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ScienceDirect
Research Policy 35 (2006) 975–993
research policy
www.elsevier.com/locate/respol

Design and the management of multi-institutional research collaborations: Theoretical implications from two case studies

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Received 7 July 2005; received in revised form 4 January 2006; accepted 3 May 2006
Available online 21 June 2006

Abstract

Over the past three decades, U.S. science and technology funding agencies have increasingly supported large-scale, centralized, block grant-based research projects that often span multiple disciplines and institutions. This trend has developed at such a rate that research focused on understanding the management of these new collaborative models has largely not kept pace. We use two case studies of large-scale, multi-disciplinary collaborations to develop an institutional framework that illuminates the relationships among (a) the epistemic norms of the disciplines represented in the collaboration, (b) the organizational structure of these collaborations, and (c) the inter-institutional collaboration success.

The results of our case study analysis demonstrate that large-scale, multi-discipline, inter-institutional collaborations need a relatively high level of development in either (1) the epistemic development of the disciplines involved in the collaboration or (2) the organizational structure of the collaboration. We argue that the domain (i.e. epistemic or organizational) that provides the highest level of institutionalization is the one that organizes the “rules” of the collaboration.

Keywords: Interdisciplinary science collaboration; Inter-institutional collaboration; Epistemic norms; Organizational structure

1. Introduction

As research in the sciences and engineering becomes increasingly multidisciplinary, research managers and policy-makers are relying more on multi-institutional collaborations to develop strong, intellectually diverse teams that can answer complex research questions. Indeed, in the U.S. the past three decades could be credibly termed the “era of inter-institutional research collaboration”, as U.S. science and technology policy[1] has moved from the decentralized support of small, investigator-initiated research projects to large scale and oftentimes centralized, block grant-based, multidiscipline research (Bozeman and Boardman, 2003).[2]

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[1] In the U.S. in the 1980s, a series of technology transfer policies (Bayh–Dole Act, Stevenson–Wydler Act, and Cooperative Research Act) increased R&D interaction among researchers throughout universities, federal laboratories, and other research organizations. In particular, technology programs such as the Advanced Technology Program (ATP) require inter-institutional collaboration for funding and research. Further, some National Science Foundation programs (Engineering Research Centers, Science and Technology Centers, Nanoscience and Technology Centers, Industry/University Cooperative Research Centers) require inter-institutional collaboration.

[2] We are not the first to make this observation. A few of our predecessors include: Hagedoorn et al. (2000) who emphasize that organizations collaborate on research projects to gain access to resources

0048-7333/$ – see front matter
doi:10.1016/j.respol.2006.05.003

Recently, innovative designs for multi-organizational research collaborations have developed at such a rate that researchers interested in understanding the management of these new collaborative modes have had a difficult time keeping pace. Thus, a primary concern of our analysis, while fundamental, is little researched. We are interested in exploring how the level of development of the organizational structure of a collaboration interacts with the epistemic domain of the disciplines involved to determine the ultimate success of the collaboration.

One of the difficulties in examining diverse institutions for science collaboration is a dearth of theory regarding new collaborative modes. Metaphors such as "Triple Helix" (Leydesdorff and Etzkowitz, 1996, 1998) provide a useful label for new collaborative modes, but little help in distinguishing among them. Similarly, broad and sweeping frameworks such as "Mode I or Mode II" (Gibbons et al., 1994) science do not adequately describe expectations about the success of the highly diverse (and only recently developed) institutional arrangements. In this paper, we present a theoretical framework that illuminates the relationship among (a) the epistemic norms of the disciplines represented in the collaboration, (b) the organizational structure of the collaboration, and (c) the level of collaboration success.

We pursue an institutional analysis because creating and managing large research collaborations has become, essentially, an exercise in building institutions and multi-organizational networks. The results of our analysis of two cases indicate that large-scale, multi-discipline, inter-institutional collaborations need a relatively high level of development in either (1) the epistemic development of the disciplines involved in the collaboration or (2) the organizational structure of the collaboration. We further argue that the domain (i.e. organizational versus epistemic) that provides the highest level of development is the one that organizes the "rules" of the collaboration.

and capabilities that enable them to develop and sustain competitive advantages; Camagni (1993) emphasizes the sharing of resources to reduce uncertainty and to realize cost savings as well as economies of scale and scope. More applicable to publicly funded R&D collaborations, Mowery et al. (1998) discuss "sticky and difficult-to-imitate resources and capabilities" as motivation for collaboration and cooperation for otherwise disparate organizations to attain a common end that is unattainable via internal R&D. In the area of biotechnology alone, for example, Hagedoorn (1993) demonstrates that from 1980 to 1988 the biotechnology field generated significantly more inter-institutional research alliances than did any other field of research; Fisher (1996), moreover, identifies for the period from 1988 to 1996 the establishment of more than 20,000 inter-institutional research alliances in the field of biotech.

The purpose of this paper is to introduce our theoretical contributions and to explain them more clearly using the two accompanying cases. To explain both the theory and the cases in one paper, we had to think carefully about how much text to spend on both. When choosing between a fuller description of the theory or a fuller description of the cases, we have erred on the side of more fully explaining our theory. The role of the cases in this paper is to further illuminate the theoretical framework that we proposing—not to fully test the theory (which will be the topic of another article in the near future). We recognize that the two cases introduced here do not span the full range of our proposed theoretical framework. Even though the cases are different enough to help us flesh out the theoretical framework that we are presenting, we cannot test all ranges of the theory with only these two cases. Yet these cases do contribute to a better understanding of the relationship between collaboration success, the epistemic domain of research and the organizational structure of collaborations.

2. The epistemic and organizational domains of research[3]

Many variables determine the effectiveness of inter-institutional research collaboration (see Boardman and Bozeman, 2006, for an overview of these determinants), but in the present study our predominant focus is on institutional design variables. Our framework posits that the success of these research collaborations is in large measure dependent on two factors: (1) the level of development of the epistemic norms within the disciplines represented in the collaboration and (2) the type and level of development of the organizational structure of the collaboration.[4]

When considering the institutionalization of a research center or collaboration, past studies have often focused on the character and structure of the organization, rather than the internal dynamics of the science. We believe it is important to distinguish between two different, but interacting, dimensions of science before we assess the level of institutionalization of each of these contexts. The first, the epistemic domain, pertains to the internal workings of research communities, particularly norms and practices for research, research agenda-setting, incentives and rewards. The second, the

[3] The theoretical framework employed here draws in part from Youtie et al. (2006) and from Bozeman et al. (2005).

[4] For analysis of the institutional development of scientific communities see, among others, Hagstrom (1965).

organizational domain, pertains to the workings of organizations designed to enhance the work of research communities (in this case, the inter-institutional collaborations supported by external funding agencies). Both are important and we believe that the two interact dynamically.

While there are previous studies that focus on the organizational and epistemic institutionalization of scientific specialties, they are not as explicit as our presentation here. Mullins and colleagues (Mullins et al., 1977; Hargens et al., 1980) tested various hypotheses regarding the networks of research areas and stratification among collaborating scientists. By combining co-citation analysis with qualitative data sources (which indicate frequency and density of contact), Mullins and co-workers concluded that authors of highly co-cited papers form distinctive social groups. More directly related to tandem organizational and epistemic advances in areas of science is Edge and Mulkay's (1976) sociological account of the emergence of radio astronomy in Britain. The authors not only review the development of the cognitive structure of the field and the emergence of Kuhnian consensus, as well as subsequent disquiet from anomalies such as quasars, but also consider organizational developments in the field with the emergence of research institutes.

Similar (conceptually) is Clarke's (1998) history of the emergence of the reproductive sciences in the U.S and Knorr-Cetina's (1999) comparison of a prominent high-energy physics research laboratory to a group of equally known molecular cell biologists. However, Knorr-Cetina's analysis points up differences inherent across different areas of science no matter their levels of development. Though two areas may be equally institutionalized, both organizationally and epistemically, they can differ greatly regarding the way individual scientists interact, their epistemological assumptions, and so on.

2.1. *The epistemic domain of research*

The idea that there are a number of methodological and epistemic differences across disciplines is not new (Snow, 1964; Clark, 1983; Becher, 1989; Kekale, 2002; Turner et al., 2002; Van Gigch, 2002a,b). These differences can present significant obstacles in interdisciplinary and inter-institutional collaboration because methodological or epistemic norms within a discipline often define the "rules" that the discipline uses to deal with a variety of work-related issues (for a more detailed discussion of epistemic norms see Goldman, 1986). These "rules" can include (but are not limited to): how phenomena are measured, resource allocation, scientific standards of evidence, methods of inquiry (e.g. lab versus field, observational versus theoretical), standards of scientific proof, norms of accuracy and precision, level of theory development, and theories of causation.

According to Becher (1981), the "cultural" status of a discipline is entangled in the shared epistemology between the members of the discipline. More than one scholar has shown that disciplinary norms contribute to scientists' self-identification within their home fields and mold their evaluations of the rigor, motivations and comparative intellectual and social worth of other fields to which they do not belong (Bauer, 1990; Turner et al., 2002). In 1990, Bauer based his research on an earlier study by Snow (1964), which argued that interdisciplinary research often struggles because academic disciplines represent different cultures. Bauer argued that communication across disciplines is impeded by epistemological and cultural differences that are largely implicit.

In this paper, we expand on these past studies to develop a stage model for the institutionalization of the epistemic domain of research (see Fig. 1). This model presents the developmental stages of epistemic norms within a discipline (i.e. beginning with a burgeoning research topic and ending with a full-fledged scientific discipline).

This theoretical framework distinguishes among the "burgeoning research topic", the "nascent network", the "knowledge value collective" (Rogers and Bozeman, 2001), the "stable scientific field", and the "discipline". While Fig. 1 implies time durations and movements among stages, it is important to note that any stage can lead to an end-point or stopping point. For example, an institution may culminate in a particular phase or the life cycle of the organization or institution may arrive at a terminal point.

Each of these stages can be thought of as a type of research network, except the first stage in which a fully functioning network is only beginning to emerge. In one

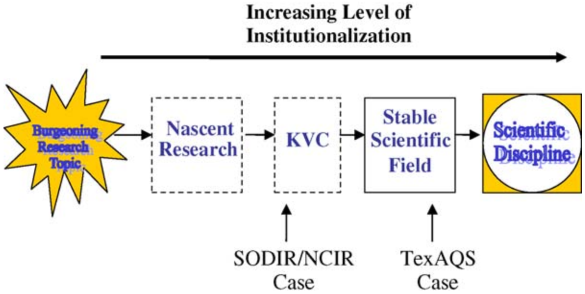

Fig. 1. Institutionalization in epistemic domain of science (figure adapted from Bozeman et al. (2005)).

of the most frequently cited overviews of network theory, Polodny and Page (1998: 59) define a network as "any collections of actors. . .that pursue repeated, enduring exchange relations with one another and, at the same time, lack a legitimate organizational authority to arbitrate and resolve disputes that may arise during the exchange". It is also useful to think about, as a scientific network progresses from left to right on the scale, the increasing agreement, and ultimately consensus, that exists in that network over relevant research questions and appropriate modes of inquiry and analysis.

In a sense, research networks are the building blocks for the epistemic context of research. If we consider a research field as an entity spanning individual research units and individual laboratories, then the network is a most basic form of social organization. Networks have multiple functions including not only the diffusion and adjudication of research results, but also career-relevant functions such as providing information about jobs, conveying informal and uncodified research norms (even though those norms are less developed than the norms shared by scientific disciplines), and even helping to determine what is and is not considered an "important" research problem (Crane, 1972).

2.1.1. Stage 1: burgeoning research topic

Fig. 1 begins with the earliest stage in the epistemic domain stage model: the burgeoning research topic or "pre-network". During this stage, several researchers have begun to work on a similar research topic, perhaps not even aware of the common attributes of their work. Gradually, the proliferation of the work is such that it leads to wider recognition among researchers and to an awareness of the need to collaborate not only on the research itself, but in the sharing of research related information, resources, and availability and attributes of researchers and students interested in the shared research topics. Eventually, the individuals in the group develop group awareness and sufficient institutionalization (i.e. shared social structures and processes) as to evolve into an informal network (i.e. a nascent research network).

2.1.2. Stage 2: nascent network

At the nascent network stage, there is a greatly increased level of communication and the beginning of structures and processes, including, ad hoc research workshops or specialty panels at larger conferences. The boundaries of the nascent network are extremely permeable, in part because the specialty is not yet fully defined. It is not entirely clear at this very early stage just who is and is not working on the specialized research topic and, indeed, the topic itself is only partially defined. This first self-conscious stage, the nascent network, usually has a relatively short life span. Many informal research networks never develop beyond this stage. The reason the stage is usually of relatively brief duration is that it is not a good holding point. If the specialized research and interest in it grows, the need for support structures and processes becomes evident and the nascent network evolves into a more fully articulated network (i.e. the KVC).

2.1.3. Stage 3: knowledge value collective (KVC)

The knowledge value collective (Bozeman and Rogers, 2002: 777) is a set of individuals connected by their uses of a body of scientific and technical knowledge.[5] It is a loosely coupled collective of knowledge producers and users (e.g. scientists, manufacturers, lab technicians, students) pursuing a unifying knowledge goal (e.g. understanding the physical properties of superconducting materials), but to diverse ends (e.g. curiosity, application, product development, skills development). The KVC is a special type of network, one that has fully emerged (unlike the nascent network), but still has only limited institutionalization, remains quite fluid and, in short, is not nearly so structured and boundary delimited as either a fully established scientific field or a scientific discipline (which is the most highly developed and institutionalized form of research network).

There is no requirement that members of a KVC interact, know one another or even be aware of one another; the only requirement is joint use of a body of information (and, in their use, creation of knowledge value). While many of the interactions within the KVC continue as informal, the first elements of formality began to emerge. For example, these could include designated panels at research conferences, small university-based research programs focused on the research specialty, or the first efforts to actually hire a researcher in this specialty.

In the KVC, as compared to the less articulated network, the boundaries begin to be much clearer. It becomes more apparent who is and is not a member of the more articulated network, it becomes clearer what is and is not a research topic within the specialty. Typically, this level of institutionalization creates demand for still higher levels of institutionalization—and consensus within the KVC emerges as to the possible uses for research resources, such as funding and programmatic structure. Whereas the informal network is usually

[5] For a detailed treatment of the knowledge value collective and related concepts, see Rogers and Bozeman (2001).

of relatively brief duration, the KVC is of indeterminate duration. A KVC can quickly move to the next phase, a stable scientific field, or it can remain for a long period-of-time, perhaps permanently, as a KVC.

As the KVC matures, the differences between the KVC and the stable scientific field are ones of degree, not kind. Thus, for example, a first specialty journal may emerge during the KVC, but the scientific field may have many. During the KVC phase, the specialty may be recognized in one or two-degree programs, but degree recognition and certification become common in the stable scientific field phase. External funding is usually focused on scientific fields with fully articulated and stable support structures emerging, whereas the KVC is more likely to have ad hoc funding. Within the stable scientific field, the boundaries are sharper and less permeable as it becomes clearer what is expected of researchers in the specialty and as educational requirements and credentialing become routine. Stable scientific fields have received a good deal of attention among students of the social aspects of science (Lemaine et al., 1976; Lenoir, 1997).

2.1.4. *Stages 4 and 5: scientific fields and disciplines*

The scientific field and discipline are the last two stages of institutionalization of a scientific specialty. Due to the extensive requirements for disciplines, very few specialty fields evolve into disciplines. As noted in the extensive literature on disciplines (Lodahl and Gordon, 1972; Bechtel, 1986; Lenoir, 1997), the most common prerequisites include (1) the widespread granting of degrees from fully accredited academic departments; (2) agreement about the purview of knowledge and the conveyance of knowledge in standard textbooks; (3) agreement about the knowledge and often the actual course of study required for disciplinary training, often as determined by professional accrediting bodies; (4) a proliferation of journals and professional groups; and (5) the development of multiple specialty fields under the disciplinary umbrella.

Disciplines generally have the sharpest and least permeable boundaries, often sufficiently so that the boundaries could be an obstacle to the progress of knowledge. Disciplines are often cited as the enemy of newly emerging research fields and a call for interdisciplinary or multidisciplinary work is often an indictment of the limitations of disciplines. But disciplines are usually quite adept at maintaining themselves and their boundaries, in large part because so many individuals develop a stake in the institutional status and legitimacy of the discipline. When there are thousands of people with degrees in specified disciplines, many can be presumed to have self-interests that require the preservation of those disciplines. It is perhaps for that reason that disciplines rarely disappear.

It would be a mistake, however, to consider disciplines as little more than fossilized agglomerations of scientific specialties. A better way to think of disciplines is as the ultimate success in institutionalization. Disciplines have resources, communication structures, socialization processes, external recognition, and domain consensus far beyond what is found in an informal network, KVC or scientific field. Moreover, most disciplines, and certainly any discipline that is not actively on the decline, will have within its boundaries persons who are, in addition to being discipline adherents, members of KVCs, networks, and nascent networks that are at the boundaries or outside the boundaries of the discipline as it is currently conceived. Often these “rear guard” activities will reshape this discipline, but in other cases they will exist apart from the discipline or even define themselves as “against” the mainstream of the discipline.

2.2. *The organizational domain of research*

Fig. 2 presents a stage model for the institutionalization of the organizational structure of research (i.e. from a nascent organization to a full-fledged academic department). In some ways, these stages run in parallel to the stage model that we just presented for the epistemic domain of research.

The organizational domain of science begins with nascent organizations and leads to early stage research collaborations, fully articulated research centers, and finally academic departments. Another way of thinking about early stage collaborations vis-à-vis research centers is that they are, respectively, informal and formal organizations designed to promote planned change. Both are entities designed to bring together researchers (and, sometimes, students and research users), permitting them to share funding resources, equipment, infras-

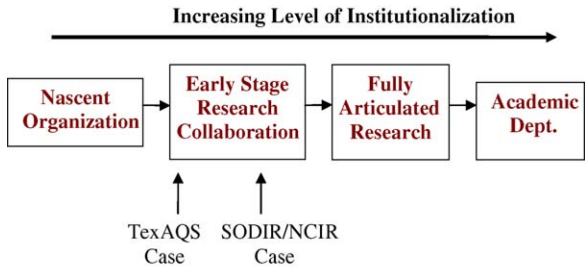

Fig. 2. Institutionalization in organizational domain of science (figure adapted from Bozeman et al. (2005)).

Table 1
Organizational characteristics of research collaborations

Characteristics of early stage research collaborations	Characteristics of fully articulated research centers	Varying characteristics
Provision of external resources	Hierarchy	Grants and contracts; multiple resources
Agreements about resource sharing and about conditions of resource access	Administrative apparatus	Center-salaried personnel; formal personnel policies and guidelines
Internal recognition of center's institutional status	Apparatus for authoritative allocation of common pool resources (i.e. beyond initial agreement)	Inter-organizational ties; multiple professional and organizational roles
Shared space (including "virtual space")	External (beyond the research specialists) recognition of center's institutional status	Multiple categories of research outputs
	Finite beginning and ending points; formal founding mechanisms	Students, educational function
	Authoritative plans and objectives	Multiple fields and disciplines
	One or more generally recognized entry portals for external actors	Diverse stakeholders; performance standards
		Research agenda setting processes

tructure and space. In many instances the shared space refers to a physical, constructed site, but oftentimes the space is either virtual or a combination of physical construction and virtual space.

Table 1 provides a simple depiction of the organizational requirements for collaborations and research centers, distinguishing the absolute minimal requirements for an early stage research collaboration, the typical requirements for a fully articulated research center, and "varying characteristics", which are characteristics that entail considerable variance even among fully articulated centers.

The importance of the table is that it provides an organizing framework for considering the level of articulation of research collaborations. Moreover, the case study and interview evidence we have gathered is considered in a later section according to the variables suggested in Table 1. This analysis will also be explicitly linked to the development of the research network along the epistemic domain stage model. Before delving into the details of our cases and the development of our theoretical framework, we briefly discuss what we mean by "success" when we talk about interdisciplinary collaborations, as well as introducing a few related studies on large scale and multidisciplinary inter-institutional collaborations in science.

3. Success and failure in interdisciplinary collaboration

Many studies focus on how inter-institutional collaborations should be managed, but few studies explain how inter-institutional scientific collaborations function within different levels of epistemic and organizational institutionalization. If for no other reason than that large scale inter-institutional scientific collaborations are relatively recent developments,[6] what is known about this mode of scientific inquiry is limited. Existing research on inter-institutional science focuses primarily on collaborative projects in particle physics and related sciences, including how those collaborations form (Shrum et al., 2001), organize (Chompalov et al., 2002), and share equipment and instrumentation (Chompalov and Shrum, 1999). While these studies have contributed to the identification of different organizational structures for inter-institutional scientific collaborations, they tend to focus only on one component of those structures: technological practice—i.e. the way a collaborative group collectively uses technological devices, such as instrumentation.

Additionally, there are more differences than similarities between our cases and the commercial-oriented collaborations prevalent in the economics of innovation literature. For example, publicly funded scientific collaborations (usually through universities or federal laboratories) often have more flexible timelines and horizontal management structures than do private, inter-firm col-

[6] How recently inter-institutional science collaboration has become "commonplace" in U.S. science is up for debate. For arguments suggesting that inter-institutional science is a fairly recent development see Etzkowitz's argument for a "second academic revolution" (Etzkowitz and Leydesdorff, 2000; Etzkowitz et al., 2000; Etzkowitz, 2001) and Bozeman and Boardman's work on university research centers (Bozeman and Boardman, 2003). For counterarguments, see Rosenberg and Nelson (1994) and Mowery (2001).

laborations, especially when the former has a high level of research partner interdependence based on knowledge and/or technological practice (Chompalov et al., 2002). Yet, one of the most significant differences revolves around the goals of the collaboration.

Collaboration goals are important to the success of an inter-institutional partnership because they are clearly linked with how the collaboration will be structured, as well as how measures of success will be defined. The goals of scientific collaborations often have a strong focus on knowledge generation, basic research, sharing of resources, interactions with the community, and career development for post-docs and graduate students (viz. de Solla Price and Beaver, 1966; Katz and Martin, 1997). Those goals are largely different from, for example, the goals of two pharmaceutical companies who are collaborating to develop a new drug or the goals of two state-level agencies that might be working together to deliver a new social service to residents of the state. It is in this latter area (i.e. collaborations involving private firms or public agencies), however, that most of the current literature on inter-institutional collaborations is concentrated.

Another characteristic of past research that differs from ours is that most previous studies of publicly-funded research collaborations have focused on individual level collaborations (for review and synthesis of this literature see Beaver and Rosen, 1979; Katz and Martin, 1997; Melin, 2000; Bozeman and Corley, 2004). Yet, our study focuses on institutional-level collaborations. Hagedoorn et al. (2000) review studies from the economics and management literatures that assess similar patterns at the organizational level of analysis, though unlike our study their focus is on private sector collaborations.

When considering the notion of collaboration "success", the institutional level studies of research collaboration are quite different from individual level studies. In previous institutional-level studies that measure outcomes (e.g. Katz, 1986; Sinha and Cusumano, 1991), research collaborations are often assumed to be positive in their impacts on productivity or, when empirical tests are provided, the empirical findings (e.g. Link and Bauer, 1987; Link et al., 1996) report a positive relationship.[7] In the individual-level studies, the findings are 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 (Landry and Amara, 1998), and at least one study (Lee and Bozeman, 2005) showing that the particular measures used are vital to understanding impacts.

Another crucial difference in the individual-level studies and the institutional-level studies is that the former typically employ a stable and easily operationalized set of dependent variables related to publication counts, whereas the latter generally use a diverse set of economic productivity measures. In employing case data rather than the productivity measures typical of institutional-level studies, our findings are not so precise as the economic productivity studies, but examine a greater number and variety of dimensions. For example, in our analysis the environmental science case (TexAQS) met with unmitigated success, while the reproductive science case (SODIR/NCIR) encountered numerous barriers. We attribute these variations in success partially to the level of institutionalization of two variables: the organizational structure of the collaborations and the epistemic norms of the disciplines represented in the collaborations.

Before moving to our case analyses using the parallel lenses of epistemic and organizational institutionalization, we want to further clarify our definition of the third variable in our theoretical framework: collaboration "success". When is an inter-institutional collaboration successful, or for that matter "effective" or "productive"? Inter-institutional collaboration success constitutes more than the generation of scientific outputs or even the attainment of the key participants' goals. Our criteria for collaboration success is similar to the definition we have employed elsewhere (e.g. Boardman and Bozeman, 2006), including (A) the satisfaction of common incentives to collaborate (e.g. resource sharing, learning, creating synergies), (B) the avoidance of barriers via effective planning and management, and (C) ensuring outcomes for the key agents involved in the collaboration, including social and policy goals in addition to scientific goals.

We discuss (A) and (B) in detail in our case development below. Suffice it here to say that our interview data reveal the Texas Air Quality Study (TexAQS—pronounced "tex-ax") collaboration to have satisfied the key participants' expectations regarding the sharing of resources and also regarding knowledge use, partially because of the effective planning that occurred prior to the field component of the study in addition to the appropriate management techniques (i.e. decentralized and informal) applied during the field component. In contrast, the SODIR/NCIR case demonstrates a failure to meet expectations regarding resource and knowledge use, accompanied by inadequate planning and management techniques.

[7] For an exception, see Becker and Dietz (2004).

Regarding outcomes and impacts (C), the TexAQS scientific goal, writ large, was to create accurate models for predicting the outcome of interaction between various mixes of meteorological and emissions conditions in and around the Houston area. Per our interviews, this goal was met with the presentation of more than 40 original papers using the TexAQS data at the 2002 American Geophysical Union Conference and continues to date with independent and combined papers published via traditional peer-review methods, mostly in scholarly journals.

The secondary goal for the TexAQS collaboration was outlined by state policy makers as well as scientists and regulators at the Texas Commission on Environmental Quality: to use TexAQS study results for developing better assessment tools and more efficient and cost-effective strategies with which to manage air quality in the region. This goal has been met with the new "State Implementation Plan" for enhanced air quality in the Houston area, which is based on TexAQS findings and may be reviewed online at http://www.tceq.state.tx.us/nav/eq/sip.html.

On the other hand, the primary goal for the SODIR/NCIR collaboration was to encourage "bench to bedside" results in the area of polycystic ovarian syndrome (PCOS). Since the SODIR center was more focused on basic research in the area of infertility studies—and the NCIR center was more heavily focused on clinical trials in infertility studies—the collaboration was formed to encourage these two groups to link their research activities in a "bench to bedside" manner. The goal of "bench to bedside" research is the translation of basic science results into clinical trials. While both centers conducted interesting research on their own, the translation goal was not realized through this collaboration. Now we will introduce the cases used in this paper to illustrate our theoretical framework.

4. Case studies

Our first case of inter-institutional collaboration focuses on the National Cooperative Program for Infertility Research (NCPIR) program funded by the National Institutes of Health (NIH). The NCPIR program was first established by the federal government in the early 1990s. The original hope was that the NCPIR program would spur basic research in the reproductive sciences, particularly in the area of polycystic ovarian syndrome (PCOS) and infertility. Additional goals of the program were to encourage "bench to bedside" translation of research to more applied settings (such as clinical trials)—and to raise the number and caliber of researchers in the field.

This case study focuses on a collaborative effort between two centers that were funded through the NCPIR program: the Specialized Ovulatory Dysfunction Infertility Research Center (SODIR) at the University of Michigan and the National Center for Infertility Research (NCIR) at Massachusetts General Hospital and Harvard University. The NCIR center was funded from 1991 until 2001 and the SODIR center existed from 1991 to 1996; therefore, for the 5-year period that the SODIR and NCIR centers were both funded by the NIH, they were expected to be scientific collaborators. From an organizational perspective, the SODIR/NCIR collaboration was a "top-down" collaboration, instigated by NIH program managers and co-managed with university research center directors.

Our second case, the TexAQS collaboration, is an instance of "bottom-up" research management that synchronized the efforts of over 300 researchers from 40 universities, private industry groups, federal laboratories, and state regulatory entities. The TexAQS case 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 (North American Research Strategy for Tropospheric Ozone). Sponsors of the TexAQS collaboration included the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), Texas Natural Resource Conservation Commission (TNRCC), and the Center for Energy and Environmental Resources (CEER) at the University of Texas at Austin.

While more detailed differences between the two cases will be explored later in the paper, the most obvious differences are: (1) the "bottom-up" nature of the TexAQS collaboration made for a much more fluid (and less defined) organizational structure, while the "top-down" nature of the SODIR/NCIR collaboration made for a much more formalized organizational structure and (2) while researchers in the TexAQS case were successful in their inter-institutional collaboration efforts, the NCPIR group failed to meet its inter-institutional collaboration goals. That is not to say that the latter program was unsuccessful as a research program, but the inter-institutional collaborations within the program did not flourish—and the objectives of the program that relied on that collaboration were not fully realized. In this paper, we explore how these varying levels of organizational institutionalization relate to the success of the collaborations, while also taking into account the level of epistemic development for the disciplines involved in the collaborations.

In sum, our extensive study of these two cases has helped us understand the management of scientific collaborations that involve multiple participants with distinct incentives, institutional cultures, and resources, as well as differing ideas about data use and knowledge transfer. Furthermore, these case studies reinforce our theoretical framework by demonstrating the need for a relatively high level of development of either the epistemic domain or the organizational domain. The TexAQS case presented in this paper represents a "flat and loose" organizational structure, while the SODIR/NCIR case represents a more "hierarchical and forced" organizational structure.

Based on our results, we speculate that when there is a high level of development in the epistemic domain, bottom-up collaboration is more likely to emerge and be successful (largely because researchers can spend time collaborating in the same "language" without having to create a new language). This was the origin of the TexAQS study. Yet, when a high level of development of the epistemic domain is absent, we believe that a top-down collaboration is more likely to emerge than a bottom-up collaboration—as with the SODIR/NCIR study. Now we will use these two case studies to further illuminate our theoretical framework.

5. Application of the epistemic and organizational stage models

We employ two cases to illustrate our institutional framework for the management of inter-institutional scientific collaborations. Because of space limitations, we do not present the cases in full form here, but rather present some general themes (outlined in Table 2) that can be derived from the cases. Our choice of the themes to present in this paper was based on how to best illuminate the details of our theoretical framework. In particular, the themes presented here are the most instrumental in our development of an institutional framework for assessing large-scale science collaborations.

As Table 2 demonstrates, the TexAQS and SODIR/NCIR collaborations were quite divergent across almost every key variable. This was the main reason why we chose these two cases for the present analysis. Another important selection criterion for the cases was the varying level of success across the two collaborations. While the TexAQS collaboration was quite successful, the SODIR/NCIR collaboration was not. We use the theoretical framework presented in this paper to explore why they differ. In the following sections, we demonstrate that this divergence was at least in part owing to different levels of organizational and epistemic development.

5.1. Analyzing the epistemic and organizational development of the two cases

In considering the SODIR/NCIR and TexAQS cases from an institutional design perspective, we consider their level of institutionalization, as well as the type of institutionalization (epistemic and organizational). Then we seek to assess the extent to which the level of organizational institutionalization leads to collaboration success based on the development stage of the epistemic norms within (and across) the disciplines involved in the research center. Our results demonstrate that inter-institutional collaborations need a relatively high level of development in either the epistemic domain or the organizational domain to be successful. The domain that provides the highest level of institutionalization is the one that organizes the "rules" of the collaboration. Now we will place both of our cases within our institutional stage models for epistemic and organizational domains—and relate those to the level of success for the collaborations.

5.2. Case analysis for the epistemic domain: the SODIR/NCIR collaboration

The SODIR/NCIR collaboration focused largely on an area that is relatively new: polycystic ovarian syndrome (PCOS). Farquhar (2000: 4) argues that PCOS "is probably the most common endocrine disorder in women, accounting for the majority of cases of hirsutism, menstrual disturbance, and anovulatory infertility"; yet, PCOS "is a subject that continues to lead to an enormous amount of debate amongst the medical and scientific communities" (Farquhar, 2000: 16).

Currently, scientists studying PCOS largely agree that women with the syndrome generally experience one or more of the following symptoms: infertility or a higher risk of miscarriage, menorrhagia,[8] amenorrhea or oligomenorrhea,[9] hirsutism,[10] anolvulation,[11] acne, male pattern hair loss, weight gain, insulin resistance and excessive androgen production (Adams et al., 1986; Farquhar, 2000). Also, most women with PCOS have large ovaries that are covered with fluid-filled cysts.

[8] Defined as excessive menstrual bleeding.

[9] Irregular or complete cessation of menstrual cycle.

[10] Defined as excessive hair growth.

[11] Anovulation occurs when ovulation does not take place during the menstrual cycle.

Table 2
Comparison of the summary variables for TexAQS and SODIR cases

Variable	TexAQS case	SODIR/NCIR case
Planning for collaboration	Extensive: scientists and funding agencies met on many occasions (in person) to develop the team and plan the project before the proposal was written	Limited: both teams developed different research plans and were forced (after receiving funding) to collaborate. Directors of both locations were chosen without knowledge of collaboration
Participants	Self selecting: all major participants knew each other before the collaboration—trust was high going into the collaboration	Involuntary: most participants did not know each other personally before the collaboration—i.e. were introduced by the collaboration
Authority and control	Informal to none: funding agencies allowed the scientists to largely function autonomously and “do what they do best”	Authoritarian: top-down authority structure. Funding agency maintained control throughout project. Funding agency ran and monitored meetings and required periodic reports from collaborators
Budget and research flexibility	Dutch: no centralized budget. Researchers brought own resources to table (reduced internal competition). Science Plan was flexible throughout the project. Scientists (and funding agencies) realized that objectives could change as the project evolved	From above: funding came solely from NIH for both parties—and both collaborators had separate budgets. This caused a problem of “who pays for what”. Researchers complained that the research plan was not flexible at all (i.e. they were not able to pursue interesting new ideas along the way)
Participation incentives	Good science: no incentives for collaboration other than the science itself. Parties only mildly interested from a science perspective were not tempted to participate for financial gain	Research funds: the only way each collaborator (University of Michigan and MGH) would get funding is if they worked together
Management	Democratic and flexible: described as “flat” and “loose” management by participants. Group of “core” scientists developed research goals while group of “secondary” scientists with projects related to the “core” had voluntary interaction with the “core”. Midstream nomination of a “mission scientist” to represent the program (coordinate meetings and get people together)	Authoritarian: funding agency involved in day-to-day activities of the collaboration. Scientists did not have control over changing research agenda. Conflicts with directors at University of Michigan and MGH—as well as internally at University of Michigan
Location	Proximity: UT-Austin and TNRCC set up a ground site for scientists to meet regularly to discuss data. Close proximity during data collection was important	Virtual: large distance separated collaborators (i.e. Ann Arbor and Boston). Most meetings held at MGH so Michigan group had to travel most of the time. Very little “face time” for both groups together
Communication	Frequent and personal: planned meetings and “science meetings” during data collection phase. Informal playbook called “key management tool” Practice makes perfect: key scientists had worked together for years before study so communication was easier	Infrequent and mandatory: communication between University of Michigan and MGH only when required—and almost always facilitated by NIH. Database sharing was encouraged, but did not happen (no incentives). Competitive, rather than cooperative communication. Bi-monthly meetings largely held at MGH. Students and post-docs allowed only limited attendance at meetings

But some researchers argue that the name of PCOS is misleading as they learn more about the disorder. Andrea Dunaif says that “as many as 30% of women who don’t have the disorder do have cysts on their ovaries” and the name of the disorder encourages people to “focus on the ovaries when this is a much more systemic disorder that has metabolic consequences” (Colino April 20, 2004). As a result of these disagreements over the definition of PCOS, the scientific community has recently made a distinction between “polycystic ovaries” (PCO) and “polycystic ovarian syndrome” (PCOS). They are realizing that some women can have characteristics of polycystic ovaries (which is diagnosed using ultrasound methods) without demonstrating the biochemical changes or clinical symptoms of full-fledged PCOS (Kovacs and Burger, 2000). Despite its initial discovery in 1935 (Stein and Leventhal, 1935), scientists have only recently agreed that PCO can be diagnosed (via ultrasound) without any of the clinical manifestations of PCOS (Polson et al., 1988).

Even though there is considerable disagreement about the details of the diagnostic definition of the disorder, some progress was made towards a universal diagnostic definition during the 1990 PCOS panel convened by NIH. At this conference, researchers agreed that PCOS encompasses a broader spectrum of signs and symptoms of ovarian dysfunction than the original diagnostic definition outlined (The Rotterdam Eshre/ASRM-Sponsored PCOS Consensus Workshop Group, 2004). But this was not the final word on developing a diagnostic definition that physicians and researchers in the U.S. and Europe would adopt. In 2003, many of the same researchers met again at the Rotterdam ESHRE/ASRM-Sponsored PCOS Consensus Workshop to further refine the diagnostic definition of PCOS. The researchers at the Rotterdam conference concluded that PCOS is a syndrome of ovarian dysfunction along with the fundamental features of PCO and hyperandrogenism (The Rotterdam Eshre/ASRM-Sponsored PCOS Consensus Workshop Group, 2004). Despite the 1990 and 2003 conferences, there are still disagreements among scientists about how to fully define PCOS.

The above discussion of the evolution of research in the field of PCOS demonstrates that basic scientists, clinical scientists and physicians have had to work closely to further the definition and understanding of PCOS. Basic scientists have largely relied upon clinical trials to help define the full range of the disease, while clinical scientists have relied upon basic scientists to help them understand the relationships between (and causes of) various manifestations of the disorder. Physicians have played a significant role in the evolution of knowledge surrounding the case of PCOS by taking information from both clinical and basic scientists and transforming that into knowledge that can be used to help individual patients.

Therefore, the field of PCOS research has developed as a truly inter-disciplinary collaboration. This notion of inter-disciplinary collaboration is clearly demonstrated in NIHs decision to encourage the "bench to bedside" collaboration between the SODIR center (which was focused more on basic-science research) and the NCIR center (which was focused more on clinical research) in 1991. But, as the previous discussion demonstrates, the level of development of the field of PCOS research was in a relatively early stage of development: the beginnings of the KVC. PCOS research has not developed into a stable scientific field—which is apparent from the high level of disagreement about the diagnostic definition of the disorder. Yet, research on the PCOS disorder has advanced beyond the nascent research network stage. It is important to point out that we are using the descriptive fact that the high level of disagreement about the diagnostic definition of PCOS only as an indicator that the epistemic domain is less developed. We are not arguing that this disagreement is a cause or consequence of the level of epistemic development in the field of research.

5.3. Case analysis for the epistemic domain: The Texas Air Quality (TexAQS) Study

The epistemic institutionalization of the TexAQS collaboration was more advanced than it was for the SODIR/NCIR case. The TexAQS case was, first and foremost, a collaboration of environmental scientists interested in the atmospheric chemistry and physical properties of the southeastern portion of Texas. The label "environmental science" rightly sounds broad, constituting an area of scientific inquiry requiring a working knowledge of physics, chemistry, and biology. Though environmental science lies at the intersection of a number of scientific disciplines long institutionalized epistemically (as well as organizationally, see below), some of this institutionalization dissipates once scientists from numerous disciplines aspire to work closely in a common field of inquiry. The overarching goal of understanding how chemical and physical processes interact with each other and also with biological forms (e.g. particulate matter) in the Earth's atmosphere is enough to bring chemists, physicists, and biologists together. It is not enough, however, to align them as closely as they align within their own disciplines (in terms of agreement over epistemic norms and "rules" for inquiry).

The TexAQS collaboration had none of the disagreement that characterizes the SODIR/NCIR case. The epistemic norms across the disciplines (physics, chemistry, biology, as well as cross-practicing "environmental scientists") embodied in the daily activities and tasks of the field researchers saw general agreement regarding relevant research questions, data collection methods, and data analysis. Overall, our interviews lead us to the conclusion that there was considerable agreement among the collaboration partners for this study (all of whom had been working in environmental science previously). This fits with the notion that the field of environmental science, while not a formal discipline in its own right (e.g. in U.S. universities, most environmental science programs are majors or specializations within chemistry or biology departments), is nonetheless quite institutionalized in the epistemic sense (e.g. there are some, though not a lot of, environmental science journals, like Atmospheric Chemistry and Physics).

Particularly indicative of this collaboration-level agreement was an official Science Plan that was drafted by the researchers participating in the collaboration. The Plan outlined the specific scientific objectives for the study, which were to explain and predict atmospheric dynamics and transport, ozone formation and distribution, and fine particulate matter formation and distribution. The Plan also designated the collection of information for emission inventories and modeling. In none of our interviews did we detect that these plans were controversial or debated, even to a minimal degree. Most of the planning phase of TexAQS was spent procuring space and electronic- and tele-communications resources for the field component of the study.

This level of agreement goes, in fact, for the entirety of the collaboration. In stark contrast to the SODIR/NCIR collaboration, the TexAQS participants that we interviewed did not cite any instances of conflict or disagreement over the overall direction of the research or the techniques associated with the field components of their research. This is probably due in large part to the general agreement over methods and techniques in the field of environmental science as a whole. Though we qualify that the history of collaboration amongst the TexAQS participants had a hand in this level of agreement, we submit that the trust and acquaintance and familiarity required for such persistent, informal, and decentralized science collaboration requires epistemic institutionalization of a higher rather than lower order, and that such collaboration is not enough to create agreement on epistemic grounds in the absence of a pre-existing and significant level of Kuhnian consensus.

However, formal scientific disciplines generally have "sharper" or "less permeable" epistemic boundaries than those posed by the field of environmental science. What distinguishes environmental science from epistemically more institutionalized disciplines (in this case biology, chemistry, and physics) is that the research questions and norms that hold this area of inquiry together are more contextually than analytically distinct. An understanding of the inter-relation of chemical and physical processes, for example, is not a new area of inquiry, but rather the application of existing modes of inquiry to a particular context, in the TexAQS case the context of the Earth's atmosphere. What is more, the TexAQS collaboration demonstrated some characteristics of a KVC in that it constituted a loosely coupled collective of knowledge producers and users (federal and university scientists, policy makers, public administrators) pursuing a unifying knowledge goal (understanding the physical and chemical properties of air plumes in southeastern Texas) with diverse ends (scientific knowledge, modeling, policy application, and industrial regulation).

Because we emphasize that the differences between the KVC, the scientific field, and the formal discipline are ones of degree, not kind, we designate the epistemic development of environmental science, at least as practiced in the TexAQS collaboration, as a "stable scientific field". The institutions participating included well and long established federal laboratories with clear and consensual expectations for researchers interested in air quality. Though organizationally the collaboration was decentralized and informal (see Section 5.4.2), to the participants the field component (data collection) and science (data analysis) of the study were straightforward. What made the study interesting or "worth doing" was joint access to an understudied area of the U.S. that has failed for decades to meet U.S. environmental quality standards.

5.4. Case analysis for the organizational domain

We now turn to the analysis of the development of the organizational domain for the two case studies. Recall from Table 1 there are four criteria for an organization to be classified as an early stage research collaboration: provision of external resources; agreements about resource sharing and about conditions of resource access and use; internal recognition of the center's institutional status; and shared space. A detailed analysis of the SODIR/NCIR and TexAQS collaborations based on these criteria indicates that these collaborations do indeed meet the minimum characteristics of an early stage research collaboration.

5.4.1. Minimum characteristics for early stage research collaborations: the SODIR/NCIR case

To clarify what is meant by the provision of external resources, it is useful to distinguish between the various external resources that are required to support a research collaboration. First and foremost, we can cite an institutional context in which the research collaboration will be embedded. This provides space, basic infrastructure, and a roster of research and administrative staff members to the collaboration. The institutional contexts of the SODIR/NCIR collaboration were universities and teaching/research hospital environments. The members of the collaboration received external resources from a variety of financial support mechanisms (grants, contracts, fellowships, and other extramural endowments).

Another diagnostic characteristic of an early stage research collaboration is the presence of agreements about resource sharing and the conditions of resource access and use. This is particularly relevant in a research environment that makes use of expensive analytical laboratory instruments and other specialized core equipment (Chompalov et al., 2002). The SODIR/NCIR collaboration did have agreements about resource sharing that were outlined by NIH early in the process.

Third, internal recognition of the institutional status of a collaboration refers to the researchers' awareness of the actual center and their identification with it. As we have seen in many other instances (Crow and Bozeman, 1998), researchers often are not familiar with funding flows and authority lines, but the question here is awareness of the research collaboration itself. Since the SODIR/NCIR collaboration was embedded in a pre-existing organizational structure (i.e. the individual centers on their own), this becomes an especially important issue. If there is little or no self-identification of the new collaboration across institutions, then the collaboration has no organizational status (though this says nothing about resources flows, especially if resources can flow through alternate channels).

All researchers interviewed at the MGH NCIR center were aware of the existence of their own center and, in most instances, the extent to which they were funded under it. In contrast, the recognition in the University of Michigan SODIR center differed in type and degree. Most interviewees often referred to the collaboration not by name but by its grant type—U54. This conforms to our analysis that the collaboration as a whole was not a stable and easily recognizable organizational unit, but rather was a loose confederation of researchers working at disparate geographical locations and institutions. By the criteria presented here, the SODIR/NCIR research arrangement could be classified as an early stage research collaboration up to the point of its de-funding.

5.4.2. *Minimum characteristics for early stage research collaborations: the TexAQS case*

Even though its provision of resources was more collective and decentralized than the SODIR/NCIR collaboration, the TexAQS study nonetheless possessed the external resources and shared space characteristic of an early stage research collaboration. A major outcome of the planning phase of the study—which was rather protracted (lasting from 1997 to 2000)—was agreement about the logistical arrangements of the field components of the project. This agreement led to the decision that CEER and the Texas Commission on Environmental Quality (TCEQ) would provide all infrastructure and "non-mission" material support for the collaboration. This support included centralized office and meeting space in which all of the core researchers were housed, computers, phones lines, IT personnel, operating and storage space for scientific equipment, and hangars for airplanes used during data collection.

While CEER and TCEQ provided the infrastructure and "non-mission" resources for the collaboration, the participant institutions provided the science or "mission" resources. We consider these resources "external" because of the way they were utilized and distributed. These science or "mission" resources were pooled and designated for open use by all participants (even by those institutions that did not contribute much in the way monies or equipment) as long as the intended use had scientific merit and did not impinge on the main research themes prescribed during the planning phase and codified in the official Science Plan.

Second, the decentralized nature of the resource base for the TexAQS study helped to generate agreement about resource sharing and conditions of resource access, another attribute of early stage research collaborations. Planning meetings—which were held twice daily during the data collection phase of the study (August–September 2000)—were also key mechanisms for arriving at resource sharing agreements and conditions.

Third, the TexAQS study met the 'internal recognition' criterion for early stage research collaborations. Through in-depth interviews, we found that the participants were aware of the collaboration's institutional status, particularly with respect to the core participants. Funds from several agencies, including NOAA, DOE, CEER, and TCEQ, were designated specifically for the collaboration.

Surprisingly, the decentralized nature of the resource provision for the TexAQS study was one of the characteristics that ensured its institutionalized status as an early stage research collaboration. Scientists from the core participant institutions were the architects of the collaboration and spent 3 years planning both the logistical and scientific components of the collaboration. During this time the TexAQS study inevitably became a major endeavor for all involved, with participating scientists from core and non core institutions alike referring to the collaboration as "the TexAQS study". If the funding had been more centralized, the core researchers may have been less aware of funding and resource flows and, accordingly, less formal in their recognition of the study.

Table 3
Assessing SODIR/NCIR and TexAQS collaborations against criteria for fully articulated research centers

Characteristics of fully articulate research centers	SODIR/NCIR collaboration	TexAQS collaboration
Hierarchy	X	
Administrative apparatus	X	
Allocation of common pool resources		
External name recognition		
Finite beginning and ending points	X	
Authoritative plans and objectives		X
Recognized entry portals for external actors		X

5.4.3. Characteristics for fully articulated research centers: the SODIR/NCIR case

The next stage in the organizational stage model, the fully articulated research center, involves a number of attributes that are listed in Table 3.

Based on our case analysis, the SODIR/NCIR collaboration did not meet all of the criteria of a fully articulated research center. Here we will discuss each criterion for this collaboration—and explain why the SODIR/NCIR collaboration cannot be classified as a fully articulated research center. First, the hierarchy variable refers to the existence of a formal hierarchical structure with vertical reporting lines. Often when researchers have a long history of working together in intra- or inter-organizational contexts, subsequent development of acquaintance and trust (Gulati, 1995) can lead to less formal management and hierarchical structures (Krige, 1993; Knorr-Cetina, 1999). Thus, more hierarchy is not always more productive than less hierarchy. But well developed research centers at least meet the minimal level of hierarchy needed for managerial control and coordination.

The SODIR/NCIR collaboration was directed by the NIH at the highest level so there was clearly a significant amount of hierarchy present in the structure of the collaboration. The two entities that made up the collaboration, however, employed a "flatter" hierarchy within their own research structures. The MGH NCIR center was directed by an authority in the field on reproductive medicine, one who was perceived by interviewees as a strong, visionary leader. The University of Michigan SODIR center was directed by a nursing professor, a well respected and experienced researcher. However, she was not mentioned by interviewees when they were asked about authority and organizational hierarchy at the SODIR center.

Second, the administrative apparatus of a center refers to the structure and processes put in place to manage the center in an effective and efficient fashion—and to develop the ability to maintain the center. In most centers, the administrative apparatus is formalized by an administrative core that provide a framework for managing and maintaining organizational processes, including, for example, payroll management, human resources management, grant management, procurement, document preparation support, and accounting and budgeting activities.

The SODIR/NCIR collaboration exhibited a certain degree of administrative apparatus that was largely focused at the NIH level (rather than specific to this collaboration). The NIH-driven administrative apparatus was comprised of all the PIs employed by all of the centers funded under the NCPIR program at NIH. This committee was responsible for decisions such as how many inter-center meetings there were, how many people would attend those meetings, how to handle funding mechanisms, and other related issues.

Third, the apparatus for authoritative allocation of common pool resources refers to the leadership abilities and processes of center management to devise a resource allocation mechanism and apply decision rules to scarce common pool resources in a judicious, cost effective and fair way. Common pool resources can extend beyond the boundaries of the research center into collaborating partners' resource bases (Link, 1990). An apparatus for authoritative allocation of common pool resources was largely non-existent for the SODIR/NCIR collaboration.

Fourth, the external recognition of the collaboration's institutional status requires that we consider the awareness of the SODIR/NCIR collaboration among the wider medical community, a factor often important to the effectiveness of research centers (Whitmeyer, 2000). External recognition of the SODIR/NCIR institutional status was perceived as a problem by some interviewees at the two collaborating centers. Some attributed the lack of external recognition to the absence of a dedicated website for the collaboration, while others argued that certain high profile researchers associated with the center were well known, but that the official names of the NCIR and SODIR centers were not known.

Fifth, an organization that is institutionalized has an identifiable beginning point and formal founding means, as well as either a known end-point or a known process for termination. We also consider the age of the research organization since age, size and institutionalization are often closely related. The SODIR/NCIR collaboration had a clear founding date—and the termination of the collaboration was easy enough to identify (i.e. withdrawal of the U54 support). The collaboration, however, did not exist long enough for the level of institutionalization one expects after some extended period of occupying an "organizational niche" (Meyer and Rowan, 1977; Freeman and Hannan, 1983) within a recognized organizational ecology (Aldrich, 1979).

Sixth, 'authoritative plans and objectives' refers to the formulation and implementation of specific research objectives and detailed research plans. As with any organization, a research center can be said to be more fully institutionalized if it has planning routines and specific, coordinated objectives. In fully articulated and institutionalized research centers, formal center-wide or project-specific research plans are normally drawn up and provide a 'roadmap' realizing shared objectives.

The prospect of research planning was inherently daunting at the SODIR and NCIR centers, in part because of the usual reluctance to plan basic research activities and in part because of the requirement—sometimes not met in the centers—of integrating diverse basic, applied and clinical research activities. Very little information was available on formal research planning processes and outcomes. This can be partially explained by the fact that a significant portion of the research in the collaboration was focused on basic science. However, having said that, a major component of the research being conducted at the NCIR and SODIR centers was clinical and translational in nature—and planning was just as spare for that research.

Seventh, for an organization to develop linkages it is important that others have some idea how to "get in the door". We consider here the processes and media by which external actors can get in touch or find out more information (general or research specific) on the research center. A portal is a communications device that enables the formation of potential collaborations, facilitates recruitment of patients for clinical trials, promotes outreach to particular segments of the user community, and constitutes a gateway for professional user community members to interact with the center. Today, the most common entry portal is a website. However, an effectively communicated presence, supported by adequate contact information of any sort, can be classified as an "entry portal".

The NCIR center at MGH did not have its own dedicated website. Some interviewees at the NCIR center noted that because of the excellent reputation of the center's researchers—and the center's high quality research—it was rather easy to keep close contact with the professional research community through word of mouth. Indeed, effective reputation and informal communication can be a useful alternative to a clear-cut organizational entry portal.

Likewise, there was no website was set up for the SODIR Center at the University of Michigan, nor was there any other generally recognized means of entry, not even agreement about a single telephone number. The lack of a recognized entry point was perhaps one factor in the limited name recognition for the SODIR center, but other factors were probably even more important, including the confusion and lack of center identification among participants. Since there was a lack of recognized entry points for the individual NCIR and SODIR centers, it is not surprising that there was no recognized entry point for the SODIR/NCIR collaborative efforts. In sum, based on the assessment of the SODIR/NCIR collaboration in terms of the seven above variables, it fails to meet several of the criteria that would qualify it as a 'fully articulated research center'.

5.4.4. *Characteristics for fully articulated research centers: the TexAQS case*

The TexAQS collaboration demonstrated fewer signs of fully articulated research centers than did the SODIR/NCIR collaboration. We believe that this is partially due to the origins of the two collaborations. The TexAQS collaboration originated from the bottom-up and had a management scheme that is best described as "flat" and "loose". In addition, the resource allocation was meritocratic, not authoritative—and the establishment of the study was based more on previous acquaintance and trust among the participants than it was on any formal mechanism or relations. Though it is clear that, internally, the study had institutional status, our interview data reveal no evidence of this type of recognition by actors external to the collaboration.

The TexAQS case did, however, meet two of the criteria for fully articulated research centers: 'authoritative plans and objectives' and 'a recognized entry portal for external actors'. The official Science Plan that was drafted during the planning phase of the TexAQS study did contain authoritative plans and objectives. This plan was drafted in an egalitarian and meritocratic manner, with each of the core participants providing input.

The TexAQS case also had a recognized entry portal for external actors. First, the study created (and still maintains) a formal web page (http://www.utexas.edu/research/ceer/texaqs/). Interestingly, the web page does contain separate links for participants and visitors so non-participants are not excluded from access to data on the web page. The TexAQS case did not meet any of the additional five criteria for fully articulated research centers.

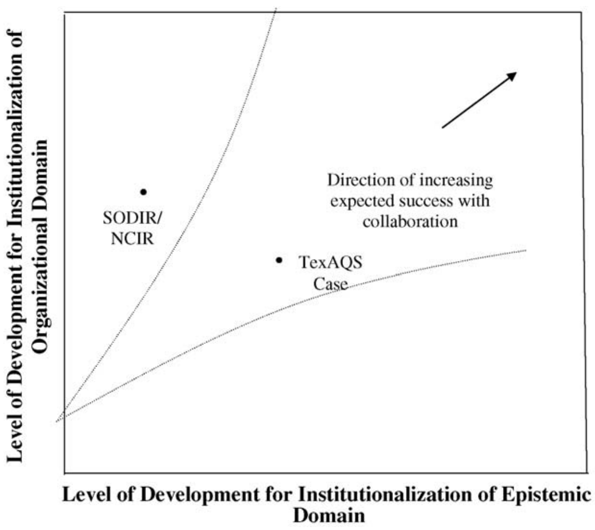

Fig. 3. Expectation of inter-institutional collaboration success based on levels of development for epistemic and organizational domains.

6. Conclusions and implications for theory of collaboration effectiveness

Before we turn to a discussion of the implications of our theory for collaboration effectiveness, we would like to remind the reader that our cases have informed the development of the theoretical framework that we have presented, but we cannot use them to fully test our theory because they represent only two points within Fig. 3. In particular, the SODIR/NCIR case represents a low level of development in the epistemic domain and a moderate level of development in the organizational domain. On the other hand the TexAQS case represents a moderately high level of development in the epistemic domain, but a lower level of organizational development. To further refine our theoretical model in Fig. 3, we would need to have additional cases that span a wide range of epistemic and organizational levels of development.

Since we are proposing our theory without that full range of cases, we have identified that there will be threshold levels of epistemic and organizational development below which it will be extremely difficult for a successful inter-institutional collaboration to form. Yet, without additional cases we cannot say empirically where these thresholds exist—and we suspect that the location of those thresholds might be partially due to the contextual characteristics of each individual collaboration. Even though we recognize these limitations in proposing a theoretical framework based on two cases, we do believe that our analysis of these distinctive inter-institutional collaborations (one successful and one unsuccessful) can push forward a theory about the relationship between collaboration success, the epistemic domain of research and the organizational structure of collaborations. Now we will turn to a discussion of the implications of our theoretical framework for scientific collaborations.

To reiterate, our theoretical framework assumes that research collaboration effectiveness is beneficially viewed in terms of the optimal fit of the degree and type of institutionalization and the epistemic character of the research fields. The above analysis of the SODIR/NCIR and TexAQS cases indicates that the respective collaborations occurred at different levels of epistemic and organizational domain development. While the SODIR/NCIR collaboration was just entering the KVC phase of our epistemic stage model, the TexAQS collaboration involved disciplines that had much stronger and more consistent epistemic norms.

The two research collaborations differed in the level of institutionalization of their organizational domains as well. Even though both collaborations crossed the mark of being "early stage research collaborations", neither could be classified as a "fully articulated research center". The organizational domain for the TexAQS collaboration, however, was less institutionalized than the SODIR/NCIR case. Even though we classify both collaborations as "early stage research collaborations", the difference in their level of organizational development is still significant. Fig. 3 below presents our theoretical framework for the relationship between three variables in inter-institutional collaborations: (1) the level of development of the epistemic domain of the science, (2) the level of development of the organizational domain of the collaboration, and (3) the expectation of collaboration success based on the institutionalization of the previous two variables.

This figure illustrates that when both the epistemic and organizational domains of collaboration are not developed, the expectation for collaboration success is low. On the other hand, when both the epistemic and organizational domains of an inter-institutional collaboration are highly developed, the expectation for the collaboration success is high. Also, as the epistemic and organizational domains of the collaboration become more institutionalized (i.e. as we travel to the top right hand corner of Fig. 3), the expectation of collaboration success increases. Our diagram is useful for summarizing the relationship between development in the epistemic and organizational domains—and collaboration success—but we do not mean to imply that a high level of institutionalization in both domains guarantees that a collaboration will be successful (because other non-institutional variables also play a part in collaboration effectiveness).

Yet, the level of institutionalization of the collaboration implies that there will be well-defined rules (both epistemic and organizational) that will guide the collaboration and be more likely to keep it on track over the long haul. The lines outlining the "direction of increasing expected success with collaboration" imply that there is a threshold for both the epistemic and organizational domains below which the development will be too low to support a successful inter-institutional collaboration. Yet, we have drawn these boundary lines as curvilinear because we believe that the location of that threshold cannot be defined through the analysis of only two cases. Our analysis of these cases does indicate that a threshold exists and that is the main argument that we are trying to make in Fig. 3; however, we do not mean to imply that the threshold levels can be well-defined through the analysis of only the TexAQS and SODIR/NCIR cases.

One of the most important lessons of this study is that "more institutionalized" does not necessary equate with "more effective". Nor is the march toward ever greater institutionalization inevitable. As we have already seen, in the TexAQS case researchers flourished in a "flat and loose" management environment that was not highly institutionalized from an organizational perspective. However, the epistemic norms of the fields represented in the collaboration (i.e. largely environmental engineering and chemistry) were highly developed—and these norms were similar across those scientific fields. Most of the scientists engaged in research in the TexAQS case were physical scientists or engineers trained in fields with similar epistemic norms. These highly developed epistemic norms were useful in organizing the norms and rule structures for the collaboration. In this environment, a loose management structure with a low degree of institutionalization led to a successful collaboration.

On the other hand, our analysis of the two cases indicates that when researchers in an interdisciplinary environment come from fields with quite different norms or fields that are at different stages in the development of their epistemic norms, they would require a more fully developed and formalized organizational research structure for the collaboration. This partially describes the case of the SODIR/NCIR collaboration. As previously mentioned, researchers in the SODIR/NCIR collaboration were focused on studying PCOS, which is an area of study that has a low level of epistemic development. Additionally, the researchers in this collaboration came from a variety of fields with divergent epistemic norms and diverse analytical tools. The collaboration involved researchers from nursing, biology, veterinary medicine, and physiology—and many of the researchers had research degrees (i.e. Ph.D.s) while others had medical degrees (M.D.s).

During our interviews, we found that the researchers all approached the question of PCOS from a different epistemic perspective—and the Ph.D.s and M.D.s had problems communicating with each other because of their differences in training. Therefore, it is clear that the epistemic norms of PCOS—or the fields represented by the researchers in the collaboration—could not provide a consistent rule structure for the collaboration. The organizational structure of the collaboration was also not sufficiently developed to provide a rule structure or normative basis for the collaboration. The result was that individual researchers conducted their own research (some of which was quite successful on an individual level), but the collaborative efforts of the group failed.

Given the limitations of our case analyses, our model leaves many important questions unresolved. Our results seem to show that both epistemic and institutional forces can contribute to collaboration effectiveness. But we do not know, at least from this case evidence, the results of high levels of epistemic and institutional structuring. Do they complement one another? Do they act as repellent forces disrupting collaboration processes? Our study suggests that "top-down" collaboration management is concomitant to a high level of institutional structuring, but the SODIR/NCIR collaboration provides only a weak sort of top-down management. Is it the hierarchical nature of the management scheme that is important or the forcefulness of the management? Is there some optimal combination of epistemic and institutional structuring during a particular stage in the development of a research field?

In short, several issues remain to be resolved. However, as a first step to understanding the effectiveness of multi-institutional research collaborations, the separate influences of epistemic and institutional factors seems well illustrated in the two cases we have examined. Our approach suggests the vital importance of both the epistemic and institutional domains without having shed much light on the interrelation between these two forces. Future research should focus on sorting out the interactive effects between these two determinants of research effectiveness. This will, in all likelihood, require a multi-method approach; taken alone, a few case studies will not be sufficient to unravel these complexities. Perhaps the integration of insights from social studies of science with ideas from the management of research organization may ultimately provide a deeper, richer understanding of large-scale research collaboration.

Does our perspective offer any lessons for policy makers and those responsible for creating and providing resources for research institutions? Only the broadest sort of lesson. However, perhaps it is not yet time for more than the broadest lessons. The recent history of interdisciplinary research centers (see Bozeman and Boardman, 2003) shows that a great deal of thought is given to the socio-economic rationales for developing these institutions and relatively little attention is given to their particular institutional designs. Thus, the observation that the institutional design, and the level of a field's epistemic development, impinge on one another is perhaps the sort of broad principle that could be digested and acted upon.

Acknowledgements

The authors would like to thank the Canada Council of Science and Technology Agencies and the National Institute of Health/NICHD for providing support for the research reported here. The authors are grateful for the contributions of Jan Youtie, Eric Sundquist and Jason Epstein for their work on the original case studies upon which this analysis is in part based.

References

Adams, J., Polson, D.W., Franks, S., 1986. Prevalence of polycystic ovaries in women with anovulation and idiopathic hirsutism. British Medical Journal 293, 355–359.

Aldrich, H., 1979. Organizations and Environments. Prentice Hall, Englewood Cliffs, NJ.

Bauer, H.H., 1990. Barriers against interdisciplinarity-implications for study of science, technology, and society (Sts). Science, Technology, and Human Values 15 (1), 105–119.

Beaver, D.D., Rosen, R., 1979. Studies in scientific collaboration: Part Ii. Scientometrics 1 (2), 133–149.

Becher, A., 1989. Academic Tribes and Territories: Intellectual Enquiry and Cultures of the Disciplines. Society for Research Into Hugher Education and Open University Press, Milton Keynes, England.

Becher, T., 1981. Towards a definition of disciplinary cultures. Studies in Higher Education 6 (2), 109–122.

Bechtel, W. (Ed.), 1986. Integrating Scientific Disciplines: Case Studies from the Life Sciences. Nijhoff, Dordrecht.

Becker, W., Dietz, J., 2004. R&D cooperation and innovation activities of firms—evidence for the German manufacturing industry. Research Policy 33 (2), 209–223.

Boardman, P.C., Bozeman, B., 2006. Implementing a "bottom-up", "multi-sector research collaboration: the case of Texas air quality collaboration". Economics of Innovation and New Technology 15 (1), 51–69.

Bozeman, B., Boardman, C., 2003. Managing the New Multipurpose, Multidiscipline University Research Centers: Institutional Innovation in the Academic Community. IBM Center for the Business of Government.

Bozeman, B., Corley, E., 2004. Scientists' collaboration strategies: implications for scientific and technical human capital. Research Policy 33 (4), 599–616.

Bozeman, B., Rogers, J.D., 2002. A churn model of scientific knowledge value: internet researchers as a knowledge value collective. Research Policy 31 (5), 769–794.

Bozeman, B., Youtie, J., Libaers, D., 2005. Institutional Design and the Organization of Research: A Cross-Case Analysis of National Institutes of Health Research Centers. Research Value Mapping Program, Georgia Tech, Atlanta, GA.

Camagni, R., 1993. Inter-firm industrial networks: the costs and benefits of cooperative behavior. Journal of Industry Studies 1 (1), 1–15.

Chompalov, I., Shrum, W., 1999. Institutional collaboration in science: a typology of technological practice. Science Technology and Human Values 24 (3), 338–372.

Chompalov, I., Genuth, J., Shrum, W., 2002. The organization of scientific collaborations. Research Policy 31 (5), 749–767.

Clark, B.R., 1983. The Higher Education System: Academic Organization in Cross-National Perspective. University of California Press, Los Angeles.

Clarke, A.E., 1998. Disciplining Reproduction: Modernity, American Life Sciences, and the "Problems of Sex". University of California Press, Berkeley.

Colino, S., 2004. No Longer a Mere Nuisance: As Incidence Rises with Obesity, Medical Community Begins to Take Pcos Seriously. Washington Post April 20. Final Edition ed., sec. Health.

Crane, D., 1972. The Invisible College. University of Chicago Press, Chicago.

Crow, M., Bozeman, B., 1998. Limited by Design: R&D Laboratories in the U.S. National Innovation System. Columbia University Press, New York.

Edge, D.O., Mulkay, M.J., 1976. Astronomy Transformed: The Emergence of Radio Astronomy in Britain. Wiley-Interscience Press, New York.

Etzkowitz, H., 2001. The second academic revolution and the rise of entrepreneurial science. IEEE Technology and Society Magazine 20, 18–30.

Etzkowitz, H., Leydesdorff, L., 2000. The dynamics of innovation: from national systems and 'Mode 2' to a triple helix of university–industry–government relations. Research Policy 29, 823–833.

Etzkowitz, H., Webster, A., Gebhardt, C., Terra, B.R.C., 2000. The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm. Research Policy 29 (2), 313–330.

Farquhar, C., 2000. History of polycystic ovary syndrome. In: Kovacs, G.T. (Ed.), Polycystic Ovarian Syndrome. Cambridge University Press, Cambridge.

Fisher, L.M., 1996. How strategic alliances work in biotech. Strategy and Business.

Freeman, J., Hannan, M.T., 1983. Niche width and the dynamics of organizational populations. American Journal of Sociology 88 (6), 1116–1144.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. Sage, London.

Goldman, A., 1986. Epistemology and Cognition. Harvard University Press, Cambridge, MA.

Gulati, R., 1995. Social structure and alliance formation patterns: a longitudinal analysis. Administrative Science Quarterly 40 (4), 619–652.

Hagedoorn, J., 1993. Understanding the rationale of strategic technology partnering—inter-organizational modes of cooperation and sectoral differences. Strategic Management Journal 14 (5), 371–385.

Hagedoorn, J., Link, A.N., Vonortas, N.S., 2000. Research partnerships. Research Policy 29 (4–5), 567–586.

Hagstrom, W., 1965. The Scientific Community. Basic Books, New York.

Hargens, L.L., Mullins, N.C., Hecht, P., 1980. Research areas and stratification processes in science. Social Studies of Science 10 (1), 55–74.

Katz, J.S., Martin, B.R., 1997. What is research collaboration? Research Policy 26 (1), 1–18.

Katz, M.L., 1986. An analysis of cooperative research and development. RAND Journal of Economics 17, 527–544.

Kekale, J., 2002. Conceptions of quality in four different disciplines. Tertiary Education and Management 8, 65–80.

Knorr-Cetina, K., 1999. Epistemic Cultures: How the Sciences Make Knowledge. Harvard University Press, Cambridge.

Kovacs, G., Burger, H.G., 2000. Introduction—Polycystic Ovarian Syndrome Is Not Just a Reproductive Problem. In: Kovacs, G.T. (Ed.).

Krige, J., 1993. Some socio-historical aspects of multinational collaborations in high-energy physics at Cern between 1975 and 1985. In: Crawford, E. (Ed.), Denationalizing Science: The Contexts of International Scientific Practice. Kluwer Academic Publishers, Dordrecht, pp. 233–262.

Landry, R., Amara, N., 1998. The impact of transaction costs on the institutional structuration of collaborative academic research. Research Policy 27, 901–913.

Lee, S., Bozeman, B., 2005. The effects of scientific collaboration on productivity. Social Studies of Science 35 (5), 673–702.

Lemaine, G., Macleod, R., Mulkay, M., Weingart, P. (Eds.), 1976. Perspectives on the Emergence of Scientific Disciplines. The Hague, Mouton.

Lenoir, T., 1997. Instituting Science: The Cultural Production of Scientific Disciplines. Stanford University Press, California.

Leydesdorff, L., Etzkowitz, H., 1996. Emergence of a triple helix of university–industry–government relations. Science and Public Policy 23, 279–286.

Leydesdorff, L., Etzkowitz, H., 1998. The triple helix as a model for innovation studies. Science and Public Policy 25 (3), 195–203.

Link, A.N., 1990. Strategies for cooperation in R&D. In: Khalil, T., Bayraktar, B. (Eds.), Management of Technology. Institute of Industrial Engineering, Miami.

Link, A.N., Bauer, L.L., 1987. An economic analysis of cooperative research. Technovation 6, 247–260.

Link, A.N., Teece, D.J., Finan, W.F., 1996. Estimating the benefits from collaboration: the case of sematech. Review of Industrial Organization 11 (5), 737–751.

Lodahl, J.B., Gordon, G., 1972. The structure of scientific fields and the functioning of university graduate departments. American Sociological Review 37, 57–72.

Melin, G., 2000. Pragmatism and self-organization—research collaboration on the individual level. Research Policy 29 (1), 31–40.

Meyer, J.W., Rowan, B., 1977. Institutionalized organizations: formal structure as myth and ceremony. American Journal of Sociology 83 (2), 340–363.

Mowery, D., 2001. The Changing Role of Universities in the 21st Century U.S. R&D System. Aaas Science and Technology Policy Yearbook.

Mowery, D.C., Oxley, J.E., Silverman, B.S., 1998. Technological overlap and interfirm cooperation: implications for the resource-based view of the firm. Research Policy 27 (5), 507–523.

Mullins, N.C., Hargens, L.L., Hecht, P.K., Kick, E.L., 1977. Group structure of co-citation clusters: a comparative-study. American Sociological Review 42 (4), 552–562.

Polodny, J.M., Page, K.L., 1998. Network forms of organization. Annual Review of Sociology 24, 57–76.

Polson, D.W., Adams, J., Wadsworth, J., Franks, S., 1988. Polycystic ovaries—a common finding in normal women. Lancet 1, 870–872.

de Solla Price, D.J., Beaver, D., 1966. Collaboration in an invisible college. American Psychologist 21, 1011–1018.

Rogers, J.D., Bozeman, B., 2001. Knowledge value alliances: an alternative to the R&D project focus in evaluation. Science Technology and Human Values 26 (1), 23–55.

Rosenberg, N., Nelson, R.R., 1994. American universities and technical advance in industry. Research Policy 23, 248–323.

Shrum, W., Chompalov, I., Genuth, J., 2001. Trust, Conflict and Performance in Scientific. Social Studies of Science (Sage), vol. 31. Sage Publications Ltd, p. 681.

Sinha, D.K., Cusumano, M.A., 1991. Complementary resources and cooperative research: a model of research joint ventures among competitors. Management Science 37 (9), 1091–1106.

Snow, C.P., 1964. The Two Cultures: And a Second Look: An Expanded Version of the Two Cultures and the Scientific Revolution. Cambridge University Press, Cambridge.

Stein, I.F., Leventhal, M.L., 1935. Amenorrhea associated with bilateral polycystic ovaries. American Journal of Obstetrics and Gynaecology 29, 181–186.

The Rotterdam ESHRE/ASRM-Sponsored PCOS Consensus Workshop Group, 2004. Revised 2003 consensus on diagnostic criteria and long-term health risks related to polycystic ovarian syndrome. Fertility and Sterility 81 (1), 19–25.

Turner, J.L., Miller, M., Mitchell-Kernan, C., 2002. Disciplinary cultures and graduate education. Emergences 12 (1), 47–70.

van Gigch, J.P., 2002a. Comparing the epistemologies of scientific discipline in two distinct domains: modern physics versus social sciences. Part Ii. Epistemology and knowledge characteristics of the 'New' social sciences. Systems Research and Behavioral Science 19, 551–562.

van Gigch, J.P., 2002b. Comparing the epistemologies of scientific discipline in two distinct domains: modern physics versus social sciences. Part I. The epistemology and knowledge characteristics of the physical sciences. Systems Research and Behavioral Science 19, 199–209.

Whitmeyer, J.M., 2000. Effects of positive reputation systems. Social Science Research 29, 188–207.

Youtie, J., Libaers, D., Bozeman, B., 2006. Institutionalization of university research centers: the case of the national cooperative program in infertility research program. Technovation, forthcoming.