The organization of scientific collaborations

Ivan Chompalov

Georgia Institute of Technology

Joel Genuth

American Institute of Physics

Wesley Shrum

Louisiana State University

Abstract

Based on empirical analysis of 53 multi-institutional collaborations in physics and allied sciences, we find that generalizations about the essentially informal and collective social organization of collaborative projects in science stem largely from a narrow analysis of high-energy particle physics experiments. Cluster analysis reveals that the variety of organizational formats of collaborative projects can be grouped into four types, ranging from bureaucratic to participatory. Except for particle physics, which is overwhelmingly participatory and non-bureaucratic, the membership of the other three types is mostly cross-disciplinary. The four-fold typology discriminates collaborative projects with respect to their technological practices. The structure of leadership is related to the character of interdependence in data acquisition, analysis, and communication of results: greater interdependence leads to decentralization of leadership and less formalization. We conclude that extrapolation of the organizational characteristics of particle physics to scientific collaborations in general is unjustified.

Keywords: Scientific collaboration; Bureaucracy; Organizational typology; Interdependence;

Science policy

1. Introduction

In his history of the UA1 and UA2 particle physics experiments at CERN, John Krige discusses the "tenacious image" that besets accounts of collaborative projects in physics, an image that generates a typical contrast. On the one hand there is the scientist as autonomous craftsperson, who controls all the tools needed to create new knowledge, with free rein to use those tools in experimental demonstrations for other autonomous craftspeople. On the other hand, there is the scientist as factory worker--part of a multilayered, managerial structure that emulates an industrialized workplace--without the means to produce new knowledge, contributing only a specialized segment to a larger project. Hierarchical relationships replace the "free exchanges among equals...bureaucracy is rampant...decision-making processes have become increasingly formalized" (Krige, 1993, p. 234). At the extreme, such activities are boring, exploitative work that provide little scope for creativity and alienate scientists from research and the new knowledge it produces: the "free-wheeling, creative atmosphere of the university laboratory has been supplanted by the constricting procedures and regimentation of the large corporation" (Krige, 1993, p. 254).

Krige finds the contrast inappropriate and unenlightening for understanding particle physics experiments. Our view, based on a broader survey of specialties in which collaborations form, is that the dichotomy is useful when properly qualified. Like many of the early studies of bureaucracy, this dichotomy employs an undifferentiated mingling of features that are better conceptualized as independent components. Max Weber's classic definition of bureaucracy specified the presence of such features as a division of labor, hierarchy of authority, written rules and regulations, a principle of technical expertise, and so forth (Weber, 1978). His successors in organizational theory have come to recognize that social formations are not necessarily bound to a specific configuration of these features. They argued for examining the components of bureaucracies with an eye to their variability, rather than viewing "bureaucracy" as an undifferentiated concept (DiMaggio and Powell, 1983; Bozeman, 2000). To complicate matters further, while bureaucracy was originally conceived as a rational and efficient form of organization, most of its present-day connotations involve unnecessary formalization, waste of time and resources, and the proliferation or rules and "red tape." Following Bozeman, we distinguish between "normal bureaucracy" and "bureaucratic pathology"(2000). In this essay we examine normal bureaucracy in multi-institutional, scientific collaborations, defined as research projects carried out by three or more organizations.[1] ~~**Modern universities, which often enter such co-operative arrangements, can be described as *de facto* bureaucratic organizations, albeit to varying degrees (Schultz, 1998). We examine the extent to which formalization and hierarchy are transferred to scientific collaborations when these "vitual organizations" are created.**~~

We examine the internal organizational and managerial mechanisms of interorganizational collaborations as temporary or transient forms of scientific research practice. Regrettably, although there is a vast literature on interorganizational relations (Levin and White, 1961; Van de Ven et al., 1974; Kuhn, 1974; Pfeffer and Nowak, 1976; Laumann and Pappi, 1976;

[1] We use the terms 'multi-institutional' and 'interorganizational' collaborations interchangeably, restricting our focus to research projects involving three or more organizations. Research collaborations take on a variety of forms and operate at different levels of abstraction (Katz and Martin, 1997). Recently, a great deal of attention has been devoted to the changing organization of R&D, including the complex features of 'Mode 2' research (Gibbons et al., 1994) and the new mode of interaction between the state, academia, and industry that has gained currency as the "Triple Helix" model (Leydesdorff and Etzkovitz, 1996; Leydesdorff and Etzkovitz, 1998; Etzkovitz and Leydesdorff, 2000). These frameworks operate on a macrolevel of analysis with a focus on innovation, technology transfer, and mechanisms for enhancing the economic applicability of scientific research. Our focus is narrower.

Koenig, 1981; Zeitz, 1985; Wiewel and Hunter, 1985; Alter and Hage, 1993) organizational studies have largely ignored scientific interorganizational collaborations as objects of inquiry, and have focused instead on production (Pfeffer and Salancik, 1978; Browning et al., 1995; Gulati, 1995; Powell et al., 1996), service (Alter and Hage, 1993), government (Clarke, 1989), and non-profit organizations (Kang and Cnaan, 1995).

Research on multi-institutional collaborations in the physical sciences has ~~been dominated by historians, sociologists, and anthropologists who have documented particular~~ collaborations and ~~demonstrated~~ their importance for understanding ~~new forms of~~ social ~~organization,~~ cultural construction~~, and changing social relationships~~. ~~The extant literature on research collaborations has focused disproportionately on~~ high energy particle physics (HEPP) has received a disproportionate amount of attention.

Analysts have highlighted such features of particle physics as (1) the specific culture of this community (Traweek, 1988); (2) the two traditions of doing particle physics science—use of devices to generate "golden images" of events and the utilization of computational techniques to establish logic in quantitative data (Galison, 1997); and (3) the characterization of collaborative experiments in HEPP post-traditional communitarian formations with object-centered management, collective consciousness, and decentralized authority (Knorr Cetina, 1999). The excessive emphasis on particle physics collaborations has led some to argue that such 'mega-experiments' introduce a new form of collaborative work predicated on collectivism, erasure of the individual epistemic subject, non-bureaucratic mechanism of work, lack of overbearing formal structures, and absence of hard and fast internal rules (Knorr Cetina, 1999). This flexible, democratic, and interdependent organizational and management configuration is viewed as the antidote to the hierarchy and control that might otherwise accompany the move toward 'Big

Science' and which, paradoxically, has spawned HEPP 'mega-experiments.' Such a configuration has come to be viewed as the model for collaboration in science. Our results suggest that it is exceptional.

We developed a data set of 53 interorganizational collaborations from seven specialties in physics and allied sciences.2 We coded more than 100 variables for each collaboration, and use univariate, bivariate, and cluster analysis. We conclude that only particle physicists have had a distinctive style of organizing and that their organizational style is but one of several possible ways to organize a collaboration. ~~American particle physicists not only enjoy a uniform infrastructure of funding agencies and accelerator laboratories. During the period covered by our study (roughly 1975-1990), they built electronic detectors at accelerator laboratories to conduct experiments. Competition for time and space at accelerator laboratories, routinized institutional politics, and the limited range of experimental styles heightened the competition for making discoveries and for testing theories. These conditions imposed extraordinary discipline that pushed collaborators to adopt similar organizational structures, granting broad rights of participation to all members of the collaboration, from graduate students to senior faculty. Such Athenian-style democracy has produced remarkably successful outcomes. Yet, when we set aside preconceived notions of disciplinary peculiarities and investigate a broader sample of physics collaborations, we discover that a narrow focus on particle physics as a model for collaboration is misleading. This is only one of several possible organizational formats and it is the only field-specific arrangement.~~ A variety of more overt formal

2 Because of travel and budget limitations, our sample was drawn heavily from collaborations of U.S. organizations. However, we also included numerous collaborations between U.S. and foreign organizations and one entirely

structures describe collaborations in other areas of physics. It is likely they do in other sciences as well.

The contrasting images of the scientist as autonomous craftsman and the scientist as factory-worker are ideal types that historians, ethnographers, managers, and policy analysts are quite unlikely to encounter, as extremes of a spectrum whose mid-ranges need to be differentiated and characterized. The analysis that follows reveals that multi-organizational collaborations display patterned organizational diversity. Application of cluster analysis to organizational and managerial dimensions shows that collaborations have been mixing and matching the features associated with classical bureaucracy--there are many ways of organizing.

We found that a four-category taxonomy of collaboration was the best compromise between the elegant but simplistic appeal to diametrically opposed ideal types and the empirically unassailable but conceptually limited focus on the traits of individual collaborations. Most interestingly, with the single exception of particle physics, there is no significant relationship between organizational type and disciplinary specialty. Even in space science, where NASA and ESA space flight centers have always managed collaborations, and where flight-center project managers have always overseen the design, construction, integration, and uses of instruments developed by external teams of scientists, the collaborations in our sample varied significantly in the ways projects were organized and the ways scientists dealt with project managers. Some geophysics and space science collaborations more strongly resemble each other in terms of organization and management than other collaborations in their respective disciplines. Disciplinary traditions, infrastructure, and idiosyncracies are *not* of much importance to the organization and management of multi-organizational collaborations. Within every discipline

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European collaboration.

studied, the organizational and managerial needs of collaborations spanned a broad range. Yet the ranges for each discipline have been similar, reducing to four distinct types of collaborations: bureaucratic, leaderless, non-specialized, and participatory.

In the section that follows we discuss the data set, methodology, and the distribution of indicators. Next we employ cluster analysis to develop a typology of the organization and management of scientific collaborations along broad dimensions of bureaucracy: formalization, hierarchy, leadership, and division of labor. This empirical approach yields the four distinct categories of collaborative projects that we illustrate with descriptions of representative cases. The typological analysis reveals that particle physics collaborations are not typical of all collaborations and perhaps not many collaborations in the physical sciences, which prompts us to highlight their 'exceptionalism.' In the fourth section, we examine the relationships among organizational type and the acquisition of instruments, data collection, and communication of results. The major connection that emerges is between the structure of leadership and the character of interdependence—greater interdependence leads to decentralization of leadership and less formalization. In the conclusion, we re-examine the major empirical findings and suggest that collaborations be viewed in terms of the principle that 'consensus precedes hierarchy.'

2. Data and Methods

These data were collected as part of a three-phase study of multi-institutional collaborations in physics and allied sciences begun in 1989 by the American Institute of Physics (AIP).[3] The first stage was devoted to an examination of collaborations in high-energy physics.

[3] For a more extensive description of the methodology, sampling, and data collection procedures of the study see the series of AIP reports referenced in the bibliography and available from the

The selection of subjects to be interviewed was accomplished after consultations with the spokespersons of the collaborations. They included spokespersons, physicists, graduate students, engineers, postdocs, computer specialists, technicians, and women physicists. Separate interview guides were created for five of these groups of respondents. Approximately 300 interviews were conducted. During phase II attention shifted to collaborations in space science, geophysics, and oceanography. After an intensive preparatory stage, approximately 200 interviews were carried out with academic, government, and corporate scientists. Phase III was, in a certain sense, the most challenging and crucial. The methodology used in this stage moved away from the collection of exhaustive data in favor of a more selective approach that favored fewer interviews per collaboration and collaborations ~~in~~ a larger number of fields. Five fields were covered: 1) heavy-ion physics; 2) ground-based astronomy; 3) materials science; 4) medical physics; and 5) computer-centered collaborations. In most of these areas interorganizational collaborations are a more recent phenomenon than in high-energy physics, space science, or geophysics. The process of selection yielded a final sample of 23 collaborations. Seventy eight interviews were conducted with scientists in administrative and leadership positions. The interview guide for this final phase was designed after reviewing the results of phases one and two, and contained indicators of variable dimensions of collaboration that were common to all fields. After phase III was complete, we went back and coded 110 interviews on 30 collaborations from the first two phases in order to carry out the present analysis. ~~An attempt was made to conduct follow-ups on projects or experiments. Thirty~~ follow-up interviews were sought for collaborations where missing data

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American Institute of Physics, Center for the History of Physics, One Physics Ellipse, College Park, Maryland.

remained (the return rate for ~~follow-ups~~ was 60 percent). Thus, the data for the current empirical analysis contained information on 53 multi-institutional collaborations across all three phases of the AIP study.

Once the data were collected, cleaned, and coded, the information from the individual interviews was aggregated by averaging across respondents within collaborations to create a "collaborations file" with fifty-three units of analysis. Next the data were prepared for cluster analysis[4] by selecting and recoding variables that measured features of organization and management. Finally, since the number of these variables was fairly large, factor analysis[5] was performed to achieve data reduction prior to input into cluster analysis.

[Table 1 about here]

Table 1 shows the averages and percentages on the organizational dimensions used in the present analysis. Under virtually all circumstances, formal organizations have a single official or position at the top of the organizational hierarchy, but this is not the case in multi-organizational collaborations. In about one fifth of the collaborations in our sample, there was no scientific

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[4] We resorted to exploratory factor analysis with principal components as the extraction method and oblique rotation to a terminal solution. The scree test provided an easy graphic way to discern a plausible factor pattern, since factors below an eigenvalue of 1 tend to be located on a flattening curve. On the basis of the factor solution we created indices by averaging across variables that loaded heavily on a particular factor.

[5] Cluster analysis is an appropriate procedure in this case because its chief purpose is to help create classifications. It is more suitable than discriminant analysis, since the latter requires the prior definition of groups. Cluster analysis, on the other hand, does not demand such predetermined sets, but is rather a procedure to find out how many clusters (groupings) are discernible for the particular cases under investigation. As there is no convincing organizational typology of multi-institutional collaborations to date, cluster analysis was useful for the discovery of "groupings" of collaborations. We employed agglomerative, hierarchical clustering with standardized, squared Euclidean distance as a similarity measure and Ward’s linkage algorithm as a joining rule.

leader—defined as a scientist who was viewed by other collaborators as inspiring the collaboration intellectually *or* a scientist who actively managed resources or made judgements for the other collaboration scientists. In 70% of the cases, there was an administrative leader—defined as an engineer, or a scientist-by-training who views his contribution to the collaboration as being its engineer, who managed the collaboration's resources, or who oversaw the assembly and integration of its instrumentation. About half the collaborations had both--scientific and administrative authority were divided in these collaborations.

We assessed the elaboration of the leadership structure by inquiring about the division of labor, levels of authority, and means of evaluation. Collaborations varied in dividing tasks in specialized or non-specialized ways. In most collaborations, each team had differentiated tasks or functions, and the leadership sought to integrate interests and relationships between teams. But in some, teams had similar tasks or functions, and the purpose of the collaboration was to aggregate team efforts. For example, a collaboration that conducted clinical trials of medical instrumentation~~-~~required that all participants use the same diagnostic protocol so that their data could be aggregated into a pan-collaboration data base~~. **Such a product**~~ **would be more statistically robust and representative than anything a single medical center could collect.**

Since most of our interviewees had advanced degrees, we asked them to use a university department as a reference point in evaluating the degree to which the collaboration was hierarchically structured. Interviewees in nearly 70% of the cases viewed their collaborations as similar to the structure of university departments or containing fewer levels of authority. In the other collaborations, interviewees spoke of multiple lines of authority involving middle managers that leaders used to organize aspects of collaboration activities or of supervisory committees that oversaw the leaders and considered collaboration-wide issues or adjudicated collaboration-wide disputes. These projects clearly involved a greater degree of ~~structuring~~ hierarchy than is common in a standard academic setting.

The exercise of leadership within an organizational structure is not the only form of control[6] employed by formal organizations. We inquired into the use of other procedures associated with bureaucratic organizations: (1) formal contracts that specify roles and assignments, (2) well-understood rules for reporting developments within the collaboration, (3) rules for reporting developments outside the collaboration, and (4) hierarchical procedures for making decisions on several aspects of collaboration activities. As with forms of leadership, multi-organizational collaborations used arrangements that would be untenable for permanent organizations.

Over 60% of the collaborations in our sample had a system of well understood rules for reporting on intra-collaboration work and developments. In the absence of powerful, unified leadership, such rules (in combination with individual competitive pride) could be the principal source of accountability within a collaboration—no one wants to be the bottleneck, in the eyes of fellow collaborators, in the accomplishment of a project's goal. Such was a common and successful strategy in particle physics collaborations, which labored under the external discipline of the accelerator schedule and competing collaborations, but could break down in collaborations that were developing autonomous or unique research facilities. Finally, for most collaborations in our sample decision-making was a mixture of consensual and hierarchical processes, as reflected in the degree to which leadership subgroups participated in decisions concerning scientific,

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[6] One of the oldest, if still disputed, ideas in organization theory is that formalization and centralization of decision-making represent alternative forms of control, rather than being associated in a general dimension of bureaucracy.

engineering and administrative matters.

In the next section, we turn our attention to the way organizational characteristics classify projects into distinctive categories along a general dimension of bureaucracy. We provide illustrations of these categories with typical cases of collaborative projects and set the stage for an exploration of the way organizational form structures knowledge production—a topic that is specifically addressed in section four.

3. The Organization of Collaborations

The concept of bureaucracy, understood as a rational system of organization based on formal rules, written documents, graded levels of authority, impersonality in administrative relations, and clear division of expertise, underlies the empirical analysis in this section. **We sought an empirically derived classification, because past research does not give us sound theoretical grounds for postulating both a specific number of types of scientific collaborations and the nature of these types.** Although scientific establishments in general may have less pyramidal and formalized organizational structures than government offices, industrial units, and corporations, they can still be described in terms of their degree of bureaucratization. A wealth of features can be used to characterize organizational arrangements. Even focusing on macrosociological, synchronic aspects yielded too excessive variables for cluster analysis. However, the dimensions measured here were sufficiently inter-related to justify their reduction to four factors: formalization (presence of written contracts, presence of administrative leader, division of authority, self-evaluation of the project, and outside formal evaluation), hierarchy (levels of authority, system of rules and regulations, style of decision-making, and degree to which leadership subgroups made decisions), scientific leadership, and division of labor.

[Figure 1 about here]

The results of the ~~cluster analysis~~ are presented in Figure 1. Inspection of the dendrogram reveals four groups of projects at rescaled distance level 5. With one notable exception, organizational types are not field specific, but rather cut across fields. The exception is type 4, which is constituted almost exclusively of particle physics collaborations.

[Table 2 about here]

Table 2 assists in interpreting the four clusters (types) substantively. The organizational clustering produced within-group standard deviations that are overwhelmingly smaller than the total standard deviations. This indicates t the clusters are quite homogeneous internally and heterogeneous externally, a hallmark of a good classification solution.

The first type is comprised of collaborations with high formalization, hierarchy, scientific leadership, and a specialized division of labor. We therefore designate this type "bureaucratic."[7] The second and third types both contain collaborations with medium levels of formalization and hierarchy. In that sense they are both semi-bureaucratic. They are distinguished from each other in their need for scientific leadership and their method of dividing labor. Type 2 collaborations never have a designated scientific leader, whereas type 3 projects always have an unspecialized division of labor. We designate them “leaderless”[8] and “non-specialized” respectively. The

[7] Over one-third of the multi-institutional collaborations in our sample fall into this group, which is noteworthy in light of the view, propounded by authors who examine collaborations in a narrow range of specialties, that collaborations in science are essentially very loose, flexible organizations with informal relations, decentralized management, and an absence of central authority (Zabusky, 1995; Knorr-Cetina, 1999).

[8] By “leaderless” we mean collaborations without a scientific leader, not without an

collaborations in the fourth, "participatory" type register the lowest amounts of formalization and hierarchy, while still possessing scientific leadership and a specialized division of labor.

(1) *Bureaucratic* collaborations are characterized by a high incidence of the classical Weberian features of bureaucracy: hierarchy of authority, written rules and regulations, formalized responsibilities, and a specialized division of labor (Weber 1978). Although there are variations among the highly bureaucratic collaborations we studied, several manifestations of this organizational pattern are common: extensive external evaluation, committees upon committees with various designations and functions, officially appointed project managers, clear lines of authority (administrative and scientific), and a well-defined hierarchy of authority. Such a set of characteristics originates with the need to make sure that no organization's interests inappropriately dominates the collaboration, but it also ~~benefits~~ befits multi-organizational collaborations ~~when participating~~ whose scientists can sharply distinguish the collaboration's "engineering" from its "science." In these cases collaborators can pursue science autonomously ~~from each other and~~ from the engineers (and often each other)—provided the engineering is well done and competently documented.

This type of arrangement is illustrated by the collaboration between the University of California system and the California Institute of Technology (with secondary participation by the University of Hawaii and NASA) to build the Keck Observatory. In the late 1970s, University of California astronomers responded to encroaching light pollution at UC's Lick Observatory by entertaining novel telescope and observatory concepts that would vault them into the vanguard of

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administrative leader. As a matter of fact, most of the projects belonging to this type had an officially designated administrative leader.

optical observing power. They calculated that a telescope with a much larger primary mirror than they had ever constructed, if placed at an optimal site and accompanied by state-of-the-art detecting instruments, could yield as much as 100 times the observing power they currently enjoyed. The UC chancellor provided seed money to enable proponents to flesh out their ideas and organized a formal review of the resulting proposals. The result was an endorsement for the idea, championed by Jerry Nelson of Lawrence-Berkeley Laboratory (LBL), of an optical telescope with a segmented 10-meter mirror that would be unprecedented in its size and operating mechanisms.

The technical challenge of the mirror plus the overall size and sophistication of the observatory promised to make the project extraordinarily expensive. Even dedicated fund-raising efforts and excellent luck only brought UC within two-thirds of the $65 million calculated cost for the observatory. UC needed partners. With the support of UC astronomers, UC administrators contacted the California Institute of Technology, UC's arch rival in astronomy. Though UC intended Caltech to be a junior partner, Caltech ended up as an equal because UC's fund-raising luck turned sour[9] while Caltech found Keck, who insisted on giving the money needed for a complete observatory and having it named for him. The University of Hawaii became a junior partner on the strength of contributing a site with the observing conditions that put the mirror in "best light." The Keck Foundation subsequently offered to provide two-thirds the cost of a second telescope that would make optical interferometry possible, and NASA also became a junior partner by providing the last third. The total funds invested in the construction of the twin telescopes exceeded $140 million.

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[9]A promised donation of $40 million failed to materialize when the donor died before finishing the legal arrangements that would have made her intentions indisputable.

The quantities of money involved and the history of competition between Caltech and the UC campuses induced the university administrators to explicitly formalize their arrangements in order to guarantee that neither university imposed its interests on the other. They created a corporation, the California Association for Research in Astronomy (CARA) whose sole purpose was to design, build, and operate the Keck Observatory. A Board of Directors, comprised of equal numbers of representatives of UC and Caltech, oversaw CARA. CARA's leader was the Project Manager, Jerry Smith, an engineer from the Jet Propulsion Laboratory, who was the unambiguous decision-maker over all issues faced by his staff:

> CARA is absolutely hierarchical. There's a manager. He makes the decisions. There's no negotiations about it. There's no 'what do we all want to do.' There isn't any 'we,' there's only the director or the manager.

Finally, a Science Steering Committee (SSC), comprised of astronomers from the universities, was responsible for producing a set of scientific instruments and for advising the Board and CARA staff about engineering options that could affect the Observatory's scientific capabilities. The SSC made its internal deliberations consensual on the assumption that it would not encounter issues that required an exercise of authority to resolve. But the SSC, through its chairperson (who changed over the course of the project) and Project Scientist (the chief author of the segmented-mirror concept), was the authoritative conduit of messages from astronomers to CARA and the Board. These arrangements successfully eliminated the interests of the individual organizations from observatory policies and eliminated administrative ambiguity from the collaboration. Individual participants disagreed strenuously over the substance of observatory design and construction, and their arguments may well have been enflamed by personality conflicts, but there was little if any doubt about the proper procedures for reaching decisions or the good faith of the decision-makers..

(2) *Leaderless* collaborations are similar to the bureaucratic type in their formally organized, highly differentiated structures. The reasons for the formalization and differentiation are much the same: participants whose common history is either competitive or non-existent need to insure that private interests were not stamped on the collaboration, especially when high levels of resources are at stake. Collaborations that wish to separate "science" from "engineering" need to insure that the appropriate people stay focused on tasks. Unlike the bureaucratic collaborations, these collaborations did not designate a single scientific leader to represent scientists' interests or to decide scientific issues. The strong sense of hierarchy present in Keck—in which some scientists were more important than others, the important scientists felt they were outranked by project management, and the Board of Directors actively monitored developments and adjudicated disputes—did not apply to the formalization and the division of labor in leaderless collaborations. In this form of semi-bureaucratic collaboration, administrators sought the input of research scientists regarding collaboration affairs, appointed scientists in charge of developing instrumentation, and attended to the collaboration's external relations while benignly neglecting internal politics.

The DuPont-Northwetern-Dow Collaborative Access Team is a good illustration of this kind of organization. Initially DuPont and Northwestern—Dow joined later—agreed to build a beamline at the Advanced Photon Source at Argonne National Laboratory for various kinds of materials, chemical, physical, engineering, and biological research. With the two organizations varying in their ability to capitalize the collaboration and their needs to produce proprietary and published results--and lacking a history of collaborating on this level—they spelled out their rights and responsibilities in a legally binding agreement that was just short of formal incorporation. As with Keck, the legal agreement stipulated the time and quantities of payments member organizations would make to fund the collaboration, which insulated the collaboration from changes in budgetary politics, and set up a hierarchical authority structure. As with Keck, the ultimate authority was a Board, comprised of representatives of the member organizations, to insure that the collaboration did not become an extension of the interests of any single member organization. For that purpose, DND-CAT rotated the chairperson of the Board among representatives of member organizations. As Keck entrusted design, construction, and operation of the telescope and observatory infrastructure to CARA, so DND entrusted the design, construction, and operation of the bulk of the beamline to a professional group with the *de facto* responsibility of serving the collaboration. (Unlike Keck, these professionals were *de jure* employees of one of the participating organizations, since DND did not incorporate.) And as Keck commissioned scientists at its member organizations to design and build instruments for use in conjunction with the telescope, so DND relied on scientists at member organizations to design and construct "end station" instrumentation to be used in conjunction with the beamline.

The authority structure made for a well-understood system of responsibilities and reporting. The DND Board, like Keck's Board, controlled the budget. However, ~~but~~ the relationships among Board, staff, and scientists at member organizations were quite different. From the outset, DND was to serve a multi-disciplinary set of scientists—many of whom had not previously used synchrotron radiation in their experiments—with a beamline whose components stretched the state-of-the-art but were not novel in their design. Instead of a single Science Steering Committee to decide on instrumentation and channel the views of technically experienced scientists to the staff and Board, DND had working groups for each of the major scientific disciplines that would be using the beamline. Many of the prospective users were as much in need of learning about synchrotron radiation from the staff as they were in need of making their expectations known to the staff.

Instead of a scientist with pride-of-authorship in the innovative design of the central component looking over the shoulder of a project manager with an autocratic style, DND had as its staff director a scientist experienced in developing synchrotron beamlines for academic materials research and charged him with developing a beamline that could simultaneously serve a wide variety of scientific disciplines. Instead of scientists constantly seeking to convince the project manager to provide them with the observatory of their dreams and an activist Board making sure the disputes were properly aired, DND's success hinged on collegiality between the collaboration's full-time staff and the scientists at member organizations. So long as the scientists at member organizations found the staff director and his staff responsive and forthcoming, and so long as the staff could meet the technical burdens they assumed within the limits imposed by the collaboration's budget, the Board was passive instead of active. The staff proposed an annual budget and Board meetings became so mundane that the Board came to operate by tele-conferencing rather than by meeting. The Board also had the luxury of knowing that Argonne's staff carefully monitored collaboration activity in the interest of health, safety, and prevention of developments that could harm the accelerator or the instrumentation of other users.

(3) *Non-specialized* collaborations are the complement of leaderless collaborations. While leaderless collaborations are similar to bureaucratic collaborations in formalization and differentiation (but distinctive in their collegial management), non-specialized collaborations are similar to bureaucratic collaborations in their hierarchical management but with less

formalization and differentiation. The most obvious difference between the two types of semi-bureaucratic collaborations is the presence of scientific leadership.

An instance of this pattern is the International Satellite Cloud Climatology Project (ISCCP). ISCCP has been using radiance data from weather satellites to generate statistics on the global distribution and characteristics of clouds. Cloud-radiation feedback, along with the ocean's circulation, had long been viewed as a major source of empirical uncertainty confronting climate modelers. However, until the International Council of Scientific Unions and the World Meteorological Organization jointly created the World Climate Research Programme, scientists with climatological interests were inhibited from even trying to launch projects by the technical difficulties of collecting and processing data and the higher priority given to the more localized or shorter-term phenomena of relevance to weather prediction. In the late 1970s, an international band of atmospheric scientists, with the help of computation experts, had begun to convince themselves that they could obtain model-relevant global cloud statistics from the information that weather satellites produced (even though those satellites collected higher quantities of lower-quality information than climatologists would have liked). The prospect of addressing a major scientific need without undertaking research and development of instrumentation had obvious appeal to the fledgling WCRP, and in 1982 it formally made ISCCP its first project.

The scientists' principal need was to agree on a single algorithm for deriving characteristics of clouds from the sampled and calibrated data. Before the formal start of ISCCP, they realized they had no intellectual consensus for the algorithm. The route towards consensus made them realize that they lacked the organizational structure the project would need to succeed. Ideally, the scientists advocating algorithms were to take the same data sets, use their algorithms to derive the same ~~quantities for~~ parameters from each data set, and reconvene to decide whose approach worked best. The inter-comparison was done on two weeks of data from three geographic regions. The problem was that the advocates of various approaches to an ISCCP algorithm were not all equally capable of handling data sets that were large enough in size to be a fair test of what an ISCCP algorithm faced.

It can be impossible for all members in a collaboration to accomplish the same tasks without similar levels of resources. ISCCP and the other collaborations in this category were distinctive in their lack of a specialized division of labor. Each ISCCP team was to perform the same manipulations on its data—first in the attempt to arrive at a consensus for the algorithm and then for the processing of the daily data from weather satellites. If scientists with pride of authorship in their algorithms were going to vary in their ability to subject them to competitive tests by processing the same data, *a fortiori* how was the project to impose a uniformly high standard on the teams that were going to sample, calibrate, and process the data that the project assigned to them? A team could not much advance its own interests, the collaboration's interests, or the scientific community's interests by lavishing specialized craftsmanship on a task that was valuable insofar as others did it in just the same way. Thus the collaboration could not much rely on either the narrowly or broadly defined interests of its members to insure the teams would perform to their best capabilities.

A more formal agreement, as in the case of Keck or DND, could have committed participants to making specified contributions or set up a collaboration budget and management that the teams would try to please in order to acquire funding. However, the scientists had shunned formalization as unsuited to their need to reach a scientific consensus on a data-processing algorithm. When they wanted their several organizations to step up to the task of preparing daily weather data for climatological use, they were left contemplating the somewhat bitter truth that:

> .....in this kind of environment where things aren't really that formal, you don't have much control. So if a center is either not doing the job they said they would do on the schedule they agreed to do it on, you can't do anything because you're not paying the bills.

In the absence of formalization as a viable source of project discipline, ISCCP opted to centralize its operations in a member organization that could then be responsible for adhering to standards. The question of which organization should be the central place was ~~academic~~ decided pragmatically. Among the agencies interested in supporting ISCCP, only NASA was prepared to support a global processing center. Among American organizations showing interest in processing some of the data, only the Goddard Institute for Space Studies (GISS) in New York City was prepared to take on the task.

ISCCP remained without an administrative leader. Its various managerial duties were performed by different scientists from the nations and agencies whose weather satellites were tapped for ISCCP's data. However, GISS's role as the global processing center did make the GISS scientist most involved in ISCCP, William Rossow, the *de facto* scientific leader. Because it made no sense to analyze the data before checking its quality and no sense to redistribute the corrected raw data sets for analysis only to recollect them, Rossow, by virtue of his willingness to take on the problems of guaranteeing the quality of ISCCP data, acquired authority over the development of the algorithm that made the weather data climatologically relevant. All recognized that Rossow, using the ideas of others, kept improving the algorithm and reanalyzing the earlier data, and GISS made ISCCP's corrected raw data available, so Rossow's competitors could try their algorithms on the same global data.

Although most major participants wished the collaboration had a well-defined organization, ISCCP never reached Keck's or DND's level of formalization. ISCCP internalized personal rivalries among atmospheric scientists, but the involved organizations did not have the sense of competition-among-equals or independence-of-purpose that led Keck and DND to draft the formal agreements that precluded any organization from being dominant. However, ISCCP did surpass DND and rival Keck in hierarchy and centralization once GISS became the global processing center. As project manager Smith and CARA set the detailed designs and construction procedures for the Keck telescope, Rossow and his colleagues at GISS determined what was authentic ISCCP data. Dissenters within ISCCP could in principle appeal to the WCRP program manager and advisory committee, but the burden of proof would plainly be on those suggesting that ISCCP would be better off if GISS changed course (as those within Keck could appeal to the Board of Directors knowing that the Board was inclined to support CARA). By contrast, the professional staff building the DND beamline served the diverse interests of the scientists of the member organizations. To hold the confidence of the DND Board, the staff had the burden of showing it was well serving those interests.

(4) *Participatory* collaborations are characterized by the absence of the classic features associated with Weberian bureaucracy. This type is the only one whose membership is dominated by a single speciality. Among all the specialties in physical research we examined, particle physics alone has a distinct style of collaboration. Occasionally, particle physics collaborations fall outside the participatory category. Occasionally, collaborations in other specialties resemble a typical particle physics collaboration. Yet it seems justified to speak of *particle physics exceptionalism,* owing to this strong association.

Particle physics collaborations are exceptional in their combination of two characteristics. First, the participants describe their collaborations as highly egalitarian. Compared to collaborators in other disciplines, particle physicists view decision-making as participatory and consensual, define their organizational structure through verbally shared understandings or legally non-binding memoranda rather than formal contracts, and create fewer levels of internal authority. At the same time, the scope of particle physics collaborations encompasses nearly all the activities needed to produce scientific knowledge, including those activities most important for building a scientific career. These collaborations always collectivize the data streams from the individual detector components built by the participating organizations. They frequently track who within the collaboration is addressing particular topics with the data. They routinely regulate the external communication of results to the scientific community.

Particle physics collaborations minimize the powers that managers may exercise in order to insure their members are comfortable with the breadth of activities that the collaboration as a whole regulates. In all other research specialties we examined, scientists in collaborations were more independent than particle physicists in the generation and dissemination of scientific results. They allowed collaboration managers to exercise discretionary powers to secure what they could not individually obtain and then worked as individually as possible with what the collaboration provided. The relationship can be stated as a rule: *the greater the breadth of a collaboration's activities, the more egalitarian its structure and the more participatory its management.* Athenian-style democracy in particle physics produces publications rather than cacophony because competition for discoveries and for career-advancing recognition limit collective tolerance for intra-collaboration dissent.

The organizational and management features of particle physics are well illustrated by

Experiment 715 at Fermilab. The collaboration succeeded with little formalization. The collaborating organizations did not pool funds, so they did not need formal rules to insure that no member received an unfair share of benefits. Rather, each major American organization had its own contract with DOE or NSF, while the Soviet government supported the participation of the Leningrad group. The collaboration did depend on the ability of Soviet participants to travel to the United States. By not pursuing a formal agreement, the collaboration effectively gambled that neither government would prove an obstacle. At times it appeared the collaboration might lose the gamble, but each time participants were able to secure their governments' cooperation. No administrative or engineering leader for the collaboration was needed in the context of a well-understood division of labor. Most participants were recapitulating or building on the past successes that were the foundation for their scientific reputations. The only desired component for which there was no experienced team was a lead glass array, which was built by Roland Winston's team at the University of Chicago. Given the university's reputation and Winston's level of interest in the experiment, that was hardly cause for anyone to worry. The experiment did have a designated scientific leader, whose title was spokesperson (Peter Cooper of Yale). But it had no hierarchy of scientists. Once Fermilab approved the collaboration's proposal for beamtime, Cooper's duties were a mixture of scientific coordination (which was intellectually strenuous since he had to become well versed in the technical needs and characteristics of each component), and administrative routines (e.g. making sure the collaboration covered all the data-taking shifts). However, whenever the collaboration met as a whole to discuss the operation of the detector, the combination of data streams, and the analysis, all titles disappeared. Not even the most vituperative of Cold War rhetoric put a damper on uninhibited, egalitarian discussions of the project:

> It was entertaining to watch in fact. The Russians first came shortly after Reagan's speech in which he declared the Soviet Union the evil empire. They were understandably circumspect and a bit clannish in general .... We'd finally sit down around the table and start to discuss physics and that evaporated. On a given day, Chicago and Yale would gang up on Leningrad and Fermilab and on the next issue they would change sides, they would split. It was the usual physics free for all, as in all collaborations.

Thus, even strong cultural and ideological differences could not inhibit these physicists from a participatory exchange of scientific ideas and criticism.

4. Organization and the Production of Scientific Knowledge

In this section we explore the ways in which the organization of collaborations shapes the social processes involved in producing scientific knowledge. We focus specifically on how collaborations acquire instrumentation, how they manage data, and how they disseminate results. Pronounced relationships are found between major organizational types and all three stages of producing knowledge.

[Figure 2 about here.]

Figure 2 presents the association between organizational type and three factors in the acquisition of instrumentation: whether a collaboration designed its own instrumentation, built its instrumentation, and subcontracted for its instrumentation. Consider first the design of instrumentation. All collaborations, except the non-specialized, usually design their instrumentation. Why should this be the case? The scientific value of collaborations with an unspecialized division of labor depends on the creation of uniform, standardized data. A major virtue of self-designed instrumentation lies in the potential for customizing or improving data collection for the idiosyncratic interests and objectives of a project. A collaboration that aims to standardize data collection over a range of data-collecting sites should not design instrumentation unless inadequate instrumentation exists for its purposes--a participant who produces an innovative design could well be making the collaboration's task more difficult.

In the case of ISCCP, the goal was to assemble a continuous record of global cloud coverage and cloud characteristics. Data from several satellites were needed to produce global coverage. The data from the several satellites had to be calibrated against a common standard for the data set to be internally consistent. ISCCP was not the appropriate context for experimenting with novel ways to ascertain the cloud characteristics that were customarily measured, because that would potentially undermine the common calibration of the satellites. ISCCP was not the appropriate context for trying out measurements of novel cloud characteristics, because that would potentially undermine the global coverage. A centralized hierarchy under a scientific leader served its need for setting standards for data-collection.

All other forms of organization—bureaucratic, leaderless, and participatory—supported a specialized division of labor that enabled participants to design instrumentation. Allowing multiple teams to design instrumentation is an obvious prescription for problems of compatibility and integration. Organizational members provided the bureaucratic collaborations with sufficient powers to compel participants to make their designs compatible with the rest of the instrumentation—e.g., the Keck scientists developing the novel mirror, which had elaborate interfaces with the rest of the telescope had two choices. Either they accepted the project manager's decisions about the capabilities of the instrumentation the mirror would rely on or they appealed to the Board of Directors to compel the project manager to be more ambitious in designing the interfacing instrumentation. In the semi-bureaucratic, leaderless collaborations, participants assumed that the instrument designers had sufficiently generic and routine needs that no strong hierarchy was needed to keep designs from interfering with each other. For example, the DND-CAT staff concentrated on designing the instrumentation that would deliver radiation with desired characteristics to targets, scientists at member organizations concentrated on designing end-station instrumentation that would detect radiation-target interactions, and the end-station and beamline instruments would work together because the end-station instrumentation would need only standard infrastructure support (space, power supplies, etc.) from the CAT staff. Members of participatory collaborations assumed they would be collectively alert and dedicated enough to catch compatibility problems on the spot—e.g., Fermilab 715 participants kept checking their instrumentation when the beam was off and averted disaster when a member found that the controls for a magnet were not properly regulating current flow through the magnet.

Construction of instrumentation closely follows the design of instrumentation and does not generate much differentiation among the three organizational types that designed instrumentation. In sub-contracting, however, the participatory collaboration more closely resembles the non-specialized type, while the bureaucratic and the leaderless are similar. Why?

Both bureaucratic and leaderless collaborations specified in their legal agreements a schedule of payments through which members funded the collaboration. Both designated an individual to be its administrative or engineering leader. In several cases, this individual's career was in project management. When effectiveness in acquiring hardware and keeping to budget and schedule was a defining element in an individual's contribution or professional competence, sub-contracting was more likely to be used to acquire instrumentation. In the case of Keck, an engineer served as project manager. Since the organizational members formed Keck to build and operate one observatory on a finite budget, not to create an ongoing observatory development business, the project manager assembled a modest staff to let and oversee contracts for most elements of the observatory (including a contract with LBL to provide the segmented mirror).

In the case of DND-CAT, the CAT-staff director was a scientist who had previously helped to design and build more specialized synchrotron-radiation beamlines. He and his chief staff members were described as "senior scientists slash engineers." Construction of the beamline was their full-time job, and quickly getting the beamline installed and reliably operating was ~~his~~ their professional challenge. To that end, "what can be purchased is purchased. We contract for the services of a small engineering firm that has experience with designing instrumentation like ours, so they design some of our components and supervise their construction." By contrast, most of the organizational members of Fermilab 715, which had no administrative or engineering leader and did not sub-contract for significant instrumentation, were effectively functioning as ongoing businesses in the production of components for hyperon physics. The Yale, Fermilab, and Leningrad teams all refurbished or recapitulated components they had previously built. All continued to develop their instrumentation specialties after the completion of 715. Whereas members of the DND-CAT staff enjoyed working with "gadgets," the attitude of one of Fermilab 715 leaders was:

> We don't invent new things in terms of apparatus. If it wasn't a piece of technology that wasn't readily doable we weren't interested. The Yale chambers from the earlier experiment were in fact very high technology when they were built in 1971. By 1981 they were not, but thank you we had them. Our motto is steal first. Plagiarism is the sincerest form of flattery.

Rather than create organizational hierarchy and limit the range of member participation in collaboration affairs, Fermilab 715 fostered self-sufficiency among its members, even to the point of foregoing the pursuit of technological innovations.

[Figure 3 about here.]

Figure 3 illustrates how organizational type is related to data acquisition and sharing. In general, more bureaucratically run collaborations tend to collect data in a less collective fashion and do not share them as much as non-bureaucratic projects. But the relationship is more complicated than this simple observation might suggest. In order to clarify this complexity, we consider instances of the extremes for each of the three associations.

The clearest contrast for data acquisition practices is between the leaderless collaboration and the participatory collaboration. The separate teams in the former disproportionately engaged in autonomous data gathering, while teams in all participatory projects took data collectively. The flip side of this correlation concerns data sharing agreements between the principal investigators, where the situation is reversed: all participatory interorganizational collaborations had such agreements, whereas fewer than one half of the leaderless did.

DND-CAT exemplifies the leaderless formation. Instead of a single scientific leader there were six: five for each of the interdisciplinary teams of researchers who designed the end-station instruments and one for the group that built the beamline for the scientists. At the time of our interviews no experiments had been run yet, but it was clearly understood that the various research groups would try to collect their own data without much interaction with the other teams owing to differences in disciplinary orientations, research foci, and organizational interests. The separate teams were assembled according to the particular interests of participating scientists. As a rule they did not envisage collaborating with other teams in terms of agreements to share data.

> We have done some joint experiments, but my estimation is going forward we will actually share data less than 10%. [Less than 10%] Of the experimental time that's done at the A[dvanced] P[hoton] S[ource] will be actually shared data.

Some of the instruments destined for use at the collaboration's beamline, such as DuPont's fiber spinning apparatus, were being built by one organization, without collaboration funds, for its proprietary use.

Fermilab Experiment 715 is a counterpoint to DND-CAT in terms of the manner of data collection as well as agreements between teams to share data. As has been typical of high-energy physics experiments, this one required information from several detector components, each of which had to be adjusted for sensitivity to the same range of phenomena, in order to increase the chance of obtaining statistically significant signals for the processes under investigation. P~~articipants had to take data collectively, as well as coordinate the parameters of the instrumentation they employed to acquire the data. Unlike most particle physics experiments FNAL 715 had to be done in one run and quickly, but as in most particle physics experiments, participants from all teams took turns recording events from the hyperon beam line according to a pre-determined schedule. The latter was compiled by a spokesperson who was relatively egalitarian when the time came to "mass the troops."~~

Agreement between the PIs to share data was never an issue within FNAL 715, ~~as with all high-energy physics experiments,~~ for the simple reason that integrating data taking and merging data streams was the purpose of collaborating. A~~ccess to the data set by all collaborating teams is presupposed. Of course, this does not mean that everybody does a separate analysis, although they might~~. As is often the case with particle physics experiments, ~~the main participants in the hyperon beta decay experiment at Fermilab~~ decided to create one set of summary tapes from which everyone worked. Not everyone in the collaboration was equally interested in all the data streams. Here, and often, one group took the lead in the analysis of a particular topic for which a particular component's data was more or less important. Nevertheless, each team was responsible for providing the other with its data and the information needed to build scientific arguments from them.

[Figure 4 about here.]

Figure 4 shows that the most general difference in terms of communication pattern is between the participatory collaborations and all other organizational types. The participatory category again manifests "exceptionalism" in the sense of lack of press exposure~~, highly variable communication modes depending on the phase of the project,~~ and collective discussion, circulation, and signing off on papers. The other three organizational types exhibit a striking uniformity in their communication and dissemination practices, which run counter to the situation in particle physics experiments. To illustrate this disparity, contrast the Keck observatory, a bureaucratic collaboration, with FNAL 715, a typical participatory project.

The Keck project was widely publicized because the Keck Foundation wanted the world to know the good things it was doing with its money, and because the UC system and Caltech wanted the world to know that they were ~~building~~ the largest twin optical telescopes in the world. ~~In and of itself this is a monumental achievement, and relatively easy to elicit public attention.~~ The collaboration took public relations seriously, and the participating scientists appreciated professional competence in public relations:

> ~~Oh, I think the public eats it up. They love it. And X, who's been~~ Our public relations officer for the last few years, is very effective. He really gets out and gets news releases when interesting science discoveries are made, he really encourages photographers to come and magazine reporters and newspaper reporters to come so they can write glorious articles about it.

~~The Keck collaboration itself formed for the purpose of building the twin telescopes (i.e. the project had only one phase, the construction of the observatory). Logically, for such an expensive venture, everything was well-organized including the manner of communication which remained stable throughout the duration of telescope-building. Communication was formalized,~~

~~with two centers of incoming and outgoing information: the Project Office and the Science Steering Committee. The latter had regular monthly meetings.~~ However, the collaboration as a whole provided no support for the communicating scientific results to scientific communities. Member organizations controlled the telescopes' observing time and let their scientists compete independently for the time. Those who took data were on their own to analyze them and to incorporate their analyses into publishable papers. In short, users of the Keck telescopes publish independently without consulting each other.

FNAL 715 is the exact opposite of Keck in terms of public relations and dissemination of results. There were no press releases about the scientific or technical merits of the experiment. Its greatest source of publicity, the defection of a Soviet participant, was not sought and caused consternation for the collaboration's future among all its physicists.10 ~~Communication was variable depending on the phase of the project. During the preparatory stage it was not v intense and consisted mainly in coordination of the building and modification of the proportional wire chambers, drift chambers, lead glass array, and the transition radiation detector. During the experimental run participants communicated on a daily basis. Finally, the stage of analyzing the observed events was accompanied by a reversal of the communication pattern to a less frequent and less well-organized interaction.~~

~~Asked whether the communication patterns changed from running the experiment to data analysis, one of the physicists ruminated:~~

> ~~I think so. I think they became less good, whatever the word is. The run was an intense period of great cooperation, and it was actually well, very well organized.... The data analysis, as I think was inevitable anyhow, was less well organized; and there were competing analyses at Yale which never really got~~

10 The defection was an unmitigated disaster for the Soviets and a source of mixed feelings for the Americans.

~~incorporated into the final result. So the data analysis was less smoothly located in the run, less well-organized.~~

Presentation and publication of results to the scientific community, on the other hand, was subject to strict collaboration-wide control. Although individual members, especially graduate students writing dissertations, were principally responsible for drafting articles, manuscripts were circulated among all the participants for approval and only ~~then~~ submitted for publication as a multi-authored paper to a physics journal.

5. Conclusion

The recent shift from bureaucratic to flexible, distributed, and informal organizational arrangements has been described as the advent of network forms of organization (Powell, 1990; Burt, 1997). It has been extensively covered in studies of industrial firms, trade organizations, nonprofit organizations, government, and the service sector, but the formal aspects of interorganizational R&D formations have received less systematic attention. We focused on the organization and management of 53 multi-institutional collaborations in several fields of physics and allied sciences. ~~An argument can be made that the more fluid, project-like organizational format originated to a large extent in science and technology, since teamwork and collaboration have become common. Alternatively, it may be argued that the management of 'Big Science' projects has often been modeled after the administration practices of large firms or government offices. These arguments notwithstanding,~~ our intellectual problem has been whether the observed variability in interorganizational collaborations can be systematically reduced to several common types and whether these types are associated with other (non-organizational) features of these collaborations.

To what degree are scientific collaborations structured bureaucratically? We emphasized that 'bureaucracy' itself is often used as an undifferentiated concept that combines a multitude of organizational aspects. For scientific collaborations, we operationalized bureaucracy in terms of formalization, hierarchy, leadership, and division of labor. The analysis showed that claims for scientific collaborations as informal, free-wheeling formations, without hierarchical structures or clear leadership, that utilize strong communitarian organization are only partially true (Zabusky, 1996; Krige, 1996; Knorr Cetina, 1999). Generalizations about the essentially informal and collective social organization of collaborative projects in science are often based on a narrow analysis of high-energy physics. Our thesis of particle physics "exceptionalism" rejects the extrapolation to scientific collaboration in general.

Cluster analysis revealed four types of scientific collaborations: bureaucratic, leaderless, non-specialized, and participatory. The last category is dominated by particle physics and is the only field-specific type. If anything, particle physics collaborations are atypical. Since few projects from other areas of physics and allied sciences share common features with particle physics, their marked "egalitarianism" must be considered exceptional. They are more likely than other fields to endorse strong collectivism and consensus in decision-making. At the same time, they tend to be run less bureaucratically, with fluid organizational structure, fewer levels of authority, and infrequent formal contracts. Both qualitative and quantitative analysis showed the utility of distinguishing between two kinds of formality: administrative and scientific. These two types are unrelated to each other. For example, the pattern that emerges in particle physics experiments is that they tend to exhibit informal administrative/managerial structures, but retain tight control over research, data acquisition, topics for data analysis, and external communication of results.

Another feature of “particle physics exceptionalism” is that these experiments typically have no lead center, but always have a host organization--the accelerator site. The latter is specific for high energy and heavy-ion physics collaborations due to the limited number of facilities and the enormous costs of building and operating particle accelerators and detectors. Thus, particle physicists are forced to collaborate. No single institution can afford to build, maintain, and operate such expensive facilities. The more informal organization of multi-institutional particle physics experiments can at least partially be attributed to their long tradition of co-operative research (Knorr Cetina, 1999; Krige, 1993; Galison. and Hevly, 1992), the well-established funding pattern, and the greater monodisciplinarity of the field as compared with materials science, medical physics, or geophysics.

Most interorganizational projects do not mirror the structure of those in particle physics, but vary substantially across fields in terms of organizational and managerial arrangements and styles. Except for particle physics, which is overwhelmingly participatory and non-bureaucratic, the membership of the other three types proves to be cross-disciplinary. The juxtaposition of the four types of collaboration indicates the importance of organization for the acquisition of instrumentation, the analysis of data, and the communication of results. The most salient connection here is between the character or structure of the collaboration’s leadership and the character or degree of its interdependence. The more integrated a collaboration’s data acquisition, the less meaningful are the independent interests of the member organizations and the less likely the collaboration is to be highly formalized. Particle physics experiments routinely coordinate the parameters of the instrumentation they employ to acquire data and then integrate the data streams from experimental components. And particle physicists have committed themselves and their organization to experiments with no more formalities than signing proposals and then, when an accelerator laboratory so requested, signing memoranda of understanding that specify the division of labor the collaborators had already determined. Rarely are their participants concerned with defining and protecting the interests of their employing organizations.

If we leave aside variations in detail, the overall pattern that emerges for most collaborations is "hierarchy within consensus" rather than "consensus within hierarchy." One informant expressed this general notion as follows:

> It's consensual--or collegial is another word--at the board level. Once you get down to an individual institution then from the director on down its more hierarchical than, say, an academic department would be. It's more the director has control of all the money. If I want to hire a student, for example, then I have to go to X and...he'll say, 'Well, is this student going to work on BIMA science or other stuff?' and he generally will agree to that, but he has the final authority. So it's very hierarchical down each institution's path, but at the top level its much more collegial.

Collaborations are based on a model of consensus before hierarchy. In a more general sense, although scientific collaborations are organizationally diverse, they are all consensual in that organizational members are not compelled to participate. They are not required to submit to whatever hierarchy the collaboration creates for itself. Moreover, they share the common experience of university training. To be recruited into a traditional work organization is to accept employment in a hierarchical work structure. However, as students of informal organization have long pointed out, patterns of practice are often organized into consensual groupings at a micro level. The ephemerality of the multi-institutional collaboration sets it apart. The voluntary commitment to enter the collaboration often means that at the highest levels, there are relatively egalitarian relationships between representatives of participating institutions—the relationships among faculty members within a department is one analogy, with differences in rank, seniority, and reputation that are often inconsequential, and chairs that are often temporary.

The four patterns of organization, as well as the linkage between the management and technological interdependence of the constituent research teams, can benefit science policy makers, program managers, and scientific leaders, given the crucial role that public science plays in technological innovation, transfer, and industrial development (Narin et al., 1997; McMillan et al., 2000) and the fact that a growing portion of publicly funded research is carried out in collaborations.

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