Institutional Collaboration in Science: A Typology of Technological Practice

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An increase in the scale of modern science is associated with the proliferation of a new kind of research formation: collaborations involving teams of researchers from several organizations. Historical and sociological studies indicate substantial variation in such formations, but no general classification scheme exists. The authors provide the outline of a scheme through a systematic analysis of multi-institutional collaborations that span a variety of fields in physical science. First, general dimensions of scientific collaborations were identified through a qualitative, historical analysis of collaborations in high energy physics, space science, and geophysics. Next, the authors used informants in five new areas to collect systematic information on twenty-three recent collaborations. Finally, cluster analysis was employed to develop a variety of classification schemes and examine their relationships with outcome dimensions. Results show that a classification based on a broad conception of technological practice is superior to others in its ability to predict perceived success, trust, stress, conflict, and documentary routines.

One of the most significant developments in twentieth-century science is the proliferation of projects that require the resources and expertise of multiple teams of researchers. Indeed, the growth of big science is not simply an increase in the scale of research, measured by exponential growth of the number of scientists and the number of their publications (de Solla Price

AUTHORS' NOTE: This article was presented at the 1997 annual meeting of the Society for Social Studies of Science in Tucson, Arizona. Funding for the project was provided by the Andrew W. Mellon Foundation, the National Historical Publications and Records Commission, and the National Science Foundation. Our collaborators at the Center for the History of Physics at the American Institute of Physics completed the first two phases of this study. Joan Warnow-Blewett, Joel Genuth, Spencer Weart, Anthony Capitos, and Joe Anderson were also instrumental in the planning and design of this project.

Science, Technology, & Human Values, Vol. 24 No. 3, Summer 1999 338-372

1963), but an increase in collaborations involving a variety of different institutions. Such interorganizational efforts are found in all areas of science that require significant resources and complex instrumentation. Whether the objective is to produce experiments in particle accelerator centers, build instruments or telescopes, or explore the ocean depths, the copresence of scientists, engineers, project managers, technicians, graduate students, and staff from a variety of organizations constitutes a novel development in the social organization of science. Following the tradition from the first two phases of the American Institute of Physics (AIP) project, we term these formations *multi-institutional collaborations*.[1]

Why are collaborations important for social studies of science? Historians, sociologists, and anthropologists have demonstrated that the examination of multi-institutional collaborations helps us to understand processes involving external relationships, consensus formation, and cultural construction. Owing to the financial requirements, risk, and visibility of many research projects, decisions about resources and participation cannot be left to a single scientist or even a single program manager. They may result in public controversy and congressional debates (Galison and Hevly 1992). Because some collaborations encompass a large proportion of researchers in a given scientific specialty, their establishment can have a major impact on consensus formation or genealogical change in a field (Knorr-Cetina 1995). Since instrumentation brings together large numbers of participants—physically or electronically—subcultures may develop with implications for stratification processes (Traweek 1988).

In a broader sense, multi-institutional collaborations are important sociologically because modern production and services have increasingly become knowledge based, with the new knowledge often being created as a result of collaborative endeavors. Efforts to empirically describe and theoretically explain this recent form of organization of research work have just begun in social studies of science (Zabusky 1995; Schild 1997; Knorr-Cetina 1998). Most of these studies share a microsocial focus, qualitative methodology, cultural-anthropological orientation, case study approach, and emphasis on a single location (ESA, CERN) and on a single research specialty (space science, high-energy physics, polar research). They provide a useful discussion of some of the important variables that describe scientific collaborations. At the same time, they suffer from the following weaknesses: insufficient examination of structural characteristics at the expense of cultural processes, unrepresentativeness and lack of generalizability, focus on a particular location instead of multiple locations (a more typical case of a multi-institutional collaboration in a number of fields), failure to distinguish factors in order of importance (multiple factors like communication, division of labor, work as a process, technology, negotiation, size are all considered “crucial”), inability to systematically codify the proposed theoretical concepts, and neglect of the relationships between properties of collaborations and their outcomes. One way to overcome these shortcomings is to put greater emphasis on a more structural, macrosociological, and comparative quantitative analysis of multi-institutional collaborations and their consequences. The first step is to systematically study the variation in forms of interorganizational collaborations across scientific fields by constructing multiple typologies along basic structural dimensions.

Thus, although a great deal of research has demonstrated the importance of multi-institutional collaborations and identified many of the significant dimensions involving structure and process, two questions still confront scholars: What types of collaborations are there? How, if at all, are these types related to important outcomes?

Significant variation among collaborations is now widely recognized. Its mere demonstration is no longer as important as the question of whether there are identifiable patterns of social organization. Maienschein (1993), with reference to the biological sciences, proposed a threefold classification of collaborations based on the reasons for collaborating: to promote an efficient division of labor, to enhance credibility, and to build community. In view of the scarcity of such endeavors, our guiding question is whether we can usefully characterize multiple types in a systematic fashion; that is, can a robust classification scheme be developed? Accordingly, the first problem is to determine the general dimensions that characterize multi-institutional collaborations in science, operationalize these dimensions, and examine the extent to which they allow us to distinguish empirical clusters to form a classification. But such a classification scheme is of limited value in the abstract. It becomes significant insofar as the types defined are related to important sociological outcomes. The second problem is to identify and develop indicators of these processes and determine whether they bear any relationship to the groups identified in the classification.

Previous classifications have not specifically focused on multi-institutional collaborations in science and technology. However, there exists an extensive body of literature that deals with classification of organizational forms. There are three broad categories within which general organizational classifications can be grouped: the functionalist approach, which classifies organizations according to their goal or function (see Parsons 1960; Etzioni 1961; Blau and Scott 1962); the empirical approach, or the attempt to derive a taxonomy of organizations from a representative sample of a variety of formations without a preconceived model (Haas, Hall, and Johnson 1966); and the structural approach, which uses structural characteristics as the basis of the typology (Pugh, Hickson, and Hinings 1969). Since these general organizational classifications commonly deal with establishments outside the sphere of R&D, they can be of limited use here.

Three classifications that deal specifically with science are Whitley's (1984) typology of scientific fields, Crow and Bozeman's (1987) typology of R&D laboratories, and Shrum and Morris's (1990) typology of technical systems. Whitley (1984, 159-63) argues that sciences can be classified into seven major types based on the degree of mutual dependence between researchers and the degree of task uncertainty in producing and evaluating knowledge claims. Crow and Bozeman (1987), on the other hand, claim that the old classification of government, industry, and university laboratories has outlived its usefulness. They propose a typology of research organizations that is based on a "publicness matrix." The latter results from the cross tabulation of two measures—level of governmental influence and level of market influence—with three categories each. Thus, laboratories fall into nine types, ranging from public generic to independent market. Shrum and Morris (1990, 249-53) employ three dimensions to classify large scientific structures consisting of multiple organizations (technical systems), forms that are similar to multi-institutional collaborations. These axes are identified as economic (collective or private beneficiary of the outcome), size and complexity, and epistemological (degree of uncertainty).

In the first part of this article, we specify five dimensions previously identified as important to the operation of scientific collectivities. Next, general findings from a qualitative, historical analysis of collaborations in high-energy physics, space science, and geophysics are described, an analysis we incorporated directly into the design of the questionnaire. Then, the methodology for the study of twenty-three recent collaborations in five general areas is outlined, followed by an analysis that develops a variety of classification schemes and examines their relationships with outcome dimensions. The results indicate that a classification based on technological practice is superior to other structural dimensions in its ability to predict perceived success, trust, stress, conflict, and documentary routines.

Outcomes of Multi-Institutional Collaborations

Contemporary scholars have distinguished trust, stress, documentary practice, conflict, and perceived success as critical dimensions in knowledge production.[2]

The role of trust in interorganizational relations has been well documented (Alter and Hage 1993; Ring and Van de Ven 1994; Browning, Beyer, and Shetler 1995; Gulati 1995; Kramer and Tyler 1995). Prior interactions and repeated ties contribute to the establishment of high trust, which facilitates efficient cooperation in alliances, joint ventures, partnerships, consortia, and other forms of collaboration (Ring and Van de Ven 1994; Gulati 1995). In fact, social ties and capital links reinforce a culture of trust, which in turn stimulates cooperation between various sorts of organizations (Alter and Hage 1993). Some initial degree of trust is a necessary prerequisite for successful foundation of R&D consortia such as Sematech (Browning, Beyer, and Shetler 1995).

It is not an exaggeration to claim that trust is required for all systems of knowledge production, especially when scientific institutions and individual researchers have to coordinate their efforts toward a common goal. Since most multi-institutional collaborations are typically complex social formations that tackle varied and complex research problems, trust within the collaboration acquires even greater importance. The recognition of trustworthy persons is a necessary component in building research networks (Shapin 1995). In collaborations, it is not merely the identification of trusted associates at the outset but the continual reliance on mutually agreed objectives, practices, technical alterations, and project deadlines that makes trust such an important factor for the duration of a project.[3] We decided to focus on trust as a result of the social organization and practices of collaborations, although in other circumstances it can be studied as a prerequisite of successful interorganizational arrangements.

Scientists engaged in interorganizational research collaborations are often exposed to high levels of stress for a variety of reasons: complex technological demands, unclear or changing social arrangements, the need to coordinate geographically dispersed groups, the clash of interests, ambiguity in the distribution of authority, and the pressure to perform according to the expectations of funding agencies, as well as time constraints. The last factor is especially important, giving rise to "existential worries," since time is a critical resource in working together (Zabusky 1995). In many cases, the degree of stress induced by schedules and deadlines is higher than in routine academic settings.[4] This is mainly due to pressure from funding agencies and participating institutions to perform within tight budgets and under time constraints.

Communication demands are intense among large projects involving multiple organizations, requiring both informal and formal means of communication. Given the resources involved and the complexity of projects, massive documentation in the form of notes, memoranda, proposals, plans, minutes, blueprints, analyses, and drafts must be transferred among teams long before published results begin to appear. Such documentary practice is not the detritus of science but the very stuff of its construction, the backbone of its work organization (Latour 1987). The production of inscriptions is significant for the process of multi-institutional collaborations long before the outside scientific community can begin to assess and absorb the results of the project.

The role of accounts as explanations of social behavior and social events has long been recognized in sociology (Orbuch 1997). The reconstruction of such accounts depends heavily on the preservation of written documents. Documentary practice as the generation and preservation of inscriptions is essential for the work organization of multi-institutional collaborations. In the form of artifacts, such practice also constitutes the “social memory” of collaborations in science.

The extent to which these records are dispersed is an indicator of project centralization and the degree to which accounts of the collaboration may be reconstructed by historians and archivists (Warnow-Blewett 1997).

All social formations that involve ongoing use of resources, even those that involve only prestige, have the potential for conflict. Conflict is an inherent element of organizations because the bases of conflict such as functional differentiation between subunits, heterogeneity of the staff, styles of supervision, form of power, the reward system, and so on are part of the organizational system (Hall 1977). As organizations sui generis, multi-institutional collaborations are not devoid of disagreements, contentions, and conflict. From a sociological point of view, conflicts are especially interesting because they provide insight into the dynamics of social cohesion in the collaboration, as well as what this might be due to. Conflicts may arise not only in negotiations for resources but because of differences in technical approaches, task dependencies, the allocation of credit, and timelines for the completion of work.[5] Disagreements can be both disruptive and stimulating for the social fabric of interorganizational formations (Assael 1969; DiStefano 1984; Alter 1990). In multi-institutional scientific collaborations, conflict is not necessarily associated with negative outcomes—the positive functions of social conflict are well known and have been, if anything, more obvious in science and technology studies given the importance of intellectual contention in both positivist and constructivist accounts of science. But the macrostructure of conflict within scientific disciplines cannot be understood without first describing the microstructure of conflict within large-scale projects that generate fundamental directions for a field (Knorr-Cetina 1995).

Of course, success or “performance” is the most valued outcome of science, the criterion in terms of which projects are justified and evaluated. Various measures of success have been used, including the number of publications, citations, and patents (Pelz and Andrews 1966; Irvine and Martin 1985). These are usually considered as objective indicators that reflect productivity. Without recapitulating the debates about the problems with these measures, we feel that even were there an independent, aperspectival standpoint from which success could be determined, *perceptions* of success are crucial. This is because the ultimate evaluation of a program affects the reputations of collaborators and their likelihood of acquiring further resources, as information about project outcomes is circulated within the network of significant actors. Multi-institutional collaborations may be defined as successful or unsuccessful in terms of many dimensions—the extent to which they accomplish objectives, are completed on time or within budget, produce results that are used by others within and outside the field, and so forth. Yet, there is often a general sense in which projects—especially those that require substantial commitments of resources and personnel—are evaluated positively or negatively by the scientists who work on them. It is in this sense that we speak of the success of a collaboration.[6]

These five variables reflect important aspects of collaborations in science. Conflict, trust, and stress are instances of interpersonal relations. Such relations are essential for gaining insight into how cooperation between organizations can be viewed as a process. Interpersonal relations and documentary practice can be analyzed as both independent and dependent variables in a study of multi-institutional collaborations. Here, we emphasize their interpretation as outcomes of structural properties of interorganizational scientific formations. This is consistent with the goals of the AIP study on which this research is based. Moreover, from the point of view of science policy makers, it is more important to determine how the origin, social organization, structure, and management of collaborative projects affect their social climate, performance, and documentary routines than how these aspects of collaborative work manifest themselves.

Structural Dimensions of Multi-Institutional Collaborations

The origin of this work dates to the late 1970s when researchers at the AIP, engaged in a study of government laboratories, recognized the existence of a documentation problem for multi-institutional collaborations. The problem arose from the fact that teams of researchers from multiple institutions, often involved in large-scale experiments, were disbanding after the project was completed. What kinds of records did these projects create, and where were the most important records kept? A long-term project began in 1989 to address the problem of documentation from a historical and sociological perspective in three phases. The first phase examined twenty collaborations in high-energy physics. The second examined six collaborations in space science and eight in geophysics. In these phases, a total of approximately 500 unstructured interviews were conducted by historians and archivists, focusing on the history and organization of the collaborations, as well as communication practices, management, and outcomes.[7]

In high-energy physics, most collaborations formed around accelerators in two general patterns. In some, a few leaders were committed to the exploration and use of all facets of a particle, process, or experimental technique. Such collaborations performed strings of experiments in succession. In others, coalitions of physicists, representing diverse scientific interests but with a common interest in a detector and accelerator, performed freestanding experiments. Although all collaborations had a spokesperson who would serve as a link between the collaboration and the laboratory, their responsibility and duties varied considerably. In string collaborations, the spokespersons were typically physicists who had conceived of measurements that could be accomplished with incremental changes to previous designs; in freestanding collaborations, the spokespersons were those who initially suggested detector components or other arrangements that could attract physicists with diverse interests. In the latter, administrative burdens were much greater. Spokespersons were more likely to shift owing to the lack of required organizational skills or simply the onerous level of work required. Hence, collaborations differed in terms of their levels of organization, leadership, joint planning, and interdependence, as well as the technological practices that were constructed around fixed-target and colliding-beam experiments.

Phase 2 began to reveal more diversity in multi-institutional collaborations as the focus shifted to space science and geophysics. Here, the role of government was extremely significant. The formation of collaborations was a longer, more political endeavor. Industrial contractors played a key role in the development of instruments that operated in the field for long periods. A wider range of sectors was involved in these collaborations than in high-energy physics.

In space science, collaborations were managed by government in space flight centers, whereas in geophysics, collaborations formed with multiple funding agencies and interests. Projects in these areas were field oriented, with important structural contrasts to high-energy physics. Often, experimental techniques were borrowed from other branches of physics, and detection techniques were developed by the military. Agencies such as NASA and ESA provided management authority for engineers in flight centers, whereas teams of senior and junior scientists built instruments to meet the engineering constraints of a spacecraft. Because they could deal individually with project managers, the autonomy of individual projects could be maximized, with a project scientist designated to coordinate issues among principal investigators. In some cases, a new subcommunity of scientists was created, but only after political campaigns to marshal support within the space agency and the scientific community.

In geophysics, numerous funding agencies with diverse goals and structures did not impose a single organizational form, but projects tended to differentiate according to whether they imported or aggregated techniques (for instance, in the study of a strategic geographical area or a project to broaden the scope of coverage to a global scale). In the former, capabilities or techniques that had proven useful in other scientific areas or in industrial work were introduced to academic geophysics. Scientists formed consortia and hired executives to manage deployment of instruments with the input of standing committees. In the aggregating model, a diversity of experimental specialists were mobilized to investigate a site or process. A science management office (SMO) was then organized to oversee the collection of data. Rather than recruiting scientists from outside the group to fill positions based on the unique opportunities offered by a technique-importing project, the director of an SMO had to persuade specialists that they would be better off working within the project framework rather than pursuing individual interests. Again, the scale, importance, or complexity of the aggregation meant that instrumentation played a fundamental role in the collaboration.

The study of high-energy physics, space science, and geophysics enabled us to identify seven primary dimensions that were important in multi-institutional collaborations.[8] All of the interviews from the first phases were assessed and categorized in terms of major topics or themes.[9] These major themes, along with other factors identified in the qualitative analysis, led to the recognition of general and specific properties of collaborations. Specific properties included aspects that seemed to be idiosyncratic for a particular field (such as geophysics), whereas general properties included traits characteristic of interorganizational entities that were common across fields. We identified seven major structural dimensions of multi-institutional collaborations: project formation, magnitude, interdependence, communication, bureaucracy, participation, and technological practice. These dimensions and some of their constituents are summarized briefly.

1. *Project formation and composition*. Collaborations have a variety of origins. In some, one sector is dominant, both in origin and constitution. Others encompass academic, governmental, and private sectors. The role of preexisting relationships varies, as well as supervision and funding agency involvement.
2. *Magnitude*. Some collaborations are larger than others, in terms of the number of organizations, individual participants, subcontracts, graduate students, and teams. Costs for personnel and instruments differ a great deal, as does the length of the project.

3. *Interdependence*. Data sharing, the autonomy of organizational teams with respect to instrumentation, and the analysis of joint data distinguish collaborations in terms of the interdependence of their constituent social formations.
4. *Communication*. Relations with the public are sometimes managed by a designated public relations officer. Results may or may not be popularized, and restrictions may be placed on publications. Internal to the project itself, a communications center is sometimes used, and projects may depend more or less on formal communication modes.
5. *Bureaucracy*. The degree of bureaucracy is a fundamental aspect of organizational structure and has been conceptualized in a wide variety of ways. Phases 1 and 2 showed that collaborations could be distinguished according to the presence of a lead center, designated scientific and administrative leaders, and the division of authority between them. The degree of formalization encompasses the presence of written contracts and coordination of schedules, as well as the presence of outside formal evaluation. Projects also vary in terms of levels of authority, style of decision making, and presence of advisory committees.
6. *Participation*. Graduate students are involved more in some collaborations than in others. Principal scientists may be more or less interested in and devoted to a project. International involvement is sometimes crucial for a project, but in others it plays no role.
7. *Technological practice*. Multi-institutional collaborations always use technological devices but vary in the extent of their dependence and the forms of use. Characteristics of these uses allow us to distinguish a broad array of factors that may be designated the technological practice of the collaboration. Some design and build their own equipment. Some of these instruments are state-of-the-art innovations. Instruments may be changed during the course of the project. Technological practice is not merely instrumentation—it also includes the management of topics and results checking.

Scientists themselves are keenly aware of the crucial role that technology plays in pushing forward the state of the art in their respective fields:

> It turns out that nearly all of the really exciting discoveries in astronomy in this century have been a result of technological innovation. So there's no question that the instrumentation side of things is absolutely vitally important, and I think it's often the scientists who get the glory for having discovered something. (interview with scientist-based astronomer)

Not only are the building and use of hardware significant, but also the notion of practice as technical change, innovation, management of research topics, and organization of analytical tasks. Thus, technological practice could provide the most potent typological framework for explaining the social organization of multi-institutional scientific collaborations and predicting their consequences. Several findings and observations seem to favor this line of reasoning. First, most collaborations are heavily instrumental. Even when their main purpose is to do fundamental research, they depend to a substantial degree on experimentation, observation, or some other form of data analysis involving sophisticated equipment or some sort of technical procedure. Second, past research shows that in a number of fields, interorganizational projects are socially organized and managed in specific ways according to the particular manner in which they rely on technology or use facilities to acquire data. A case in point is the differentiation between fixed-target and colliding-beam experiments in high-energy physics (HEP) (American Institute of Physics 1992), as well as between technique-importing and technique-aggregating projects in geophysics (American Institute of Physics 1995). The technological imperative is also obvious in other studies of cooperative arrangements in science. Both Zabusky (1995) and Knorr-Cetina (1998), for instance, notice that technical objects have the ability to shape group structure and management of large projects in space science and HEP, respectively. Third, often the sole objective of a collaborative venture is to build equipment (e.g., telescope-building collaborations in ground-based astronomy). Thus, the success of such interorganizational projects is measured by the extent to which this objective has been accomplished. Fourth, other sociological outcomes of R&D collaborations like conflict, documentary routines, trust, and stress could reasonably be expected to be affected by decisions on technical matters, deadlines to get certain instruments running within preestablished parameters, the selection of topics to be analyzed, and other aspects of technological practice.

So a strong case can be made on theoretical grounds that a broadly defined concept of technological practice ought to be useful as the most important factor shaping the social organization of multi-institutional collaborations. However, it is our belief that given the present state of our knowledge on collaborations in science, this issue can and should be resolved empirically.

Methodology

A structured questionnaire, including both fixed and open-ended items, was developed to provide indicators of the dimensions identified for this third phase of the study. Following consultations with science historians, journalists, and government program officers, ten broad fields were chosen. These were reduced to five after preliminary interviews: uses of accelerators, ground-based astronomy, materials research, medical physics and clinical medicine, and computer-centered collaborations. The last category is not as clear-cut as it might seem from the subsequent discussion, but is probably the term that captures one of the few common features of the projects in this group.

Twenty-three multi-institutional collaborations were examined. The first area, uses of accelerators, was chosen because experimental groups have long used particle accelerators in special energy ranges in ways similar to HEP (n = 6 collaborations). Ground-based astronomy was chosen because interorganizational collaborations are prominent in the construction of telescopes (Wisconsin-Yale-Kitt Peak project, Columbus, and Magellan), as well as in doing very long baseline interferometry (n = 7 collaborations). Materials research illustrates collaborations between university, industrial, and government laboratories such as the Superconductivity Center, microchip consortia, and Polymer Interface Center (n = 4). In medical physics and clinical medicine, multi-institutional collaborations are usually formed to pursue a new technique or therapy such as digital mammography or image-guided needle biopsy (n = 3). The final area, computer-centered collaborations, is not as traditional as the other four, but we felt it was important to provide for a type that may become significant to the future of scientific research. The upper atmospheric collaboratory was included, as well as collaborations in parallel computation and cosmology (n = 3).

Interviewees were scientists in top administrative positions, those who performed scientific leadership roles in a particular project, and those that held key roles throughout the duration of the collaboration. Our goal was to interview at least three participants in each project. Personal interviews were conducted with seventy-eight researchers. The number of interviews ranged between two and six per collaborative project, with a mean of slightly over three.

Once the data from these interviews were collected and coded, individual records were aggregated to create the collaboration file used as the primary data source in the following analysis. The latter contained one observation for each collaboration. First, information on each of the variables was averaged over the several informants for each project. Next, each aggregated variable was examined in relation to the individual component scores to determine the most reasonable aggregate score. Aggregate file variables were recoded to reflect the closest approximation to this “best summary” of the opinions of the individual scientists involved in a particular collaboration according to the following judgmental procedure.

The mode, median, or, in a few cases, opinion of the scientific leader was used. The mode was used as the primary selection factor, since it represents the dominant opinion with regard to the designated trait more accurately than the median and the mean. (In the case of a collaboration represented by three interviews, the mode would indicate an agreement by at least two informants.) However, in some cases there was no clearly defined mode, or there were two. Then, the median served as a way to provide an estimate for a particular variable. Finally, if this last criterion also failed, the value produced by the interview with the scientific leader was applied.[10]

Results

We first describe the characteristic features of our sample in terms of seven structural dimensions. Evidence is then presented to suggest that a general concept of technological practice is superior to other types of clustering in its ability to predict five outcome dimensions. Finally, mean differences produced by the classification on these dimensions are tested using analysis of variance methods. In the next section, we examine the groups produced by this classification and their characteristics in detail.

Table 1 presents three measures for each structural dimension, indicating the general dimensions of our sample of multi-institutional collaborations. Universities instigated almost half of the projects, whereas the remainder originated as a joint effort of two or more sectors (either universities and national laboratories, as in uses of accelerators, or universities and the corporate sector, as in materials research). There was a single dominant sector in the formation of most collaborations, which were largely built on preexisting relationships. In over four-fifths of the collaborations, the participants knew each other or had previously worked together.

The magnitude of collaborations in ground-based astronomy, heavy-ion physics, materials research, medical physics, and computer-centered projects is indicated by size and duration. Averaging nearly forty participants from six different organizations (scientists, engineers, graduate students, and postgraduates), the size of the interpersonal network comprising these projects ranged from a minimum of 11 to maximum of 120 individuals.[11] On average, two years lapsed from the original idea for the project to its funding.

Overall, the fact of interdependence between teams in a project does not entail close mutual dependence on a daily basis. The reported degree of autonomy of individual research teams with respect to instrumentation, data sharing, and the analysis of shared data was fairly high. This suggests that as a whole, collaborations were fairly loosely run and the separate units were comparatively autonomous in most technical matters. In these five scientific fields, project completion required various areas of expertise provided by the separate participating organizations rather than a common endeavor in which all share the same or similar specialization.

Table 1. Characteristics of Multi-Institutional Collaborations (*N* = 23)

Variable	
Project formation and composition	
% University instigated	48
Mean preexisting relationships[a]	2.74
% Dominant sector	70
Magnitude	
Mean number of participants	39.39
Mean number of organizations	6.13
Mean years from original idea to funding	2.09
Interdependence	
Mean degree of instrumentation autonomy[a]	2.48
Mean degree of data-sharing autonomy[a]	2.83
Mean degree of autonomy in analysis[a]	2.61
Communication	
% Communications center	61
% Receiving public attention	70
% Managing external communication	44
Bureaucracy	
% Designated scientific leader	70
% Designated administrative leader	70
% Fewer levels of authority than university department	61
Participation	
Mean degree of graduate student participation[a]	2.48
Mean degree of central interest[a]	2.52
% International participation	35
Technological practice	
% Designing own equipment	70
% Building own equipment	65
% Advance in the state of the art	74

a. 1 = *low*, 3 = *high*.

Networking involved communication patterns within the collaboration and relations with outside agencies. In a majority of projects, communication was directed from a center, with a single primary location for incoming and outgoing information concerning scientific or administrative issues. (Sixty-one percent of the multi-institutional collaborations had such a communications center.) But external communication of scientific results, primarily in scientific forums, was not generally managed by the collaboration. Compared to high-energy physics, where reading the first drafts and signing off papers within the collaboration was a common practice, publication and presentation at conferences in the five fields here was much less regulated.

Most of the projects also received a fair amount of public exposure. Informants in more than two-thirds of the cases studied believed that their collaboration had been a focus of public attention.

Over two-thirds of the projects in our sample had both a designated scientific leader and a designated administrative leader. The majority of the remaining collaborations had some administrative body such as an executive committee or board of directors responsible for decision making on various issues. However, when we asked our informants to compare the collaboration with a typical academic department, most said that their projects had fewer levels of authority. Hence, it is a mistake to overemphasize the degree of hierarchy present in multi-institutional collaborations.

Three aspects of participation in collaborative research projects stand out. Collaborative projects are not in general peripheral interests of the participants. In the large majority of cases, the collaboration is the central interest of scientists. Of course, graduate student participation is important with regard to training and hands-on experience of future researchers. Most graduate students are heavily involved in research and experimentation, even though they often represent a small part of each collaboration. About one-third of the multi-institutional collaborations in the sample included significant international participation.

As in high-energy physics, space science, and geophysics, the multi-institutional collaborations in the third phase are truly technoscientific collaborations. Seventy percent and sixty-five percent of all collaborations designed and built their own equipment, respectively. Roughly three-quarters of these interorganizational projects made a contribution to the state of the art. It appears that for the most part, scientific research proceeded hand in hand with solving technical problems, constructing and adjusting instruments, and continually modifying equipment.

Our principal analytical question is whether collaborations may be classified into types based on structural dimensions that are related to important outcome variables. Cluster analysis provides a useful tool for categorization,[12] whereas analysis of variance is appropriate for determining the relationship between types of collaboration and outcome dimensions.

Cluster analysis was performed for each of the seven major structural dimensions described above. Each analysis produces groups of collaborations based on different distinguishing criteria. The solutions used anywhere from two factors for interdependence to five factors for magnitude and participation. In addition, we developed two clustering solutions that cut across these seven structural dimensions.[13]

Which clustering solution is best? Clearly, different solutions may be preferred for different purposes, but we are unaware of any compelling theoreti-

Table 2. Summary of Analysis of Variance Results

	Outcome Dimensions				
Type of Clustering	*Success*	*Trust*	*Conflict*	*Documentary Practice*	*Stress*
Project formation					
Magnitude			X		
Bureaucratic organization			X	X	
Interdependence					
Participation					
Communication					
Technological practice	X	X	X	X	X
Seven-variable clustering			XX	X	
Four-variable clustering			XX		

NOTE: X denotes a significant analysis of variance at $p < .05$. The variables that measure the five outcome dimensions are described in Appendix B.

cal grounds for selecting one solution over another. Moreover, it seemed useful to examine the extent to which classifications were related to important outcome dimensions regardless of their theoretical significance.

Table 2 shows that clustering based on technological practice is superior to other structural dimensions in providing a classification that relates to outcomes. Each of the nine dimensions along the rows of the table was used to define discrete groups of collaborations. These discrete groups, or types, were used as independent factors in an analysis of variance for five sets of dependent variables. Clusterings by magnitude and bureaucratic organization—as well as the seven- and four-variable solutions—are related to reported conflict and documentation. However, only the clustering based on technological practice is related to each of the five outcome indicators.[14] The other solutions are at best related to two outcomes, whereas clusterings by project formation, participation, interdependence, and communication are unrelated to any outcome.[15] We conclude that technological practice is the most promising dimension for framing a classification of multi-institutional collaborations and devote the remainder of the article to its elaboration.

Figure 1 provides a dendrogram, or graphic representation, of the clustering by technological practice. This device facilitates a judgment about the number of clusters that best characterizes multi-institutional collaborations. There is no statistical means of determining a “correct” number of clusters. However, if we select the rescaled distance nine as a cut-off point for the final solution, there are four well-defined groups of collaborations. With a three-cluster solution, the distances at which clusters combine are quite large (i.e.,

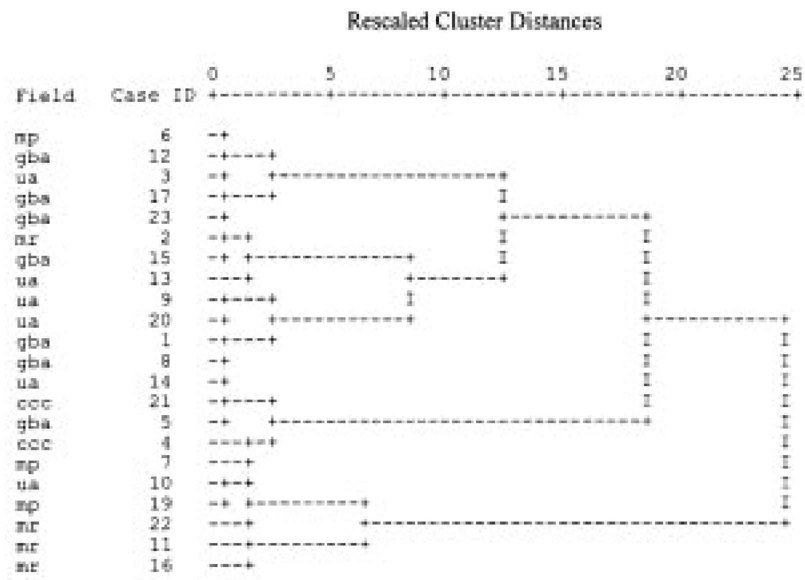

Figure 1. Dendrogram for technological practice clustering (Ward's method).
NOTE: mr = materials research, gba = ground-based astronomy, ua = uses of accelerators, mp = medical physics, ccc = computer-centered collaborations.

relative dissimilarity between the clusters being combined). A five-cluster solution is also a possibility, but then one cluster (at the bottom of the dendrogram) has a substantially different elevation than the other four. Increasing the threshold value by just one unit results in a four-cluster solution, which yields interpretable clusters of roughly equal sizes. Figure 2 provides the names of collaborations in each cluster, complementing the results from examining the dendrogram. Four clusters (types) were identified: managerial, decentralized, noninstrumental, and routine. A description of the distinguishing characteristics of these types is provided in the discussion.

The dendrogram shows that with one exception, the clusters do not exhibit field-specific differentiation. Three of four materials research projects are concentrated in cluster 4, but the main divisions are otherwise unrelated to the scientific areas that provided the basis for our sample. Collaborations in ground-based astronomy are found in every cluster except cluster 4. In

Type 1: Managerial

Case	*Field*	*Collaboration*
1	gba	Astrophysical Research Consortium
2	mr	S&T Center for Superconductivity
8	gba	Keck Telescope
9	ua	Positron Diffraction and Microscopy
13	ua	BNL E-814 and E-877
15	gba	Sagittarius A
20	ua	BNL E-878 and E-896

Type 2: Decentralized

Case	*Field*	*Collaboration*
3	ua	Dupont-Northwestern-Dow CAT
6	mp	Angiography Diagnostics
12	gba	VLBI Network
17	gba	Hobby-Eberly Telescope
23	gba	BIMA Array

Type 3: Noninstrumental

Case	*Field*	*Collaboration*
4	ccc	Grand Challenge Cosmology Consortium
5	gba	3mm. VLBI
7	mp	Radiology Diagnostic Oncology Group
14	ua	Crystal Structure of CTA and CTP
21	ccc	Upper Atmospheric Research Collaboratory

Type 4: Routine

Case	*Field*	*Collaboration*
10	ua	Advanced Light Source Beamline Collaboration
11	mr	Center for Polymer Interfaces and Macro-molecular Assembly
16	mr	Materials Partnership for Hybrid O-I Semiconductors
19	mp	National Digital Mammography Development Group
22	mr	Smart Materials Consortium

Figure 2. Classification of multi-institutional collaborations based on technological practice.

NOTE: mr = materials research, gba = ground-based astronomy, ua = uses of accelerators, mp = medical physics, ccc = computer-centered collaborations.

Phases 1 and 2 of this study, technological differences were fundamental to projects in high-energy physics, space science, and geophysics, but they were based on special characteristics of the practices that these fields entail. When technological practices are considered in the abstract, the distinctions are considerably more complex.

The mean differences in technological characteristics of the four types of projects are shown in Table 3 for the factors used in cluster analysis. Judging by the dispersion, clusters 1 and 4 are the least homogeneous among the four, with the largest standard deviations on most variables. Table 4 presents means and standard deviations for the nine variables that were used to con-

Table 3. Technological Practice Cluster Characteristics

	Factor 1		*Factor 2*		*Factor 3*		*Factor 4*	
	Mean	SD	*Mean*	SD	*Mean*	SD	*Mean*	SD
Cluster 1	.88	.16	.55	.38	.14	.20	.86	.24
Cluster 2	.97	.07	.33	.12	.75	.25	1.00	.00
Cluster 3	.00	.00	.60	.30	.35	.22	1.00	.00
Cluster 4	.63	.38	.13	.18	.35	.34	.00	.00
Total	.64	.42	.42	.32	.38	.33	.73	.43

NOTE: See Appendix A for factor composition.

Table 4. Cluster Means for Nine Technological Practice Indicators

Indicator	*Cluster 1*	*Cluster 2*	*Cluster 3*	*Cluster 4*	*Average*
1. Designing equipment	1.00	1.00	.00	.80	.73
	(.00)	(.00)	(.00)	(.45)	(.46)
2. Building equipment	1.00	1.00	.00	.60	.68
	(.00)	(.00)	(.00)	(.55)	(.48)
3. Subcontracting	.64	.90	.00	.50	.52
	(.48)	(.22)	(.00)	(.50)	(.48)
4. State of the art	.79	.80	.80	.40	.70
	(.39)	(.45)	(.27)	(.55)	(.43)
5. Time pressure	.57	.20	.40	.00	.32
	(.53)	(.27)	(.55)	(.00)	(.45)
6. Topic segmentation	.29	.00	.60	.00	.23
	(.39)	(.00)	(.55)	(.00)	(.40)
7. Team control	.29	1.00	.50	.60	.57
	(.39)	(.00)	(.50)	(.55)	(.47)
8. Instrument change	.00	.50	.20	.10	.18
	(.00)	(.50)	(.45)	(.22)	(.36)
9. Results checking	.86	1.00	1.00	.00	.73
	(.24)	(.00)	(.00)	(.00)	(.43)

NOTE: Standard deviations are in parentheses.

struct these factors. In the discussion, we return to these tables to examine each collaborative type in more detail.

Descriptive statistics showing differences between clusters on the five outcome dimensions are presented in Table 5, whereas Table 6 shows the results of an analysis of variance with each type of collaboration representing a separate group. The models for perceived success, trust, conflict, stress, and

Table 5. Descriptive Statistics for Five Dependent Variables by Technological Practice Cluster Membership

Dependent Variable	*Groups*	n	*Mean*	SD	SE
Success	1.00	7	3.3929	.4756	.1798
	2.00	5	4.0000	.0000	.0000
	3.00	5	3.7500	.2500	.1118
	4.00	5	3.3000	.4472	.2000
	Total	22	3.5909	.4401	9.384E-02
Trust toward others	1.00	7	2.3571	.4756	.1798
	2.00	5	3.0000	.0000	.0000
	3.00	5	3.0000	.0000	.0000
	4.00	5	3.0000	.0000	.0000
	Total	22	2.7955	.3982	8.489E-02
Conflict between teams	1.00	7	2.8571	.4756	.1798
	2.00	5	2.8000	.8367	.3742
	3.00	5	2.0000	1.0000	.4472
	4.00	5	1.6000	.5477	.2449
	Total	22	2.3636	.8616	.1837
Dispersion of records	1.00	7	1.7143	.4880	.1844
	2.00	5	3.6000	1.5166	.6782
	3.00	5	2.4000	1.1402	.5099
	4.00	5	2.0000	.7071	.3162
	Total	22	2.3636	1.1770	.2509
Stress	1.00	7	2.7857	.3934	.1487
	2.00	5	2.6000	.5477	.2449
	3.00	5	2.2000	.8367	.3742
	4.00	5	1.8000	.4472	.2000
	Total	22	2.3864	.6534	.1393

documentary practice are statistically significant at the .05 level, indicating that one or more contrasts between means is significant.

Projects from type 2 are rated as more successful than other technological types. The omnibus test provides support for the hypothesis that the sample means came from populations with significantly different means.[16] The strength of this relationship is measured by η^2. Thus, 41 percent of the variation in rated success is explained by the classification—a rather strong relationship by normal standards in the social sciences.[17]

For trust toward other researchers, the primary differences are between the first cluster and each of the other three types. Clusters 2, 3, and 4 exhibit uniformly high levels of trust toward colleagues.[18] The analysis of variance confirms that significantly lower levels of trust are perceived in collaborations

Table 6. Analysis of Variance Summary Table for Five Dependent Variables as Functions of Technological Practice Cluster Membership

Dependent Variable	*Source*	*Sum of Squares*	df	*Mean Square*	F	p
Success	Between groups	1.661	3	.554	4.140	.021
	Within groups	2.407	18	.134		
	Total	4.068	21			
Trust toward others	Between groups	1.972	3	.657	8.720	.001
	Within groups	1.357	18	7.540E-02		
	Total	3.330	21			
Conflict between groups	Between groups	6.234	3	2.078	3.997	.024
	Within groups	9.357	18	.520		
	Total	15.591	21			
Dispersion of records	Between groups	11.262	3	3.754	3.790	.029
	Within groups	17.829	18	.990		
	Total	29.091	21			
Stress	Between groups	3.237	3	1.079	3.391	.041
	Within groups	5.729	18	.318		
	Total	8.966	21			

from the first type. The value of η^2 indicates that 59 percent of the variation in trust toward other researchers in the collaboration can be explained by the clustering.

Table 5 indicates similar differences for conflict and stress. The greatest conflict between teams (perceptions of serious disagreements) was reported for collaborations of type 1, and the least conflict was reported for type 4. Forty percent of the variation in conflict between teams is explained by the simple analysis of variance model.[19] The degree of stress caused by deadlines is on average higher in multi-institutional collaborations from the first technological type as compared to projects from type 4.[20]

Differences in documentary practice are especially large between types 1 and 2, with greater dispersion of records in the latter. The overall test for the difference between multiple means is significant, with 39 percent of the variance in the dispersion of records explained by the classification.[21] In the following section, we provide a more detailed examination of the four groups identified through cluster analysis and shown to have an impact on significant outcome dimensions.

Discussion

The most distinctive feature of the seven multi-institutional collaborations that constitute the first cluster was the combination of analytical management and planned development of instrumentation. We propose to designate these collaborations as managerial to reflect not high levels of bureaucracy but relatively high levels of control over instrumentation and analysis.[22] Collaborations from the first type included the Astrophysical Research Consortium (ARC), the Science and Technology Center for Superconductivity, the Keck telescope, the Positron Diffraction and Microscopy project, BNL E-814 and E-877, BNL E-878 and E-896, and Sagittarius A.

Cluster 1 is the only cluster in which most of the collaborations actively managed the topics to be analyzed by individual members (row 7, column 1 in Table 4). Topical management implies not the imposition of research themes on the participants but the coordination of analysis by the collaboration team. For example, the observation of the Galactic Center Sagittarius A at 3-mm frequencies had to be done at four observatories according to a maser time standard. Some, but not all, of these projects exhibited overlap of topics. For instance, the relativistic heavy-ion experiments at Brookhaven, known as E-814 and E-877, had several graduate students working with electromagnetic interactions. Although they were measuring slightly different things, some items—like a total cross section—needed to be compared.[23]

These interorganizational collaborations typically designed and built their own equipment, although most did some subcontracting to outsiders for construction of instruments. Indeed, constructing a complex and unique instrument was sometimes the sole, or main, purpose of the collaboration. For example, in one of the projects, a specific corporation was created—the California Association for Research in Astronomy (CARA)—by two participating organizations (University of California and Cal Tech) with the sole purpose of designing, building, and operating the Keck telescope. The mirror was designed and built by Lawrence Berkeley Laboratory (LBL). Subcontracts with outside firms were signed for components such as the glass; the polishing, cutting, and testing of the mirror segments; and the construction of the dome and foundations. Interestingly, LBL selected the subcontractors but opted to let CARA actually have the contracts with outsiders to avoid unnecessary overhead. Some projects in this group put forth much effort in designing and building instruments for their dedicated use but did not contract out (Positron Diffraction and Microscopy, BNL E-814 and E-877).

Managerial collaborations constructed instruments or used procedures that represented an advance in the state of the art at the time. Interestingly, this innovation was sometimes measured in terms of cost-effectiveness. For instance, the leader of the ARC thought that the 3.5-m telescope, built by the collaboration, was unique in the sense that it cost $9 million as compared with the 4-m telescope at Kitt Peak.[24] In this case, the price was brought down by reducing the weight of the mirror, which in the late 1980s was considered a significant achievement. The collaboration successfully addressed the problem of complex tracking motions so that the mirror would be exposed to less gravitational stress and, therefore, would need fewer steel supports. Other collaborations from this group emphasized the size of the instrument they were trying to construct. The majority of participants in only one project (BNL E-814 and E-877) did not believe that their cooperative research made a major contribution to the field (relativistic heavy-ion experiments), although one of them considered the equipment quite innovative (the calorimeter and drift chambers).

The technological configuration associated with cluster 1, centered on analytical management, is associated with lower levels of trust between project teams and relatively high levels of stress and disagreement (Table 5). These collaborations are also perceived as less successful than all collaborations except those in cluster 4. Apparently, the relatively standardized, planned development of instruments is not associated with lack of conflict. Rather, attempts to maintain high levels of control may themselves generate difficulties. The multi-institutional collaborations in cluster 1 are in this respect the opposite of those in cluster 2, which have the lowest levels of topical management and the highest perceived success.

The second cluster consists of Dupont-Northwestern University-Dow Collaborative Access Team (DNDCAT), the Angiography Diagnostics project, the VLBI Network, the Hobby-Eberly telescope, and the Berkeley-Illinois-Maryland Array (BIMA). Cluster 2 characteristics are in some respects quite similar to those of cluster 1 in terms of a focus on technological instrumentation and cross checking of results between teams.

However, the most significant difference is the one that sets cluster 2 apart from the other clusters. In none of these projects was central management of topics analyzed by its constituents. Topics were controlled by independent teams. For this reason, cluster 2 is considered decentralized. An exemplary case is the BIMA. This collaboration built an array of six short radio wavelength antennas for astronomical observations using a decentralized group of project teams. In answering a question of whether the collaboration managed topics that were analyzed by its individual members, one of the participants replied: “No, no. We do it in the usual [academic] way. The faculty individuals have their special science interests, and the students that work for them work with them depending on the style of the individual faculty” (interview with ground-based astronomer). The instrument in this case turned out differently than originally proposed—the panels for the antennas came out much better than initially expected. Because of this, the impact of the collaboration was favorable.

The absence of topical management is striking, especially since in every collaboration in this cluster there were overlapping analytical topics. Most of the time, this resulted from the attempt to solve a common problem (e.g., Angiography Diagnostics). Occasionally, the attempt to study the same topic by two separate teams within the collaboration created some tension (the VLBI Network), but the important feature is that the collaboration did not seek to control or coordinate the analysis of independent project teams.

Like managerial collaborations, this class of projects maintains a strong focus on instrumentation. All five collaborations designed and constructed instruments, subcontracting the manufacturing of certain pieces of equipment. A typical example is DNDCAT. One university and two corporations agreed to cooperate in order to build and use a beamline at the Argonne National Laboratory's synchrotron radiation facility. That agreement reflected a common interest of researchers from each of the three participating organizations in using the beamline. Design and construction of the instruments was principally carried out by the three founding member institutions, but they subcontracted the building of certain pieces of equipment to outside machine shops.

All collaborative arrangements of the second type made contributions to the state of the art, although these tended to be of a different nature. Some built complex facilities (DNDCAT). Others constructed advanced equipment at a much lower cost. For example, the Hobby-Eberly telescope is one of the largest in the world, with a mirror of 11 m, yet it was constructed for one-fifth of the cost of comparable telescopes. Of course, this was accomplished at the expense of somewhat lowered capability, since the Hobby-Eberly telescope gives access to declinations that cover only 70 percent of the range of a general purpose telescope at the same site. This trade-off between scientific capacity and cost-effectiveness is what makes the Hobby-Eberly telescope somewhat different from the ARC in cluster 1. Still others sought improvements on previous procedures. The Angiography Diagnostics project was the first to put patients under a synchrotron radiation beam.

The difference between managerial and decentralized collaborations is reflected in their documentary practices. The dispersion of core records is much greater in the latter, with records kept at almost two locations more than in cluster 1. This state of affairs is a result of their characteristic of team control. Decentralized collaborations tend not to exert control over analysis, whereas managerial collaborations exercise a great deal of control. Management of topics for analysis and lack of changes in the instrumentation seem to have contributed to the greater centralization of records in type 1. It is worth emphasizing here that decentralized collaborations view themselves as extremely successful, perhaps because they are patterned on the traditional, academic organization of science.

Five interorganizational collaborations were included in the third technological cluster: the Grand Challenge Cosmology Consortium, the 3-mm VLBI Collaboration, the Radiology Diagnostic Oncology Group (RDOG), the Crystal Structure of CTA and CTP project, and the Upper Atmospheric Research Collaboratory (UARC). This cluster is considered noninstrumental because its primary distinction is that these collaborations do not design and build their own equipment, nor do they subcontract the construction of such equipment. Two of the collaborative projects (the Grand Challenge Cosmology Consortium and the Upper Atmospheric Research Collaboratory) were computer centered, which explains why they were not engaged in instrument construction. The other three performed sophisticated experiments by making use of already-existing facilities. Thus, for example, the project on Crystal Structure brought together materials scientists, solid state chemists, and solid state physicists from Dupont, BNL, and SUNY-Stony Brook. These researchers sought to determine the structure of the high-temperature form of CTA and CTP from which the nonlinear optical material crystallizes using the national synchrotron light source at Brookhaven.

Like clusters 1 and 2, collaborations in cluster 3 boasted some kind of advance in the state of the art, but not based on instrumentation. For the Grand Challenge Cosmology Consortium, this was mainly the incorporation of parallelism into cosmological computations. For the 3-mm VLBI, the advance consisted of using existing equipment (the Mark III system, the Atomic Frequency Standards, the clocks) at several observatories for a new purpose. For the Radiology Diagnostic Oncology Group, the contribution of the collaboration was a comprehensive study of the accuracy of imaging procedures and staging of lung and prostate cancer.

In two of these projects, time pressure combined with the uncertainty of the experiment to create problems. For example, the scientific leader of the 3-mm VLBI collaboration pointed out that his group experienced difficulties several times in precise synchronizing of separate observations of a signal, since even a tiny burst of interference can offset the electronics just before the signal comes through.

Topics overlapped only in the two computer-focused collaborations (the Grand Challenge Cosmology Consortium and the Upper Atmospheric Research Collaboratory). However, projects within this cluster were not distinctive in terms of management practices. Topics for analysis were not managed by the collaboration in two of the interorganizational projects (crystal structure of CTA and CTP and 3-mm VLBI), whereas the other three collaborations actively discussed and coordinated the topics to be analyzed. Since the participants were not engaged in designing or assembling equipment for their particular experiments, there were no unforeseen changes in instrumentation. As in clusters 1 and 3, these multi-institutional projects devoted special attention to checking the accuracy of scientific results within the collaboration.

The final clustering by technological practice includes the Advanced Light Source Beamline Collaboration, the Center for Polymer Interfaces and Macromolecular Assembly (CPIMA), Materials Partnership for Hybrid Organic/Inorganic Semiconductors (MPHOIS), the National Digital Mammography Development Group (NDMDG), and the Smart Materials Consortium. What distinguishes these collaborations is relatively low innovation and coordination of results. Typically, the latter results from the division of labor within a collaboration—separate research teams tackling their specific topics. As we have seen in cluster 2, results may be subject to extensive cross checking even though teams operate with relative autonomy. Like cluster 2, these projects had relatively large overlaps in the topics addressed.[25] But for the routine collaborations in cluster 4, teams did not check the accuracy of each other's results. For example, there were three separate teams in the Advanced Light Source Beamline Collaboration, each responsible for an end station. Checking and coordination occurred within the research groups but not between them.

Another distinctive feature of these projects was that although several designed and built instruments, they were less likely than other clusters to push the state of the art in their respective scientific fields, and there was not much time pressure. Occasionally, there was some disagreement between participants on whether the collaboration had made an important advance in the state of the art. For example, the scientific leader of the MPHOIS—a collaborative venture in materials science that involves five institutions and is funded by the Defense Advanced Research Project Agency (DARPA)—expressed the opinion that in some cases, such as the organic ultra-high vacuum deposition systems, the project definitely produced an advance in the state of the art. The two other informants in the same project, however, did not think that the project generated any kind of breakthrough technology or findings.

Routine collaborations may or may not be heavily involved in design and construction of instrumentation—it is simply not a distinguishing feature.[26] Management of topics to be analyzed by the project teams in the collaboration was also split. In some instances, the organization and monitoring of what was to be analyzed and by whom even changed over time: "We have evolved to the point where projects, and more importantly IRG [interdisciplinary research group] coordinators have been required to have a clearer focus, and therefore there will need to be some management of activities" (interview with participant in one of the materials science projects). As we would expect in routine collaborations, the instrumentation in this technological class remained the same as originally proposed.

The nature of the relationships between technological types of collaboration and the dependent measures is complex, and the emerging patterns are not always intuitive. Nevertheless, at least one fairly clear-cut contrast in terms of collaboration outcomes appears to be the division between managerial and routine projects. Neither of these clusters defines itself as particularly successful compared to the other types.[27] Where they differ is in such interpersonal relations as trust, stress, and conflict. Managerial collaborations have a lower degree of trust toward other researchers, higher levels of reported stress, and more serious disagreements between teams, whereas informants from routine collaborations report higher trust toward their colleagues, lower degree of stress due to time pressure, and relatively few disagreements.

It is logical to infer that technological management here is associated with higher conflict, although our data do not allow us to determine whether management practices generated these conflicts or were implemented to reduce them. However, a closer examination shows that technological management in and of itself may or may not be positively associated with conflict and stress within the collaboration. Thus, the collaborations that constitute the decentralized type are not highly managed yet exhibit higher levels of stress and conflict than routine collaborative projects. It seems that this is due to the combination of lack of management and frequent changes in instrumentation. Managerial collaborations, which also experienced high degrees of conflict and stress induced by deadlines, did not have any changes in instrumentation but, like decentralized projects, engaged in results checking. Thus, regular checking of the accuracy of each other's results could be the common denominator of high levels of conflict and stress between research teams within collaborations.

Conclusion

Cluster analysis identifies managerial, decentralized, noninstrumental, and routine multi-institutional collaborations. The more general findings from phase 3 of the larger study may be summarized in four points.

First, expanding the scientific areas of study from the initial focus to a variety of other fields demonstrates substantial variation in collaborations. A wide range of organizational patterns exists beyond those observable in high-energy physics, space science, and geophysics. When we set aside field-specific features, seven major structural dimensions capture this range: project formation, magnitude, bureaucratic organization, interdependence, communication, participation, and technological practice. These features can be studied using a variety of indicators based on open- and closed-ended questions with principal scientists and project leaders as informants. It is always desirable to interview as many individuals as possible, but for most measures there was a high level of agreement on basic features of the project.

Second, in light of the qualitative analysis in phases 1 and 2, we hypothesized that multi-institutional collaborations would cluster by field. That is, we expected that one easy method of classification would be the kind of science or the broad topical area of the collaboration.[28] However, for most of the classification schemes we developed, collaborations did not fall into clear clusters by field, indicating that structural dimensions are not only more useful theoretically but necessary for understanding the empirical variability of collaborations.

Third, of the seven structural dimensions examined here, only one relates to a range of outcome variables. We employed a broad definition of technological practice that does not focus exclusively on hardware; rather, it incorporates the diverse ways that instrumentation and analytical tasks are organized, characteristics of the management of topics, and technical change and uses of equipment. The principle finding is that technological practice provides a structuring framework for organizing multi-institutional collaborations into types that vary in terms of stress, trust, conflict, documentary practice, and perceived success.

Finally, it is worth emphasizing that the comparative study of interorganizational collaborations in technoscience has been neglected. In spite of their significance in the past half-century, and the likelihood that they will grow in number and importance during the next, sociologists of science remain focused on the laboratory. Such laboratory studies are critical to our understanding of the dynamics of knowledge production, but an expanded scope is necessary to capture the structure and process of contemporary science owing to emergent forms of social organization. In general, these collaborations are not controlled through high levels of bureaucracy; rather, they exist as loosely coupled entities. We conclude that the important aspects of these forms, varied as they are, can be systematically described in terms of their major structural dimensions and studied comparatively. Our principal empirical finding is that multi-institutional collaborations are truly technoscience.

Appendix A
Technological Practice Dimensions

Indicators were produced by factor analysis of the original set of variables, recoding for consistency in sign where necessary. All variables were coded as dichotomous (1 = yes, 0 = no). The questionnaire items that generated the original data are as follows.

Factor 1

1. Did the collaboration put a lot of effort into designing any equipment for its dedicated use? (designing own equipment)
2. Did the collaboration but a lot of effort into building any equipment for its dedicated use? (building own equipment)
3. Were there subcontracts with outsiders to obtain the instrument? (subcontracts with outsiders)

Factor 2

4. Did the (instrument, equipment, detector, procedure) represent a major advance in the state of the art? (state of the art)
5. Did time pressure cause problematic results? (time pressure)
6. In data analysis, were there overlaps in topics addressed by collaborators? (recoded to reverse values as “topical segmentation”)

Factor 3

7. Did the collaboration manage the topics which were to be analyzed by its individual members? (recoded to reverse values as “team control”)
8. Did the instrument turn out differently than originally proposed? (instrument change)

Factor 4

9. Overall, did teams check the accuracy of each others’ results? (results checking)

Appendix B
Outcome Variables

1. Success (an index composed of two original variables)
   How successful do you think this project was as compared to your other scientific work?
   4. Very successful 1. Not successful at all
   How successful do other people think it was?
   4. Very successful 1. Not successful at all

2. Trust (measured by two original indicators)

What was the degree of trust compared with your experiences in an academic department

a. towards researchers on other teams?

3. High 2. Medium 1. Low

b. towards the project management?

3. High 2. Medium 1. Low

3. Conflict (measured by four original indicators:

In every collaboration, there are some disagreements and problems. How serious were the disagreements

a. between teams?

4. Very serious 1. Not serious at all

b. between junior and senior members?

4. Very serious 1. Not serious at all

c. between scientists and engineers?

4. Very serious 1. Not serious at all

d. between researchers and project management?

4. Very serious 1. Not serious at all

4. Documentary Practice (measured by two indicators)

Quality of record-keeping

3. High 2. Medium 1. Low

Dispersion of records (number of locations where core records are kept)

5. Stress (an indicator identical to the original variable)

Compared with an academic science department, how would you estimate the degree of stress induced by deadlines/scheduling?

3. Higher 2. Same 1. Lower

Notes

1. For operational purposes, a multi-institutional collaboration is defined as a research project involving three or more organizations. The subsequent analysis and conclusions are based only on the study of multi-institutional collaborations in the United States. Of course, much European science is conducted in a collaborative manner, but at this point we are not concerned with cross-national comparisons.

2. These five dimensions appear to be important to scientific activity regardless of the level at which social and intellectual change is examined (e.g., the work group, the organization, the specialty, or the discipline). Thus, in spite of the scarcity of comparative studies of multi-institutional collaborations, it seems likely that they are important here as well.

3. The degree of trust both toward other researchers and toward the project management was generally high, but at certain times there were doubts as to the reliability of some collaborators. Often, this happened when new people joined the collaboration. Misgivings about their

trustworthiness usually had a temporary character: “I think broadening the collaboration for this 896 experiment led to some distrust, which I believe has been almost wholly alleviated at this particular point, but it’s certainly what’s caused the problems early on. They just didn’t trust each other’s results, basically” (interview with heavy ion physicist). Interviews were conducted on the condition of anonymity. A copy of this paper with all identification is available to qualified scholars at the American Institute of Physics, Niels Bohr Library.

4. One of our informants discussed the stress from time pressure in his collaborative project: “Well, compared to an academic department I’d say it’s night and day. This was a project; this was an industrial situation, if you will, where there were real schedules. And you might fail to meet them, but it was completely unambiguous what they were, and if you failed to meet them, you’d better have a good reason for it or you’d get chewed out. Academia doesn’t work that way at all. Academia is much more democratic, touchy-feely, ‘Yeah, we think we want to do that; let’s think about it; we’ll get back to you when we’ve got it worked out’ ” (interview with ground-based astronomer).

5. Schedules, coordination of activities, and meeting deadlines sometimes become a source of tension and conflicts between teams. That was stressed by one scientist in the Astrophysical Research Consortium when she was asked what particular issues were subject to disagreements: “It was mainly not the formal design, or this or that. I think we all eventually made our compromises and stuff. It was about time scales and progress. Somebody would seem to not be doing their jobs, so to speak, this way and that way and the other way, and that’s what caused the disagreements or hard feelings” (interview with ground-based astronomer). This situation frequently arose from the division of labor. For example, the same interviewee went on to say that one of the collaborating organizations (University of Chicago) got involved in the Center for Astronomy and Astrophysics in Antarctica simultaneously with the Astrophysical Research Consortium project, and at times the astronomers and astrophysicists from that organization considered this other project more imperative, which led to delays in their commitments to the Astrophysical Research Consortium.

6. It is often not only the scientific achievement of the project, but precisely the fact that it came as a result of a fruitful common effort that was emphasized by individual participants when they elaborated on the success of a collaboration: “I would say this has been very, outstandingly successful. In terms of scientific results, relationships between people, building new relationships, being successful at a complex facility—super” (interview with member of one of the collaborations in uses of accelerators).

7. See “Report No. 1: Summary of Project Activities and Findings” (Joan Warnow-Blewett and Spencer Weart) and “Report No. 4: Historical Findings on Collaborations in High-Energy Physics” (Joel Genuth, Peter Galison, John Krige, Frederik Nebeker, and Lynn Maloney) in American Institute of Physics (1992). See “Report No. 1: Summary of Project Activities and Findings” (Joan Warnow-Blewett, Anthony Capitos, Joel Genuth, and Spencer Weart) in American Institute of Physics (1995).

8. These dimensions are all familiar in the literature on complex organizations. We initially identified ninety characteristics or subdimensions and subsequently narrowed these down to approximately fifty. The subdimensions were then classified in terms of seven major dimensions. Of course, some factors we identified as subdimensions could well be considered independent dimensions in other circumstances. In each case, we sought to provide one or more indicators of each subdimension.

9. Joel Genuth and Anthony Capitos were primarily responsible.

10. A simple example of this strategy is as follows. Say there were four respondents from the same collaborative project. If two of the respondents described trust in project management as

"high" (coded as 3), one as "medium" (coded as 2), and one as "low" (coded as 1), then trust was judged as high, using the mode. If there were three respondents, and all their answers differed (no mode), we would prefer the median. Suppose, however, that the original four respondents were answering a question coded as a categorical variable such as the source of decision making on scientific issues. If two answered "executive committee" (coded as 6) and two answered "participating scientists" (coded as 8), there is no mode, and the median does not make sense ("7" codes for another category). Our best estimate in this case would be taken as the leader's opinion. In practice, such disagreement rarely occurred.

11. Nearly one-fifth of collaborations involved representatives of more than seven institutions.

12. Cluster analysis refers to a variety of statistical procedures used to create classifications (Aldenderfer and Blashfield 1984). Unlike discriminant analysis or K-means analysis, which require the a priori definition of groups, cluster analysis is specifically designed to identify the groupings (clusters) discernible in a particular data set without prior knowledge of types. Clustering involves reorganizing a set of observations into groups of entities based on the estimation of similarity by statistical measures (coefficients). Similarity coefficients may be divided into four groups: distance coefficients, association coefficients, correlation coefficients, and probabilistic similarity coefficients (Sneath and Sokal 1973, 119-20). We employed a standardized distance measure based on squared Euclidean distance. Since our data contain variables at various levels of measurement, we rule out the use of association coefficients (the simple matching coefficient, Jaccard's coefficient) that measure similarity between observations on binary variables. The same holds true for the probabilistic similarity coefficients. Correlation coefficients are also inappropriate, since they do not satisfy at least one of the conditions of being a metric. Distance measures, however, meet the criteria of a metric and are applicable to mixed-type data. Standardization was applied by setting variable means to zero and standard deviations to one to offset the effect of relative size of variables—a transformation routinely applied by researchers (Aldenderfer and Blashfield 1984, 26). Clusters were derived using Ward's method. The number of clusters and cluster membership was determined by the cluster membership table (showing which case belongs to which cluster for a specified number of clusters) and the dendrogram (a visual display of the stages in a hierarchical clustering solution). Clusters may be derived in several ways. The most common methods are agglomerative, hierarchical, sequential, and nonoverlapping (Sneath and Sokal 1973). We began with two methods of aggregating groups—average linkage between groups and Ward's method. The former uses the average distances between pairs of observations in two different clusters to combine these clusters. Since it avoids the extremes of both nearest neighbor and farthest neighbor techniques, it is often the preferred method of linkage. Ward's method, on the other hand, is intuitively appealing, since it is designed to minimize the within-cluster variance, with the aim of distinguishing internally homogeneous and externally heterogeneous groups. Results presented here use Ward's linkage algorithm, since comparisons showed that it generated almost exactly the same solution as average linkage between groups but tended to be more robust with respect to the effect of idiosyncratic cases.

13. The seven-variable solution used one variable from each of the structural dimensions, selecting those variables that most clearly distinguished clusters in each of the previous analyses. The four-variable clustering was based on our desire to see if a simple solution could be developed based on dimensions that seemed important from prior qualitative analysis.

14. The specific indicators are given in Appendix A. Average values for each cluster are given in Table 3 (for factors) and Table 4 (for indicators).

15. This does not mean, of course, that none of the individual variables that constitute the structural dimensions are related to outcomes. Table 2 was generated by running each

classification against all variables. The same specific indicators are not necessarily related to structural classifications. An X in a cell shows that at least one indicator of a given type is related to the structural dimension.

16. The *F* ratio is significant at $p < .05$, indicating that technological practice affects the perception of success of the multi-institutional collaboration. The modification of the Tukey HSD test for groups of unequal sizes shows which individual means differ significantly from one another. Two contrasts are significant at $p < .05$—between types 2 and 1 and between types 2 and 4. In both cases, type 2 collaborations are judged to be more successful.

17. Collaborations in cluster 2 were characterized by high technological instrumentation (a composite variable combining designing of own equipment, building own equipment, and subcontracting), low technological management (technological difficulties [whether the instrument turned out differently than originally proposed] and management of topics for analysis), and high degree of results checking within the collaboration.

18. The Tukey HSD multiple contrasts test revealed significant pairwise differences between the first cluster and all the others.

19. The multiple comparisons test for unequal group sizes provides evidence that the only statistically significant contrast is between multi-institutional collaborations from type 1 and those from type 4.

20. The omnibus analysis of variance test shows that not all the group means are equal in the population. For the relationship between the technological practice and stress induced by deadlines, 36 percent of the variation in stress is explained by cluster membership. The modified Tukey multiple comparisons procedure revealed one significant pairwise contrast between types 1 and 4.

21. Only one pairwise contrast is significant at $p < .05$, showing that type 2 collaboration records are significantly more dispersed than collaborations from type 1.

22. We provide labels for each of the four clusters based on the their distinctive characteristics using the classification itself. For ease of interpretation in the discussion of specific clusters, we employ a comparison of the average values on the original measures (Table 4) rather than the constructed indices (Table 3). For example, in Table 4, a value of one in the first column of the first row indicates that each of the seven collaborations in the first cluster put a great deal of effort into the design of equipment for dedicated use.

23. Checking the accuracy of each other's results was the rule rather than the exception in managerial collaborations, since there was little segmentation in topics for analysis. Thus, the graduate students working in overlapping areas within experiment 814 at BNL sometimes discovered disagreements in the measurement of cross sections that needed checking. Typically, this had something to do with the calibration of a detector or people using different codes. However, results checking was even more common in clusters 2 and 3.

24. He estimated that Kitt Peak would cost roughly $45 million at present.

25. Overlap of topics for analysis was a common phenomenon in collaborative arrangements of type 4 and was viewed as a natural state of affairs, beneficial for participants and the project as a whole. A pertinent illustration is provided by one member of the CPIMA, who elaborated: "We have actually taken advantage of overlap in a sense that, if there is some common material that is being examined by multiple techniques, that can lead to a very important synergy" (interview with materials science researcher).

26. A case in point is the NDMDG collaboration, which pooled researchers from Harvard Medical School, the University of Chicago, GE Corporate Research and Development laboratories, the University of North Carolina, Thomas Jefferson University, and Sunnybrook Hospital in Toronto for the purpose of earlier detection and management of breast cancer. The collaborators designed and built one part of the equipment—the fiber optics that image and digitize the breast. However, they did not contract out the design or construction of instruments.

27. Recall that the most successful projects belong to the decentralized type, which is also characterized by a comparatively high degree of stress and between-team conflicts. Thus, it looks like success in multi-institutional collaborations comes at a price.

28. Of course, classifying by field is easy, but given the large number of possible fields, it would not provide a very satisfactory classification scheme, given that the purpose of having such a scheme is to reduce this complexity to more general dimensions.

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