTO, formerly known as the North American Research Strategy for Tropospheric Ozone. Sponsors of the Texas effort include:

- National Oceanic and Atmospheric Administration (NOAA): Aeronomy Laboratory, Environmental Technology Laboratory
- U.S. Department of Energy (DOE): Brookhaven National Laboratory, Argonne National Laboratory. Pacific Northwest National Laboratory
- U.S. Environmental Protection Agency (EPA)

- Texas Natural Resource Conservation Commission (TNRCC)
- The University of Texas at Austin (UT-Austin): Center for Energy and Environmental Resources (CEER)

The Texas Collaboration included both scientific and regulatory goals. Scientists at NOAA, DOE, and EPA – who have general charge to study the effects of pollutants on the environment – have since the early 1990s been dedicated to determining why, after almost fifty years of federal legislation designed to mitigate air pollution, many of the major metropolitan areas in the U.S. continue to have serious difficulty meeting national ambient air quality standards.[5] Their mission of the Texas Collaboration and previous studies included the following elements:

1. To provide an adequate understanding of the chemistry and physics of the Earth's atmosphere;
2. To understand the nature of industrial- and mobile-source emissions; and
3. To create accurate models for predicting the outcome of interaction between various mixes of meteorological and emissions conditions.

For state policymakers, scientists and regulators at TNRCC (which has since been renamed the Texas Commission on Environmental Quality, TCEQ), and scientists at UT-Austin, the purpose

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[5] Federal efforts to deal with air pollution formally began in 1955 with the passage of the Air Pollution Control Act. The language of the bill identified air pollution as a national problem and announced that research and additional steps should be taken to improve the situation. Eight years later Congress passed a more proactive piece of legislation, the Clean Air Act of 1963. This act set emissions standards for stationary sources such as power plants and steel mills. It did not take into account mobile sources of air pollution such as automobiles. Congress amended this Act in 1965, 1966, 1967, and 1969, authorizing among other things standards for auto emissions and air quality standards and compliance deadlines for stationary source emissions. By 1970, Congress deemed the existing laws inadequate. Although technically an amendment, the Clean Air Act of 1970 constituted a major revision and set much more demanding air quality and emissions deadlines. However, the standards were overly ambitious, especially those for automobile emissions. Over the next decade, Congress extended these deadlines. Congress did not amend the Clean Air Act during the 1980s, in part because President Reagan's administration placed economic goals ahead of environmental goals. By 1990, the federal government believed that they should once again revise the Clean Air Act due to growing environmental concerns. The Clean Air Act of 1990 addressed five main areas: air-quality standards, motor vehicle emissions and alternative fuels, toxic air pollutants, acid rain, and stratospheric ozone depletion. In many ways, this law set out to strengthen and improve existing regulations.

of The Texas Collaboration extended beyond the science to developing strategies to manage air quality in Texas.

Texas was selected as a study site because the eastern half of the state includes major urban areas with significant ozone pollution problems that also have difficulty meeting fine particle standards. For example, annually Houston vies with Los Angeles, California for having the "worst" air in America.[6] Moreover, the area is important from a scientific perspective in that it has a unique atmospheric chemistry vis-à-vis earlier SOS study sites. The Houston Ship Channel constitutes a vast chemical complex comprised of over one hundred chemical companies and oil refineries that butts up against an urbanized area of more than four million people. The weather patterns over the Houston area are also distinctive, with the meteorological complexity of the Gulf Coast region presenting significant difficulties that challenged the capabilities of extant regulatory models.

During the study's planning phase from 1997 to 2000, scientists and regulators from the above-mentioned organizations met on numerous occasions, usually at TNRCC in Austin or via conference call. One of the purposes of these meetings was to settle on the study themes. After much discussion, three overall themes were agreed upon:

- *Local vs. regional contrasts*. Though the meteorological conditions conducive to the production and accumulation of ozone and fine particles may cover large areas, the concentrations of these pollutants at ground level are not uniform. Contrasting local concentrations with regional conditions help to determine whether the source of pollution is home grown or the result of long-range movement or transport.
- *Ozone and fine particle formation in urban power plant plumes*. It is important to understand with accuracy the contribution that power plants, urban emissions, and biogenic emissions (from trees) make to the formation of ozone and fine particle pollution.
- *Daily cycles in chemistry and meteorology*. Generally more is known about daylight production, accumulation, and transport of ozone and fine particles than is understood

[6] Houston in late summer routinely violates the NAAQS 120 ppb ozone standard.

about nighttime transport of ozone, fine particles, and their chemical precursors. Since long-range transport is thought to be significant for both ozone and fine particles, it is important to resolve nighttime chemistry and transport issues.

From these general themes the scientists developed the Texas Collaboration's Science Plan, which was a major product of the planning phase. The Plan outlined the specific scientific objectives for the study, which was to explain and predict (e.g. ozone formation and distribution, emissions inventories). Each section of the Science Plan contains a brief discussion of the issue and its relationship to the specific meteorological and chemical characteristics of eastern Texas. Also included in each section is commentary on how best to implement each objective, including details such as which instruments are required to meet an objective and specific questions (e.g. "Are the high values of observed VOC/ NO_x ratios due to inaccuracies in the emissions inventories of hydrocarbons, NO_x, or both?"). Despite its level of detail, the Science Plan was not etched in stone. As data developed, the scientists allowed new ideas to be incorporated.

A major outcome of the planning phase, one that was to have a strong facilitating effect for the entire Study, was the establishment of logistical arrangements for the field phases of the study (data collection and on-site analysis). These arrangements included UT-Austin and TNRCC providing infrastructure and material support for study participants including office space, hangar space, facilities for storing meteorological and measurement equipment, as well as a small discretionary fund on the order of $340,000. Furthermore, the local hosts lent to the study experienced scientists who were able to translate technical information from the field into policy recommendations for state regulators.

Because of the scope of and prescribed goals for the Texas Collaboration, none of the government agencies usually involved in supporting environmental research (e.g., EPA, DOE) considered conducting the field research and data analysis unilaterally. The Texas Collaboration did not have a centralized source of funding. Accordingly, to be able to collect all of the data and perform the analyses required to get a handle on the problem, each research group brought to the table its own budget, team of field researchers, and meteorological and measurement equipment.

This "bring your own funding bottle" approach to collaborative research resulted in the acceptance of independent research goals. The major parties to the Texas Collaboration arrived onsite with resources sufficient to collect their own data and to perform their own analyses per their respective institution's research mission. However, the scientists who coordinated the study from 1997 to 2000 ensured that the research goals of the numerous participants complimented one another by offering no incentives to collaborate beyond the science of the study itself.

Because of the lack of a centralized budget and the absence of centralized expectations, there were no reported incidences of the goals of the Texas Collaboration conflicting with the overall research missions of participating institutions. Self-interest was the key to participation. Research teams from universities, industry, and agencies including EPA and NASA committed time and resources to the study to further their own research agendas and to meet their own larger mission goals.

During the study's planning phase, the scientists who coordinated the study created an open management culture by identifying a number of research questions that were peripheral yet complimentary to their own and then seeking out research groups who had specific interest in answering those questions. According to lead scientists at Brookhaven, the Aeronomy Lab, and UT-Austin, this tactic worked beautifully. None of the six lead investigators felt that any substantive research niche was neglected during the collaboration.

Lead investigators had an easy time identifying the appropriate researchers to which to extend invitations to participate in The Texas Collaboration. The major reason for this is that the community of scientists in the U.S. concerned with understanding the chemistry and physics of how emissions interact with sunlight in the atmosphere to produce pollutants is a small one. Most of the researchers from the lead institutions had worked previously with each other in one capacity or another, including numerous other air quality studies. Accordingly, very little took place during the planning phase in the way of conflict over research goals, research roles, or resource allocation.

The Field Components of the Study: Data Collection and Preliminary Data Analysis

Implementation of the Texas Collaboration entailed TNRCC and UT-Austin setting up the material and infrastructure support discussed above and the numerous field scientists showing up in Houston for data collection. Collaborators employed a variety of methods to collect multiple types of data, including:

- Ground-based stations for monitoring air quality
- Ground-based stations for monitoring meteorological conditions
- Research aircraft for conducting a broad range of experiments based on the data from both types of ground-based stations

Participants used three types of ground-based stations for monitoring air quality. "Level 1" monitoring stations collected data on ambient ozone levels. With more than fifty of these stations operated by state and local regulatory organizations as well as by industry volunteers, they provided ozone data for a broad coverage across the eastern half of Texas as well as for portions of neighboring states. Data from these stations played a key role in planning daily aircraft experiments. Three "Level 2" monitoring stations provided detailed atmospheric chemistry information on ozone, sulfur dioxide, carbon monoxide, and nitrogen oxides. A "Level 3 Super Station" was also operated out of La Porte airport, providing a detailed picture of the atmospheric chemistry of the area by using advanced developmental measurement techniques to study concentrations of ozone, fine particles, and associated precursor compounds. A smaller Level 3 site sat atop a Houston skyscraper and provided detailed chemical information about the high concentrations of pollutants in the afternoon air, the pollutants in regional air that flows aloft overnight, and the morning rush-hour pollutants as they mix into the early-morning air aloft.

One of the more unusual aspects of the Texas Collaboration was that it employed six aircraft, each with unique research functionality to provide a wide range of experimental data. For example, NOAA's Aeronomy Laboratory donated a Lockheed Electra aircraft to collect regional chemistry and meteorological measurements. Instruments on this long-range aircraft provided measurements on regional emissions, chemistry, and long-range transport. In light of its different interests, DOE provided a Grumman Gulfstream 1, which is similar in range and measurement capabilities to the Electra. This craft provided measurements that participants used to define regional emissions, chemistry, and pollutant transport. Baylor University, NASA and NOAA's Environmental Technology also contributed aircraft, all equipped differently to serve different research objectives. During the data collection almost everyone's instrumentation worked a fortunate outcome which, according to respondents, is quite rare in a large-scale environmental study.

Research Management

Interviewees described the management of the Texas Collaboration, both field components of data collection and onsite analysis, "flat" and "loose." Because there was no centralized source of funding and most of the participants were collecting their own data, the study developed no formal chain of command through which the researchers were required to collaborate. However, as the study progressed beyond the planning phase an informal command structure did emerge, with a "core" group of researchers controlling the key material assets of the program (e.g., the airplanes) and multiple "secondary" researchers orbiting that core.

Admittance into the core group was partly based on the amount of material resources that a participant organization brought to the table. Those who brought the most of course were allowed "in," including NOAA, DOE, EPA, as well as the two local research hosts, TNRCC and UT-Austin.

Some contributing institutions played an important niche role. For example, a research group from Pennsylvania State University contributed to the Texas Collaboration its expertise in measuring hydroxyl radical concentrations, which were crucial for the photochemistry aspect of the study.

Though a leadership hierarchy of sorts emerged, one focused on identifying measures, the core group did not dictate research direction to the secondary researchers, and no one organization dominated the core group. The process was participative and democratic with scientists judging research ideas on their scientific merit via peer review. Moreover, compatibility arose in part from the method for participant recruitment, with the science and extensive logistical support being the primary incentives to collaborate.

The core group was a microcosm of the larger management structure – both “flat” and “loose.” The lead institutions were all long-time colleagues and, by the time of the Texas Collaboration, had already developed a management tradition of sorts, entailing the nomination of one of their own as the “mission scientist” to represent the program and its participants in an informal capacity. The duty of the mission scientist was to head the planning meetings during the data collection phase of the study, which occurred twice daily.

To make sure that the more than 300 field researchers were kept informed of research developments and problems, TNRCC scientists and staff maintained a daily online newsletter, which they named *The Daily Plan-it*. The principal investigators at each ground-based site held weekly symposia about the data that their respective stations were collecting.

Among the core scientists and the secondary researchers whose interests aligned more or less directly with the primary goals of the Texas Collaboration, an informal project management document to ensure that the appropriate experiments were conducted in the appropriate weather conditions, the data was analyzed in the desired manner, and research activities were adequately coordinated. Before the project management document was developed, most coordination was via daily planning meetings. The infrastructure support that TNRCC and UT-Austin provided made these encounters possible, with all of the researchers housed in the same area and working in adjacent offices.

TNRCC and UT-Austin also provided the intellectual support of their in-house scientists. According to lead investigators at NOAA and Brookhaven, the support of UT-Austin and the TNRCC was the glue that held The Texas Collaboration together.

Resources and Political Serendipity

One significant lesson that the lead investigators and managers of the Texas Collaboration learned was to procure enough funding up-front and with ample lead-time to see that study all the way through the completion of its final stages of data analysis.

The Texas Collaboration would have been starved for resources were it not for a confluence of events in 1997-1998. First, at that time the State of Texas recognized the need for a dramatic change of course regarding its air quality management in areas like Houston and Dallas/Fort Worth. For over twenty years state regulations had failed to reduce air pollution, and by the late 1990s it had become increasingly apparent to policymakers that more stringent emissions regulations must be introduced. This was a dramatic direction shift for Texas, which up to that time had provided industry waivers to circumvent existing NO_x regulations. Consequently, TNRCC gained access to funds for a new study to begin around 2000.

Perhaps the most important event that ensured logistical and, accordingly, research success for the Texas Collaboration was the EPA "supersite" program. Launched in 1998 to establish seven locations around the U.S. for fine particle data collection and analysis, the program afforded UT-Austin $3.5 million to contribute to the Texas Collaboration for infrastructure and material support. Without these funds and given the sluggish way that state and federal contracting works, the Texas Collaboration would most probably not have hit the ground running as fast as it did and, thereafter by definition, been limited in the same capacity as were earlier air quality studies in California and the southeastern U.S.

After the data were collected another series of fortuitous events occurred and ensured that the Texas Collaboration scientists would have enough funds to perform thorough analyses of the data. In December 2000, the initial study results revealed some surprises, one of which was that the air pollution in the Houston area contained much higher percentages of hydrocarbons from industrial sources than investigators originally speculated. Around the time of these results, then-Governor George W. Bush signed and submitted a new implementation plan for mitigating pollution in the Houston-Galveston area that almost wholly ignored hydrocarbons emitted by industry. Consequently, a group unaffiliated with the Texas Collaboration called the Business Coalition for Clean Air challenged Bush's plan in the Texas courts, forcing a consent decree that ordered an accelerated evaluation of the scientific results emerging from the Texas Collaboration. As luck would have it, at that time the Texas state legislature, which meets for just 140 days every two years, was in its 77th session, during which it made available $10 million for additional analysis of the Texas Collaboration data.

According to lead investigators, this eleventh hour infusion of funding was critical to the data analysis aspect of the study for two reasons. First, if the researchers were forced to wait, say, a year for the state legislature to meet and allocate the $10 million, participants from places like DOE and NOAA would have returned to their base camps to publish their scholarly papers, deflating the collaborative momentum of the study.

Texas Collaboration Results

After the field components of the Texas Collaboration in August and September 2000, the data underwent three stages of analysis. In stage one, six to eight months after data collection, the interested core and secondary researchers came together for a workshop wherein they discussed the data. For many of the participants, this was the first time they were exposed to other collaborators' data and interpretative efforts. In stage two, the study participants, using the study's data, presented forty research papers at the annual meeting of the American Geophysical Union in the autumn. In stage three, papers were submitted to scientific journals and, by July 2003, more than fifty papers had been published or accepted for publication.

In addition to the scientific research that was the primary motivation for the Texas Collaboration, the information also proved of considerable use to regulatory policy makers. As a commissioner of TCEQ commented, “I’m used to making million dollar decisions with 25 cents worth of data analysis; this time with the data we have I feel comfortable enough to make a billion dollar decision in a rational way.”

One factor essential to the regulatory success of the Texas Collaboration is the technical documentation that communicated policy-relevant findings to state policymakers and regulators. This required a concerted effort at the local level – in this case mostly by a scientist at UT-Austin. This scientist, who was the lead study investigator from CEER, penned over 500 pages of documentation for state regulators.

Theoretical Implications of the Texas Collaboration

In most respects, the Texas Collaboration seems to be a success; certainly it is viewed as such by those participating in and funding the collaboration as well as by those using the project’s data for regulatory purposes. In this section, we examine some of the aspects of the Texas Collaboration with respect to the components of the collaboration effectiveness model we present above. In doing so, we return to the Contingency Model of Research Collaboration Effectiveness, using it to organize the relevant research literature, as well as our analysis.

Attributes of Collaborating Individuals

Acquaintance

Since the Texas case was initiated “bottom up,” an understanding of the collaboration and its effectiveness centers on attributes of the individual researchers who were involved in both promoting the work and performing it. A particularly important factor was acquaintance, which can decrease transaction costs for future alliances by engendering trust among partners (Granovetter, 1985, 1992; Marsden, 1981; Williamson, 1975; Commons, 1970), and in turn can also lead to progressively less formal structures for collaboration (Gulati, 1995). The principal scientists who were the originators of the Texas Collaboration had known each other for several years and, perhaps more important, had worked together on numerous projects previously.

Several of the interviewees made it a special point to tell us that the current collaboration worked well because of the previous collaborations and that some of those early experiences were not so successful. This prolonged working relationship among the principal scientists seems to have precluded for the Texas Collaboration high transaction cost events as described by Kogut (1988), such as writing and enforcing contracts and enacting formal rules for knowledge use. Instead the principals, over time, were able to identify the appropriate parties with which to collaborate (Lipnack and Stamps, 1994; Scharpf, 1978; Landau, 1991) as well as nurture the attendant relationships that ensued (Lipnack and Stamps, 1994). The "getting to know one another" issue was important, but at the beginning of the project the principals were already aware of the need to invest time and resources on acquaintance and familiarity, especially with respect to the integration of new team members. .

Incentives

In any collaboration the role of incentives is prominent. A majority of the literature on incentives in research collaborations from economics and management focus on organization-level incentives, including transaction cost minimization, risk pooling, resource sharing, economies of scale and scope, technology transfer and learning, to name a few (Hagerdoorn et al., 2000; Link, 1990; Link and Bauer, 1989). In the case of the Texas Collaboration, it is difficult if not impossible to distinguish the incentives of the principal scientists from those of their respective institutions.

The role of individuals' incentives can prove a barrier in research collaborations. Principal-agent theory tells us that jobs which are high in intrinsic motivation, involve relatively high levels of task ambiguity, and require creativity can make it difficult to employ adequate incentives (Holmstrom and Milgrom, 1991), as incentives are usually extrinsic and therefore by definition cannot account for the full range of intrinsically-motivated collaborator behaviors (Kreps, 1997). This problem did not happen in the Texas Collaboration, for which one cannot easily distinguish the extrinsic incentives – publications for the scientists, policy recommendations for air quality regulations for the policy makers – from the intrinsic ones – conducting the best science possible.

In the Texas Collaboration there were two broad sets of incentives and one was, from the outset, superior to the other. The fact that the Texas Collaboration had both pure scientific goals and goals for regulatory application did not in any way imply a problem of incentive compatibility. Indeed, it would be difficult to envision more compatible goals. Those interested in regulation needed the best possible science for their regulations and this, of course, is exactly what the researchers were seeking to produce. In light of the compatibility of incentives, participants were for the most part able to eschew contracts and hierarchical arrangements to align incentives and instead enact the "mutual monitoring" (Welbourne et al., 1995; Tosi, 1997; Alchian and Demsetz, 1972).

Heterogeneity

We can speak of many aspects of the heterogeneity of collaboration partners, including incentives. Here our chief concern is heterogeneity with respect to scientific fields, disciplines, and sub-disciplines, which can increase productivity, in terms of quantity of publications, in scientific collaborations (Porac, 2004) as well as increase the level of formality and hierarchy in the management of those collaborations (Chompalov et al., 2002). While the Texas research team clearly qualifies as multidisciplinary, the focus on air quality provides a unity and, moreover, the spread of disciplines was not enormous. But the chief goal for the Texas Collaboration was to conduct not "the most productive science" (though the project certainly was productive, with 40 papers presented to the American Geophysical Union by 2002) but the "the best possible science," and each of the principals cite the disciplinary overlap as conducive to this goal.

What is more, the relative unity of project participants, in scientific discipline as well as with respect to incentives to collaborate, perhaps facilitated a group dynamic important to the success of any large collaboration. Collaborations comprised of partners with similar characteristics and cultures more efficiently and effectively process and share information, resolve conflict, and coordinate goals, which thereby can help to ensure that partners expend most of their effort on conducting the science rather than on issues related to maintaining a positive group dynamic (Taillieu and Tharsi, 1997; Vansina et al., 1996; Kramer, 1991).

Distribution

Another issue is the geographic distribution of the parties to the collaboration. In this day of Internet linkage, "collaboratories," and teleconferencing, one might expect that geographic distribution would be irrelevant. But anyone who has collaborated long distance knows better. There can be a negative relationship between the geographic distance separating potential collaborators and the frequency with which they collaborate (Allen, 1977; Kraut 1990; Olson and Olson, 2002). Moreover, there is evidence that collaborators that work in the same building or room are more productive than ones that use electronic media such as teleconferencing and the Internet to compensate for geographic distance (Teasley et al., 2002; Covi et al., 1998; Katz, 1993). There are some aspects of collaboration for which there are no easy electronic substitutes, including serendipitous results from informal interaction, the easy access that allows one to "pop in" for a quick question, and the easy back-and-forth that occurs when people are physically in the same room. But technology-based collaborations were effective, including those relying on a tried and true old technology, the telephone (Lind et al., 1995). Several participants underscored the importance of the regular conference call for keeping geographically dispersed parties focused on project goals and aware of one another's activities.

It is also important to stress the significance of a "headquarters" in solving some of the problems associated with geographic distribution. The fact that during the field components of the study (data collection and initial data analysis) key project participants were "radically collocated" (Teasley et al., 2002) with offices away from home at a central location where they could interact with research colleagues doubtless affected the ease of communication in the project, which not only can promote productivity (Teasley et al., 2002; Covi et al., 1998; Katz, 1993), but also can facilitate two phenomena positively linked to collaboration success – inter-partner trust (Santoro and Saparito, 2003) and learning (Doz, 1996; Kumar, 1998).

Attributes of Collaborating Institutions: A "Bottom Up" Case

The Texas Collaboration was a "bottom up" collaboration among individuals well acquainted with one another. Collaborations develop at different rates, depending not only on the nature of the science and the goals of that science, but also on how well disparate fields adjust to working together, both formally (via a management structure) and informally (during actual research).

Resources

In the Texas Collaboration, project resources included a ground-based monitoring network for ozone and aerosols, a surface meteorology network including wind profilers, two aircraft carrying a suite of chemical instruments, a third aircraft for remotely sensing ozone and aerosol vertical profiles (or "plumes"), and three more for region source characterization. Perhaps more important, resources included discretionary funding and human resources – the scientific and technical human capital that each party brought to the collaboration.

Hagerdoorn and colleagues (2000) observe the popularity of resource dependence perspective among strategic management scholars, who emphasize that firms collaborate on research projects to gain access to resources and capabilities that enable them to develop and sustain competitive advantages (p. 572). Others (Becker and Peters, 1998; Camagni, 1993) emphasize the sharing of resources to reduce uncertainty and to realize cost savings as well as economies of scale and scope. Perhaps because of these scholars' their exclusive focus on private firms, neither of these approaches adequately explains the Texas Collaboration, which was squarely aimed at the science rather than on competitive advantages or reducing uncertainty or costs. Though the general resource-based axiom of bringing together people, equipment, and scientific and technological innovations that are not substitutable – Mowery and colleagues' "sticky and difficult-to-imitate resources and capabilities" (1998) – to attain a common end that is otherwise unattainable certainly applies.

Structure

Everyone interviewed in connection with the Texas Collaboration as "loose" or "informal" in its structure and attendant management practices. Several scientists pointed out that the management approach led to a "sense of ownership" that might not have occurred with a more hierarchical management.

Factors attributing to informal management in scientific collaborations include minimal disciplinary spread or heterogeneity and a high degree of integration of efforts among participants during data collection (Chompalov et al., 2002), a long history of working together among the researchers (Krige, 1993; Knorr Cetina, 1999; Galison and Hevly, 1992) and the subsequent development of acquaintance and trust (Gulati, 1995), as well as inertia (Li and Rowley, 2002 [7]). Most of these factors characterize the Texas Collaboration.

The textbook explanation for the prominence of hierarchical (or "classical functional") management approaches is that it is permits more control and, thus, more efficiency. But as our data suggest and the above-cited studies demonstrate, managerial control is generally not the prime value in scientific collaborations, especially multi-sector, multi-institution ones focused more on the science that on its commercial appropriation. It does that the management style permitted more duplication and overlap but the redundancy was in some respects beneficial; for example , the fact that there were multiple data sets at multiple locations may have to some extent strengthened the project.

[7] We should point out that the converse is also oftentimes true, that scientific collaborations can indeed be highly structured with formal rules of engagement. See Chompalov and colleagues (2002), Krige (1993), Knorr Cetina (1999), and Zabusky (1995).

There are good theoretical reasons explaining the value of redundancy (Landau, 1969; Ting, 2003). For example

Culture

While there are many definitions of organizational culture in the management literature, one that is both simple and to the point is Trice and Beyer's (1993) definition of organizational culture as patterns of shared meaning within an organization. Edgar Schein (1992), who provides a much more detailed definition of organizational culture, distinguishes among three levels: (1) the most basic assumptions of the organization (e.g. the ways in which one should respond to hierarchical authority), (2) the basic values of the organization (for example, shared ideas about how to interact with persons outside the organization) and (3) the artifacts and creations of the organization (such as administrative handbooks, rituals and ceremonies). While, as Schein points out, there are many different aspects of organizational culture, usually when one uses the term it is just another way of saying "the distinctive or unique features of the organization."

In the Texas Collaboration, UT-Austin played a large role in the collaboration and, thus, university culture was particularly important. Universities almost always have organizational cultures that emphasize shared norms pertaining to discovery and the transmission of knowledge. Naturally, much of university organizational culture is built around education, not only broad public domain education through publication and public presentations but "up close and personal" education through formal classes and mentoring. But the federal laboratories' organizational culture is not so different from universities as one might suppose. Brookhaven National Laboratory, in particular, prides itself on its "campus-like" ambience and goes so far as to award tenure based on publications (Crow and Bozeman, 1987, 1988).

The culture of the regulatory agencies differs substantially from both universities and federal laboratories. Typically, regulatory agencies have fewer (as a percentage) researchers and more personnel trained in law or management. However, the organizational culture of the regulatory agencies took a back seat to the university cultures in shaping the Texas Collaboration.

Role clarity

In our view, *role clarity* was particularly important to success in the Texas Collaboration, especially during the field phases of the study. During the field phases, data collection and preliminary data analysis, there was a clear identification of roles: resource providers, researchers, research users. While there was enough overlap in those roles to ensure effective communication and partnering, all parties understood their basic role and played the role effectively. As many works on the social construction of science suggest, starting with Robert Merton (1957), as well as some management studies (Nygaard and Dahlstrom, 2002), clearly defined roles help collaborators to distinguish easily their core program responsibilities from more peripheral duties, as well as to avoid research priority and goal conflicts.

Attributes of the Collaboration and Collaboration Processes

Since collaborators inevitably bring aspects of their respective institutions, distinguishing between attributes of the collaborators and the collaboration is somewhat artificial. Nonetheless, the distinction is worth making because the collaboration can be designed, redesigned, and changed in ways that fundamental properties of collaborating institutions cannot. Because so few studies employ this unit of analysis, much of our own analysis draws little from the literature on research collaboration.

Planning

Planning is perhaps the only literature that employs in a formal way the collaboration-level unit of analysis that we focus on in this section. In the Texas Collaboration, planning was done at a leisurely pace, was largely informal, not extensive, and flexible. There was minimal planning apparatus, including no reliance on formal contracts to, for example, align incentives. This project was about *doing* the research and the fact that it flowed from earlier projects meant that planning did not require a place at the center of work activity. This seems to imply that if a program is highly decentralized there is not need to achieve the level of detail in planning that more centralized, hierarchical collaborations oftentimes implement. But this can mislead. An important aspect of the planning process for inter-institutional collaboration is what Agranoff and McGuire (2001) call "activation," which entails identification of partners with whom to collaborate (Lipnack and Stamps 1994) and ensuring that they are an appropriate "fit" given collaboration goals (Scharpf 1978, Landau 1991), identification of stakeholders (Gray 1989), gaining access to partners' resources (Agranoff and McGuire 1999), and structuring the collaboration management schema (Klijn and Teisman 1997). Because the principal scientists had worked together previously, acquaintance and trust and not decentralization per se[8], rendered these tasks almost automatic. Moreover, the chief stakeholder, the state of Texas, approached the principals about conducting the study and not the other way around.

In the Texas Collaboration, the planning phase was protracted. During the period 1997-2000 scientists and regulators met frequently and engaged in numerous conference calls. Research themes were developed and elaborated in the Texas Collaboration Science plan, the major product of the planning phase.

One particularly important result of the planning phase was agreement about the logistical arrangements of the field study phases of the project, with UT-Austin and TNRCC providing infrastructure and material support.

Rules

The Texas Collaboration is not an especially rich source for analysis of rules of collaboration. Crozier and Thoenig (1976) and others (Leblebici and Salancik, 1982) suggest that understanding rules is paramount to understanding collaboration, maintaining that an analysis of collaboration between firms requires a study of the rules that create stability in that collaboration, rather than investigating, as we do here, the resultant network of collaboration participants. This

[8] See Gulati (1995), who finds that repeated ties leads to trust, and trust leads to progressively less formal alliance structures.

clearly does not apply to highly decentralized and informal scientific collaborations. The Texas Collaboration was so decentralized that few governing rules emerged (but the ones that did proved quite important).

Rules for Knowledge Use and Intellectual Property Rights

While intellectual property disposition has not been a major factor in either of the cases, the informal rules for use and disposition of knowledge in the Texas case are worth noting. The fact that no one group dictated the course of research and that decisions about research focus were highly decentralized also meant that there was no central body directing the dissemination or use of the research. In a game theoretic experiment, Atallah (2003) provides a private sector analog for such open and informal knowledge use in the research joint venture that is (1) comprised of most firms in a particular industry wherein there is (2) no cost for sharing information and (3) a high compatibility between firms' technologies, resulting in (A) an absence of competitive impediments and therefore (B) a willingness to share all knowledge produced by the collaboration. As we discuss above, the Texas Collaboration included most of the major players (in the U.S.) in the air quality field who brought compatible technical and human resources to the study and certainly advocated a willingness to share all data and knowledge created from the data. Accordingly, the reporting of results proceeded in much the same manner as most academic science, open, public domain reporting.

Communication

The Texas Collaboration highlights what numerous studies in the management and innovation literatures demonstrate – that communication plays a fundamental role in the success of inter-organizational collaboration (Santoro and Saparito, 2003; Doz, 1996; Lind et al., 1995; Von Hippel, E., 1988). One of the keys to the effectiveness of the Texas collaboration was the extensive and intensive communication among project participants. To a large measure this resulted from previous bad experiences under the Southern Oxidants Study.

One of the most important elements of communication effectiveness was the study's "base camp" in south of Houston, which mitigated the effect of geographic distance and facilitated frequent and informal knowledge exchange amongst the participants, which has been shown to render multi-institution collaborations more productive (Teasley et al., 2002, Olson and Olson, 2002; Covi et al., 1998).

Communication of results was one point of informal agreement that greatly enhanced the effectiveness of the collaboration, especially for the regulatory partners. The researchers agreed up front to take great care in the technical documentation of the data and in the communication of policy-relevant findings to state policymakers and regulators. The UT-Austin scientists played a particularly important role in ensuring that many of the studies communicated in a fashion appropriate for policy use. One of the participating scientists, an ardent environmentalist, wrote more than 500 pages of documentation for use by state regulators.

Leadership and management style

Our findings regarding leadership and research management style do not relate closely to the research literature, chiefly because most of it is based on private firms. are difficult to relate to the general literature on the topic, primarily because this literature assesses private firms almost exclusively. To illustrate, Croisier (1998) finds in research collaborations among private firms many characteristics of the Texas Collaboration – the performance of basic science, the sharing of many different and difficult to substitute technologies, the inclusion of a large number of participants, and a wide geographic distribution between the participants – to be associated with high transaction costs and a hierarchical leadership. However, the Texas Collaboration has an empirical predecessor in the area of high energy particle physics, for which Chompalov and colleagues' (2002) identify collaboration as egalitarian in leadership style, in part because of disciplinary overlap and the absence of formal rules for knowledge use.

Similarly, in the Texas Collaboration the leadership and management lesson can be summed up as "the power of the soft glove relative to the iron hand." The management approach was in some respects and unusual one. The fact that there was no centralized funding led the researchers to frame the study entirely in terms of its scientific interests. No one participated in the hopes of tapping into a large pool of funds; participants brought their own funds. It also was one of the reasons for a management approach described as "flat" or "loose," an approach that seemed to satisfy everyone.

What does this add up to in terms of leadership? No one in the Texas case can be said to have played the archetypal "strong leader" role, but such leadership as was exerted effective. This leadership could be described as leadership by example and participative leadership and, given diverse foci of participants, decentralized leadership.

praised by interviewees) and the a near crisis in the overspending of funds at the early *External stakeholders*

In the Texas case the role of external stakeholders was minimized, partly by design. One set of potentially external stakeholders was the regulatory community but they were brought in to the collaboration. While citizens groups could have been another set of external stakeholders, the work was for the most part basic science and, thus, the "translation" work of moving these findings into accessible public domain information was not part of the project, except to the extent that regulators played this role.

The one respect in which external stakeholders proved prominent in the Texas Collaboration was near the end of the project when political stakeholders began to play a role, especially by providing vital funding at a point at which funding had been exhausted. But this was not due to any particular strategy among participants but rather a happy coincidence of events (i.e. the EPA "supersite" program and the successful litigation by the Business Coalition for Clean Air).

Conclusion

In the previous section we provided numerous conclusions from our case study, ones relevant to the Contingency Model of Research Collaboration Effectiveness and to the literature on research collaboration. Rather than recapitulating findings, we focus in this concluding section on this question: "What does our case study and analysis of the Texas Collaboration suggest about gaps in the literature as it pertains to inter-institutional, inter-sector research collaborations?"

One of the advantages of employing and interpretive framework for a case study, especially one useful for connecting to existing literature, is that it indicates those areas in which the literature is abundant and those in which it is scant. To a large extent, the depth of findings and theories about research collaboration relates the interest of applicability of findings to issues of commerce. The vast majority of studies of research collaboration, at least those studies examining some unit of analysis above the individual researcher, have focused on private sector collaborations. As a result, theory development has, directly or indirectly, been affected by the profit and economic efficiency motives. In some cases studies are simply influenced by an implicit and generally realistic assumption that profit is the chief motivation for research collaboration and in other instances interpretive frameworks are used such as production function analysis or principle agent theory, that are especially relevant to private sector firms. Generally, the broad theoretical apparatuses that drive many studies of inter-firm collaboration are inappropriate for studies of inter-sector collaboration, especially when none of the partners (as in this case) is particularly motivated by commercial motives.

Interestingly, the many studies of scientists' collaboration are, likewise, of limited utility with respect to multi-sector, multi-institution research collaborations. Most of these studies do not focus much on the sector setting of collaboration participants and, indeed, most do not focus on institutions at all. Despite decades of research demonstrating the importance of organizational characteristics to all manner of work, most studies of scientists' collaboration seem cling to the mythology of the autonomous scientist pursuing a curiosity-driven research agenda. While there is certainly much in our case study that highlights the importance of the ideas and commitment of individual researchers, many aspects of the case study underscore the importance of institutions and their management to the success of collaboration. Some of the institution-relevant factors particularly important to the success of the Texas collaboration include: (1) the very different but nonetheless compatible goals of the regulatory, government agency and university personnel; (2) the use of one university campus as a joint resource for all participants; (3) the multiple sources of funding , the "bring your own funding" strategy and its importance to resource allocation and use; (4) the previous inter-institutional collaboration experience from the previous SOS studies. None of these factors could have easily been understood from the research literature on individual scientists' collaborations (see the overview in Katz and Martin, 1997) and the organizational-level literature on research collaboration (see Hagedoorn, Link, and Vonortas, 2000 for an overview), focusing as it does on commercial motivations is, likewise, somewhat limited in its ability to explain many of the most important implications from this case study.

We conclude, then, that the extant literature is not well suited to analysis of the collaboration environment we have described as multi-sector, multi-institutional. The business-dominated literatures in economics and management tend to begin with premises somewhat inappropriate for this category of collaboration. The sociology literature on scientists' collaborations is generally inadequate to the purpose of understanding institutions and their impacts. What then, will be needed, to develop and empirically-based literature more adapted to the peculiar problems of the increasingly influential multi-sector, multi-institutional research collaboration?

In the first place, it will be important to focus on multiple motives and multiple incentives. Most of these collaborations will be an amalgamation of, among other possibilities, commercial incentives, and traditional scientific curiosity incentives and, as this case shows in the importance of regulatory incentives, application incentives that do not impinge directly on commercial value. It will also be important to understand the role of political incentives and constraints. This case did not especially underscore the importance of political incentives, chiefly because in is a rare (for its category, large-scale, multi-sector, multi-institution) instance of a research collaboration being built from the bottom-up. But our other cases studies (see Bozeman and Boardman, 2003) illustrate the political complexities of multi-sector, multi-institution collaborations that are, as is more common, build from the top down.

Another important way in which large, university-anchored research collaborations are different is in their reliance on social capital and long-standing, assiduously maintained social networks. It seems clear to us that this case would have been fundamentally different had the key participants not benefit from long-term working relationships. It is not only the social ties from previous research that are important to such collaborations, but the ties to users who are not themselves researchers. Elsewhere (Bozeman and Corley, 2004; Bozeman, Dietz and Gaughan, 2000), we have argued for a conception of "scientific and technical human capital" that is much broader than research collaborations, networks that include diverse knowledge and technology users and well as persons who have need of labor and skills arising from such networks.

Finally, we note that Hagedoorn, Link, and Vonortas (2000) were on the mark with their effort to develop a taxonomy of research collaborations. But our case study seems to suggest that the taxonomic work has only just begun. Particular taxonomic "types" might require their own middle-range theories if we are to fully appreciate the complexities of collaboration dynamics that occur in quite distinctive environments.

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Figure One: A Contingency Model of Research Collaboration Effectiveness