Multi-Institutional Collaborations in Science: A Model for the Future of Knowledge Production

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Despite the recent prominence and ubiquity of multi-institutional collaborations and their importance for the future development of the production of scientific and technological knowledge, no satisfactory classification of these "virtual organizations" exists. This paper adopts a macrosociological, comparative perspective that allows the examination of the systematic variation of 23 recent collaborations in five areas of physics along two crucial structural dimensions. Organizationally, multi-institutional collaborations tend to fall into three categories: bureaucratic, semi-bureaucratic, and non-bureaucratic. Technologically, they follow four scenarios of origin and development: managerial, decentralized, noninstrumental, and routine. The four scenarios of technological practice acquire significance for futures studies not only because they highlight the possibilities of divergence of the evolution of interorganizational collaborations in science, but also because they bear upon the disciplinary organization and consequences of research.

Keywords: scientific collaboration, "big science", technological practice, resource dependence

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The Proliferation of Multi-Institutional Collaborations in Science

Collaboration is a growing phenomenon in all spheres of modern human activity, including such important fields as science and technology. Due to modernization, increased international exchanges, the advent of new high-tech means of communication, and the need for more efficient utilization of human, financial and technological resources, the cooperation of researchers from different nations and institutions on a common project is rapidly becoming the trend, rather than the exception. While teamwork and cooperation are not new phenomena in science (Hagstrom 1964), the magnitude, cost, scope, and proliferation of collaborative projects involving multiple teams of researchers from several institutions are a fairly recent development. Such multi-institutional collaborations, or cooperative arrangements that include three or more organizations, are increasingly becoming a model for the organization of knowledge production.

In a broader sense R&D multi-institutional collaborations are sociologically important because they are part of a general trend toward more fluid, flexible, and cooperative organizational arrangements in manufacturing, trade, services, and the public sector. In recent years the formation of joint ventures, strategic alliances, consortia, partnerships, obligational, and systemic networks has virtually exploded in all sectors of the economy (Alter and Hage 1993). As modern production and services become increasingly knowledge-based, and as the new knowledge and technological innovation become more complex and diversified, firms and other organizations need to turn more frequently to cooperation in order to stay competitive (Powell et al. 1996). Scientific work itself has been affected by global tendencies that demand greater coordination of resources.

This trend is especially evident in modern physics and allied sciences. It has become increasingly common in the age of "big science", which is associated in physics with the rapidexpansion of its scale, scope, and manpower in the half century from the 1930s through the 1980s (Galison 1992). One of the most striking features of postwar high-energy physics has been exactly the growth of large teams on the experimental workfloor (AIP 1992). Prior to the World War II experiments even with big accelerators were considered essentially an individual affair. As detectors became more complex, costly, and time-consuming to build, an increasing number of scientists, engineers, and organizations combined efforts. The history of high-energy physics after the 1950s provides strong evidence of the tendency of experimental teams to expand in size.

Thus, a typical bubble chamber collaboration at CERN in the mid-1960s consisted of about fifteen physicists. One decade later the number of researchers working in co-operation with CERN's largest bubble chamber Gargamelle was about 50 people from seven organizations. In 1985 the Delphi collaboration, working with the Large Electron-Positron Collider at CERN involved over 350 high-energy physicists from 37 organizations in 17 countries (AIP 1992).

The trend toward collaborative research in physics is symptomatic of changes in the nature of experimental work, which is steadily becoming "industrialized". The organization of this work has dramatically changed as multi-layered managerial structures have been imposed, the degree of bureaucratization has increased, decision-making processes have become more formalized, and the experimental process has become more routinized, repetitive, and tedious. The autonomous creative atmosphere of the university laboratory has been replaced with the regulated and regimented procedures of a large corporation (AIP 1992).

One important function of multi-institutional collaborations in physics is the pooling of manpower and resources when a large experiment needs to be conducted. This is especially pertinent when funding for large-scale research is limited or there is a scaling down of research budgets. This was one of the results from The American Institute of Physics (AIP) study of multi-institutional collaborations, which was conducted over a ten-year period (1989-1998) and examined projects in high-energy physics (phase I), space science and geophysics/oceanography (phase II), ground-based astronomy, uses of accelerators, materials research, medical physics, and computer-centered research (phase III). The study of interorganizational collaborations in high-energy physics, for instance, led to the conclusion that the tradition of funding experiments through the university has encouraged multi-institutionality and internationalism. The analysis of interviews demonstrated that the prevailing opinion gravitated toward a sense that there were limits on how much money would be spent on the research of any single high-energy physics group. Therefore, any group that had the ambition to build an expensive and elaborate experiment had to be able to convince physicists from other organizations and countries to dedicate some of their funds and instrumentation to the experiment (AIP 1992).

Multi-institutional collaborations in physics are important for various other reasons as well. Sometimes the factors causing the formation of co-operative research projects involving several institutions are field-specific. The three fields covered by the first two stages of the AIP project, for example, all witnessed the prominence of interorganizational arrangements due to the upsurge of government funding of science after World War II. In all of them the formation of multi-organizational collaborations was driven by the need to place complex measuring instruments on limited data-collection facilities. High-energy physicists need accelerators; space scientists, geophysicists and oceanographers need space probes, satellites, seismic networks, and ocean-going vessels. However, while high-energy physics relies on laboratory experiments, space science and geophysics count on field observations. Funding patterns are also different for HEP and geophysics/oceanography, which leads to different reasons for instigating collaborative research formations. HEP in U.S.A. is supported by only two Federal agencies, while the global data collection in the other two fields studied by AIP makes them dependent on the actions of various national governments and encourages international cooperation at the government level (AIP 1995).

Despite the recent prominence and ubiquity of multi-institutional collaborations and their importance for the future development of the production of scientific and technological knowledge, efforts to characterize these "mini-institutions" have just begun in sociology of science and organizational studies. Thus, beyond the knowledge that substantial variation in interorganizational, or, as I will interchangeably call them, multi-institutional collaborations (MICs) exists, we lack a clear understanding of how collaborations vary and what the consequences of this variation are.

Approaches to the Study of Interorganizational Collaborations

Given the prevalence of multi-institutional collaborations as a "temporary organizational form" in a variety of disciplines and their significance for the foreseeable development of scientific research, it is imperative to try to explain what their essential features are, how they can be classified, and what this entails for the future of R&D.

A number of studies by historians, sociologists, and anthropologists have documented particular cases of collaboration in science, and demonstrated their importance for understanding new forms of social organization, cultural construction, and changing social relationships. However, these disparate findings have not yet been integrated into a more general explanatory scheme. What we need now is a "middle range" theoretical framework based on a systematic comparative study of a variety of interorganizational collaborations in science that will reveal the common structural and cultural properties of these "virtual organizations" and explain how these properties relate to sociologically important outcomes. Efforts in that direction have just begun in science and technology studies (a.k.a. STS). The most important work on collaborations in this field has been done by Zabusky, Knorr-Cetina, and Schild.

Zabusky (1995) conducted an extensive one-year ethnographic study of the European Space Agency (ESA) as an instance of international cooperation in space science. Cooperation is approached from the perspective of "practice theory," and is viewed as the negotiation of differences in the division of labor. Space missions in ESA are regarded as "loosely" structured projects with no single, centralized source of authority.

A similar approach is adopted by Knorr-Cetina (1998) in her qualitative investigation of large high-energy physics experiments at CERN. An in-depth anthropological examination of one string experiment—UA2 and ATLAS—reveals that cooperative work is accomplished in non-bureaucratic ways, without a rigid formal organization, central authority, or strict internal rules. The main theoretical argument of Knorr-Cetina is that collaborations in HEP should be conceptualized as post-traditional communitarian structures that downgrade the role of the individual and stress community mechanisms such as collective authorship and free circulation of work. Collaborations are largely self-organized, and the chief organizing format is the subdivision into task-oriented or technological, object-oriented working groups.

Schild's case-study of international collaboration in polar research (1997) is based on interview data from seven cruises of three ships. It resembles the previous two works in a number of ways—the qualitative and cultural orientation, its focus on one field of science and on European cooperation, and attention to the dynamic aspects of working together. The main difference is that, in contrast to Zabusky and Knorr-Cetina, Schild puts greater emphasis on conflict than on harmony, consensus, and integration.

What all three studies share is a common microsociological focus, qualitative methodology, cultural-anthropological orientation, case-study approach, attention to international (European) scientific collaboration, emphasis on a single location (ESA, CERN, ocean-going vessels), and on a single specialty (space science, high-energy physics, polar research). Each discusses a number of dimensions (organization, size, origin, leadership, communication, technology, internationalism), social processes (collaboration as work, social integration, community-building, negotiation, collective knowledge), and outcomes (consensus, conflict, trust) that characterize scientific collaborations. Theoretically, the most sophisticated of these is Knorr-Cetina's work, which tries to advance a new conceptual scheme that views collaborative experiments in HEP as post-traditional communitarian formations with object-centered management, collective consciousness, and decentralized authority.

Although these studies are useful because they give us a sense of the important variables that describe scientific collaborations, they suffer from the following weaknesses. (1) There is insufficient examination of structural characteristics owing to preoccupation with cultural processes. The focus on cultural construction and dynamics overshadows some interesting structural traits of collaborations. Even when structural factors are considered, they are usually not operationalized or clearly defined. (2) It is not clear whether these fields are representative and whether the findings are generalizable. Two of these works focus on a single collaboration, and the third—on seven. All of them study European collaborations in one field of science. Moreover, none of the studies convincingly explicates how the respective collaborations and interviewees were chosen. It appears that convenience and access were the primary selection criteria. Thus, we cannot generalize across fields or even for the single field under investigation. (3) Third, they focus on a particular location instead of multiple locations. The latter is more typical in a number of fields—materials research, medical physics, climatology, VLBI ground-based astronomy. (4) Fourth, there is a failure to distinguish factors in order of importance. This general deficiency of cultural qualitative research is evident in the work of Zabusky, Knorr-Cetina, and Schild. Multiple factors like communication, division of labor, work as a process, technology, negotiation, size are all considered "crucial," but no attempt is made to systematically show why some factors may be more important than others. (5) Fifth, they suffer from an inability to systematically codify the proposed theoretical concepts. Even the most developed conceptual framework, advocated by Knorr-Cetina, employs unoperationalized notions and does not clarify the scope of the explanatory model. (6) Sixth, they neglect the relationship between properties of collaborations and their outcomes. The lone exception here is Schild's discussion of how size and prior knowledge of collaborators might affect conflict. Even this observation, however, is only suggestive and not tested empirically on a larger sample of cases.

In order to overcome these flaws and be able to construct a sound theoretical framework, we need to place greater emphasis on a structural, macrosociological and comparative analysis of MICs and their consequences. Thus, in view of the goal of accumulating findings about particular scientific collaborations, we need to perform a quantitative comparative study on a larger sample in a systematic fashion. For this reason, we also need to shift our analysis from the micro to the macrolevel, and change our focus from interaction and everyday practice to the examination of multi-institutional scientific collaborations as interorganizational formations. The first step is to systematically study the variation in forms of interorganizational collaborations by constructing multiple typologies along basic structural dimensions.

Traditionally, structural and systematic analysis has been the domain of organizational research. Regrettably, although there is a vast literature on interorganizational relations, organizational studies have largely ignored MICs as objects of inquiry, and have focused instead on production (Browning et al. 1995; Gulati 1995; Pfeffer and Salancik 1978; Powell et al. 1996), service (Alter and Hage 1993), and government organizations (Clarke 1989). Nevertheless, two theoretical perspectives on interorganizational relations can also illuminate the study of collaborations in science—resource dependence theory and garbage can theory.

Resource dependence theory falls into the camp of organization theories that are concerned with the relations between organizations and their environment. It was developed using a "natural selection model", or population ecology approach. The population ecology approach treats organizations at the population level and posits that the environment differentially selects organizations for survival. Resource dependence theory, on the other hand, argues that organizations should be studied as active agents, which make decisions how to respond or try to change their environment (Aldrich and Pfeffer 1976).

The starting point for this model is "the indisputable proposition that organizations are not able to internally generate either all the resources or functions required to maintain themselves, and therefore organizations must enter into transactions and relations with elements of the environment that can supply the required resources and services." (Aldrich and Pfeffer 1976, p. 83). Thus, it is the inability to generate internal resources that creates interdependencies among organizations. This is, in a sense, inevitable, since organizations as open systems presuppose exchanges and dependencies, which in turn give rise to external control. The managers and administrators of organizations attempt to manage their external dependencies for a number of reasons, one of which is to try to secure survival and success of their establishments (Pfeffer 1982). Organizations regularly try to control their dependencies utilizing various strategies. The two most common ways to manage dependencies are through acquisition and ownership (e.g. mergers) and through coordination (e.g. co-optation, boards of directors, advisory boards, joint ventures, mutual agreements). The latter represents a social agreement to stabilize mutual interdependence, and has the advantage of greater flexibility (Pfeffer and Salancik 1978).

Although the resource dependence model is predominantly an environmental perspective on organizations, it also places some emphasis on rational action and rational choice. Internal processes of decision-making are regarded as a crucial element in organizational change, despite the fact that most often they are initiated by external pressures. Not surprisingly, then, this tradition devotes substantial attention to concentration of resource control and issues of power acquisition, distribution, and maintenance. Pfeffer gives an interesting example of the establishment of power in science and technology by referring to the tendency of NSF to gain power by putting funded projects on shorter review cycles, so that it is necessary to constantly request funds and justify what has been achieved (Pfeffer 1981, p. 109).

Several features of the resource dependence model make it appealing to use as a theoretical framework in explaining multi-institutional collaborations in science. First, it strikes a good balance between external contingencies and internal conceptualization and decision-making about these contingencies. The resulting image of a loose coupling between the organization and its environment may be particularly fruitful for interorganizational projects in science. Second, it is particularly appropriate for conceptualizing interorganizational project formation, since most often research units, or expert members of such units, make agreements to work together because no single organization has the monetary resources, facilities, or expertise to undertake a demanding experiment, mission, or study. Third, it puts heavy emphasis on power as a mediating factor between the organization and its environment, but at the same time allows for the avoidance of use of power for resource-allocation, when goals and criteria are broadly shared among participants in organizations. Collaborative arrangements in science are complex organizational forms, where both the use of power for distribution of resources by certain entities (scientific leader, administrative leader, Executive Committee) and the use of consensus in decision-making are common.

Whereas resource dependence theory offers a better account of the origin of interorganizational collaborations in science, as well as the more systematic and rational processes of management, planning, and decision-making on particular issues, garbage can theory provides some clues to the uncertainty, goal changes, and ambiguity endemic in some research projects. Garbage can theory is chiefly a decision-making model, which emphasizes the problematic and uncertain nature of this process in certain types of organizations or sets of organizations. The garbage can model was developed as a result of studies of educational institutions at the end of the 1960s, when they were shaken by student demonstrations. The founders of this theory—Cohen, March, and Olsen—studied decision-making in such institutions during a time of turmoil, which appeared haphazard, opportunistic, and disorganized. Two main concepts emerged from this study: organized anarchies and garbage cans.

Organized anarchies are basically organizations, which are best described by three characteristics: problematic preferences (loose collection of ideas), unclear technology (reliance on trial-and-error procedures), and fluid participation (varying efforts and amount of time spent by participants)(Cohen et al. 1972). The most common examples of such organized anarchies are public, educational, and illegitimate organizations.

The second notion springs out of the view that choices are central to particular kinds of organizations, and the choice opportunity is "a garbage can into which various kinds of problems and solutions are dumped by participants as they are generated." (Cohen et al. 1972, p. 2). Hence, decisions are typically outcomes of four relatively independent streams within organizations: choice opportunities, problems, participants, and solutions. In a garbage can model four basic variables (each one as a function of time) are considered: a stream of choices; a stream of problems; a stream of energy from participants; and a rate of flow of solutions. These variables are then included in a computer simulation model, which relies on three key behavioral assumptions: energy additivity, energy allocation, and problem allocation (each problem being attached to one choice only)(Cohen et al. 1972, p. 3). One example of application of the garbage can model is the reduction of slack in universities. The implication of the model for situations, where slack decreases, holding technical and value heterogeneity constant, the decision structure shifts from unsegmented to specialized and to hierarchical. The predictions generated by the model are then compared to real observations of universities. Cohen, March, and Olsen point out that universities are probably the organizations for which their theory works best, since decisions there often do not solve problems, choices are by flight or oversight, and there is a frequent transformation of decisions. Further, they state that the garbage can model is not a panacea, and it works best in situations that cannot be adequately explained by rational organizational theories (Cohen et al. 1972).

Garbage can theory can be useful for the study of multi-institutional collaborations in at least two ways. First, it is especially appropriate, as Clarke (1989) argues, for investigating decision processes in groups of organizations, where responsibilities are ill defined, there is negotiation of problems and choices, and sometimes a lack of central authority. At least some interorganizational collaborations in science can be expected to have such features. Frequently interorganizational scientific arrangements are a "mixed case": there is a combination of a fairly formal structure and negotiated decision-making. In such instances garbage can theory can supplement rational explanations. Second, since scientific research and technology development are often rife with uncertainty and unpredictability, and since often diverse groups with different professional ideologies must work together in MICs, there is a propensity for loose coupling among choices, problems, participants, and solutions. The garbage can model is well-suited to cover such situations.

A brief recapitulation of the discussion so far is in order. Multi-institutional collaborations in science have been established as a sociologically important recent organizational form of knowledge production that will undoubtedly increase in importance in the future. In spite of some encouraging work in social studies of science, the description and explanation of these interorganizational formation is still at a stage of "theory in the making." We can advance this theory by a systematic quantitative comparative study of the range of variation and the sociological consequences of these "virtual organizations." This will entail the construction of typologies along selected dimensions.

These typologies, however, are of limited value in the abstract. They acquire theoretical significance insofar as we link them to explanations of how collaborations in science emerge, how they function, why they are organized in various ways, how they are related to important sociological consequences (success, conflict, trust, stress, documentary routines), and what this suggests for the future of scientific organizations.. Two theoretical perspectives from organizational studies (resource dependence theory and garbage can theory) and the conceptual insights from social studies of scientific collaborations can facilitate the establishment of these links. At present, however, there is not enough information to conclude what the possible scenarios of development of MICs are and what are their implications for science policy.

To fill this gap I conducted a systematic analysis of the most extensive data on scientific collaborations to date—the three-phase study of scientific interorganizational arrangements in U.S. physics and allied sciences conducted by the AIP. Close to 300 interviews on 19 selected experiments in high-energy physics were conducted in the first phase. The second phase expanded the data base to include almost 200 interviews on 6 collaborations in space science and 8 projects in geophysics and oceanography. Qualitative thematic analysis of these interviews led to the identification of seven basic structural dimensions that describe collaborations in science: project formation, magnitude, organization and management, interdependence, participation, communication, and technological practice. The latter were operationalized and incorporated directly into the design of the questionnaire for phase III. Face-to-face interviews were then conducted with 78 scientists from 23 collaborations in 5 areas: uses of accelerators (n=6 collaborations); ground-based astronomy (n=7); materials science (n=4); medical physics (n=3); computer-centered research (n=3). The instrument was a structured questionnaire, including both fixed and open-ended items. Altogether 96 variables within 12 broad categories were operationalized in closed-ended questions. The subsequent analysis is strictly based on data from phase III of the AIP project. I will succinctly report the results from cluster analysis of the two most important dimensions—organization and technological practice—and discuss the implications of the findings for the future of MICs.

The Organizational Dimension

Interorganizational networks in R&D are structured and managed in complex and diverse ways. This diversity was reasonably captured by thirteen indicators. Since we still had a fairly large number of variables belonging to the category of "organization and management," exploratory factor analysis was performed to test for common underlying concepts. The method of extraction was principal components. This gave an initial solution of four factors, which were then rotated using oblique rotation.

The factor analysis results served as a sound justification to create four indices from the indicators that loaded highly on the respective factors. Conceptually it appeared reasonable to use the following terms to describe the unifying four dimensions: formalization, hierarchy, administrative management, and scientific management. The "formalization" index was computed as the average of the following indicators: presence of written contracts, coordination of schedules, system of rules, and outside formal evaluation. The "hierarchy" index combined levels of authority, the presence of advisory committee, style of decision-making, and degree to which leadership subgroups were making decisions. Administrative management was the latent conceptual dimension behind the high intercorrelation of presence of administrative leader, division of authority, and self-evaluation of the project. Finally, the "scientific management" (not to be confused with Taylor's "Scientific Management Theory) index brought together the indicators for presence of a designated scientific leader, and division of labor. The standardized four composite variables were subsequently submitted to cluster analysis, using squared Euclidean distance as a similarity measure and Ward's method of clustering. This procedure yielded three distinct types of collaborative projects.

The first type of collaboration organization is clear-cut, and could be categorized as "bureaucratic." It incorporates projects with a high degree of scientific management, high degree of administrative management, high formalization, and high degree of hierarchy. It is interesting given these characteristics, that this is the most prevalent kind of multi-institutional collaborations in our sample (which oversampled successful collaborations). This at least casts doubt over the assertion of some authors in STS (Zabusky 1995; Knorr-Cetina 1998) that collaborations in science are essentially very loose temporary organizations, with a great deal of flexibility, predominance of informal relations, decentralized management, and absence of central authority.

The second kind of collaborative project is truly the "middle-ground" case. It is comprised of projects with a low degree of scientific management (in this case mainly without a designated scientific leader), and moderate levels of administration, formalization, and hierarchization. This type may be termed "semi-bureaucratic collaboration." The last type could be qualified as "non-bureaucratic." Although it tends to have both a designated scientific leader and a clear division of labor, it registers the lowest degrees on administrative management, formalization, and hierarchy. It is the only type that fits perfectly the initial expectation that most MICs will be comparatively free-wheeling, transient organizations, which lack rules and formalized structures.

The contrast between the bureaucratic and the non-bureaucratic MIC can be made more salient, if we look at two projects that are representative of these types. An instance of a bureaucratically organized collaboration is the Center for Research on Parallel Computation (CRPC). This is an ambitious collaborative venture that comes as a response to the competition announced by NSF for new science and technology centers. CRPC involves about one hundred researchers, postdocs, and graduate students from seven institutions. The lead center is Rice University, which has formal subcontracts with the other six organizations. There are two clearly defined lines of management—scientific and administrative. Consequently, there are two positions that correspond to the division of authority—scientific director and executive director. There is a vertical, hierarchical differentiation of authority that is deeper than a comparable university department. Thus, there are five levels of authority. The top level is occupied by two external bodies—the Institutional Oversight Committee and the Advisory Committee, followed by the scientific director. The third level is the Executive Committee, which is the governing body of the Center. Then come the leaders of research groups. At the bottom of the hierarchy are the graduate students. There are both internal evaluations according to well-established standards and annual external evaluations by the outside Advisory Committee. The Executive Committee makes all important decisions.

The non-bureaucratic type of collaboration, on the other hand, is exemplified by the three millimeter VLBI (Very Long Baseline Interferometry) project. This is a small collaboration of about twenty people from six observatories to dramatically reduce the wavelengths at which long-baseline interferometry is done. Most of the work in this area is collaborative and researchers know each other quite well, so there was no need for any formal structure. The collaboration did not have either written contracts or a system of rules and regulations. It did have a scientific leader, but there was no external Advisory Committee at any stage. The project was dispersed among the participating observatories and had no lead center or a permanent physical location. The three millimeter VLBI project had no administrative leader or staff, and it used a mixture of hierarchical and consensual style of decision-making.

Last but certainly not least, the comparison between CRPC and 3mm. VLBI suggests that bureaucratization may be a function of the funding pattern. For example, CRPC is a long-term NSF-funded project, whereas 3mm. VLBI is not funded by any federal agency as a project, although individual organizations receive financial support from such agencies.

Organizational behavior and decision-making processes occurring in scientific collaborations could not be uniquely explained by either resource dependence theory or the garbage can model. Each approach seems to be applicable to a specific domain of behavior. The former is better suited to deal with rational choices that organizational actors make in bureaucratically managed projects. The latter handles more successfully processes like leadership change, management by consensus, reformulation of goals, and fluid participation that are typical of non-bureaucratic collaborations. Thus, so far as the management of MICs is concerned, it is probably more useful to treat resource dependence theory and the garbage can model as complementary rather than mutually exclusive. Overall, the empirical findings suggest that while both models are somewhat incomplete, resource dependence theory has a broader scope of application and greater explanatory power with respect to multi-institutional collaborations in science.

Technological Practice: Four Scenarios for Collaboration in Science

Technological practice is perhaps the most essential structural feature of multi-institutional collaborations in science. Broadly understood as not only the design and building of equipment, but also as data acquisition, manipulation, and analysis, topical differentiation and management, coordination of instruments, technical change, innovation, and cross-checking of results, such practice powerfully shapes the daily work, interaction, and relationships in collaborative arrangements. Thus, the latter can most aptly be described as "technoscience."

On a macro-sociological level, it is often the enormity and complexity of problems created by the development of new technologies that require collaboration among organizations (Sayles and Chandler 1971). Whether this is the application of nuclear power, the exploration of outer space, or the study of global climate changes, such problems are too complex and costly to be tackled by a single organization.

Technological practice is a requisite aspect of working together to achieve a common goal. In fact, it has a pronounced structuring and integrating influence because it forces collaboration participants to negotiate and overcome their differences in order to make experiments work.

The structuring function of technology manifests itself not only with respect to participants' action but also with respect to the social organization of multi-institutional collaborations. In large high-energy physics experiments, for instance, technological objects differentiate scientists in terms of working groups. The group structure is flexible, with technical problems dictating the shape of change (Knorr-Cetina 1998).

In summary, the technology that is constructed by or for collaborations in science plays an indispensable part in their functioning. Often, the critical stage in a collaborative project is equipment design and building. Some fields (uses of accelerators, ground-based astronomy) rely more heavily on the construction of special instruments than others (materials research, medical physics). Moreover, certain social relations that persist are built up by overcoming technological problems and difficulties. Finally, instrument specifications and construction can also be a source of tension and dissensus. Thus, there are convincing theoretical grounds to argue that a broad conception of technological practice as instrument construction and utilization, as well as data acquisition and analysis, is crucial to our understanding of how collaborations vary and the patterned consequences of this variation. Of course, this argument now needs to be subjected to empirical scrutiny. The first step is to demonstrate the variability of interorganizational scientific formations in terms of their technological practices, and to examine how these formations can be classified into distinct types. In other words, what are the possible "technological scenarios" for the development of multi-institutional scientific collaborations?

Cluster analysis revealed four possible scenarios for the technological organization of multi-institutional formations.

Scenario 1. Projects that combine low team control with high innovation and heavy instrumental orientation. Such collaborations can appropriately be described as "managerial". This term accurately reflects the incidence of high levels of central control over instrumentation and analysis.

Scenario 2. Multi-institutional collaborations that follow this path of technological structuring are in essence the opposite of the first group with respect to managing instrument use, data acquisition, and analysis. Since their distinguishing characteristic is that analytical topics and instrumentation are controlled by the separate research teams, such projects could best be designated as "decentralized." Like managerial collaborations these formations are characterized by a strong focus on equipment design and building of instruments.

Scenario 3. Collaborative projects that follow this trajectory of technological practice do not design, build, or subcontract the construction of scientific equipment and facilities. Therefore, they can be classified as "noninstrumental." Such MICs typically use already existing facilities to conduct experiments or are engaged in theoretical research (which may, however, turn out to have practical applications). Nevertheless, they report high levels of innovation (pushing forward the state-of-the-art), which is more of a theoretical nature.

Scenario 4. Researchers from different organizations combine their efforts in a collaborative endeavor that focuses on elaboration of already existing models. Since these formations are distinguished by low innovation and coordination of results, with individual teams tackling their specific topics. Consequently, unlike the other three scenarios separate teams do not check the accuracy of each other's results. Such collaborative ventures in science are perhaps best labelled "routine."

The four scenarios of technological practice acquire significance for futures studies not only because they highlight the possibilities of divergence of the evolution of interorganizational collaborations in science, but also because they bear upon the disciplinary organization and consequences of research. The results so far indicate that these scenarios are not field-specific but rather have a more general meaning that transcends disciplinary and specialty boundaries. Furthermore, the different scenarios have patterned consequences. Findings from analysis of variance demonstrate some clear differentiations among types of MICs. For example, the most successful projects ("successfulness" was measured on a four-point Likert-type scale, ranging from 4=extremely successful to 1=not successful at all) tend to follow the "decentralized" scenario. At the same time, they are also characterized by heightened degree of stress and between-team conflicts as compared to experiments of the "routine" type. Thus, it seems that success in multi-institutional collaborations comes "at a price."

Finally, the finding that technological practice provides a viable structuring framework for scientific collaborations to follow distinct trajectories that systematically vary in terms of their sociological consequences may have a broader meaning that extends beyond cooperation in science. Indeed, a number of organizational studies have documented that industries with a higher degree of technological intensity are more likely to experience alliance formation (Freeman 1991; Hagedoorn 1995; Powell et al. 1996). On a more general level, the increase in various forms of cooperation in industrial production, services, trade, and the non-profit sector has been linked to the rapid expansion of knowledge and the concomitant changes in technology (Alter and Hage 1993). These changes place higher demands on organizations to adapt quickly and be more flexible, which may make large-scale bureaucracies with a focus on a particular product or service inadequate. In the new environment, interorganizational cooperation that brings together different kinds of expertise becomes a necessity.

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