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The organization of scientific collaborations

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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 multi-layered, 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.

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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 (2000), we distinguish between "normal bureaucracy" and "bureaucratic pathology". 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 (Schulz, 1998). We look at the extent to which formalization and hierarchy are transferred to scientific collaborations when these "virtual organizations" are created.

The study of patterns of organizational and managerial arrangements in multi-institutional R&D collaborations is not purely academic, but has profound research policy implications. They stem from at least two conspicuous trends: the growth of collaborative research and the redefined role of publicly-funded R&D. The former is a well-documented phenomenon that has manifested itself not only in the proliferation of all sorts of collaborative formations (consortia, partnerships, alliances, collaboratories, co-operative research and development agreements, multi-organizational science and technology centers), but also in the blurring of traditional boundaries between types of research (basic, applied, development), sectors (industry, government, university), and disciplines. The latter is associated in the US with a number of developments, notably the declining share of federal funding for R&D at the expense of increased spending by industry, the changing mix of publicly-funded branches of science (e.g. a rise in the relative proportion of funds for the life sciences and a dip in the proportion of these funds for the physical sciences and engineering), the greater demands for accountability (e.g. the Government Performance and Results Act, passed in 1993), and the stimulation of linkages with industry through a series of legislative acts, among others. Thus, a major concern of science policy makers, program managers, and scientific leaders alike has been the understanding and emulation of successful and efficient models of setting up and managing multi-institutional R&D collaborations.

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 (Levine and White, 1961; Van de Ven et al., 1974; Kuhn, 1974; Pfeffer and Nowak, 1976; Laumann and Pappi, 1976; 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).

[1] We use the terms 'multi-institutional' and 'inter-organizational' 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.

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).

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 as 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 dataset of 53 interorganizational collaborations from seven specialties in physics and allied sciences.[2] We coded more than 100 variables for each collaboration and used 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[3] 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 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,

[2] Because of travel and budget limitations, our sample was drawn heavily from collaborations of US organizations. However, we also included numerous collaborations between US and foreign organizations and one entirely European collaboration.

[3] This characterization describes the typical case in high-energy particle physics. It does not imply that all such experiments are democratic. As a matter of fact, one of the atypical collaborations is precisely the UA1 experiment at CERN in which Carlo Rubbia's leadership has been marked by inability to tolerate opposition and a strong effort to impose his will on the other participants (Krige, 1993).

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 idiosyncrasies are not of much importance to the organization and management of multi-organizational collaborations. Within every discipline 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 dataset, 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, 1992, 1995, 1999).[4] The first stage was devoted to an examination of collaborations in high-energy physics. 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 from 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

[4] 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 American Institute of Physics, Center for the History of Physics, One Physics Ellipse, College Park, MD, USA.

Table 1
Organizational structure ($n = 53$)

Variables	Percentages/means
Percentage with designated administrative leader(s)	70%
Percentage with designated scientific leader(s)	79%
Percentage with clear division of authority	45%
Percentage with specialized division of labor	85%
Percentage with more levels of authority than a university department	29%
Percentage with formal contracts	67%
Percentage with self-evaluation	43%
Percentage with outside evaluation	78%
Percentage with well-established system of rules	64%
Style of decision-making[a]	1.94
Degree to which leadership subgroups made decisions[b]	2.06

[a] Scale: 1 = consensual; 2 = neither consensual nor hierarchical; 3 = hierarchical.
[b] Scale: 1 = low; 2 = medium; 3 = high.

for collaborations where missing data remained (the return rate for follow-ups was 60%). 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 53 units of analysis. Next the data were prepared for cluster analysis[5] by selecting and re-coding variables that measured features of organization and management. Finally, since the number of these variables was fairly large, factor analysis[6] was performed to achieve data reduction prior to input into cluster analysis.

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 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 judgments 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

[5] 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.

[6] We resorted to exploratory factor analysis with principal components as the extraction method and oblique rotation to a terminal solution. The screen 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.

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.

The exercise of leadership within an organizational structure is not the only form of control 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. 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, 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.

The results of the cluster analysis are presented in Fig. 1. Inspection of the dendrogram reveals four groups of projects at re-scaled 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 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 that 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

[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).

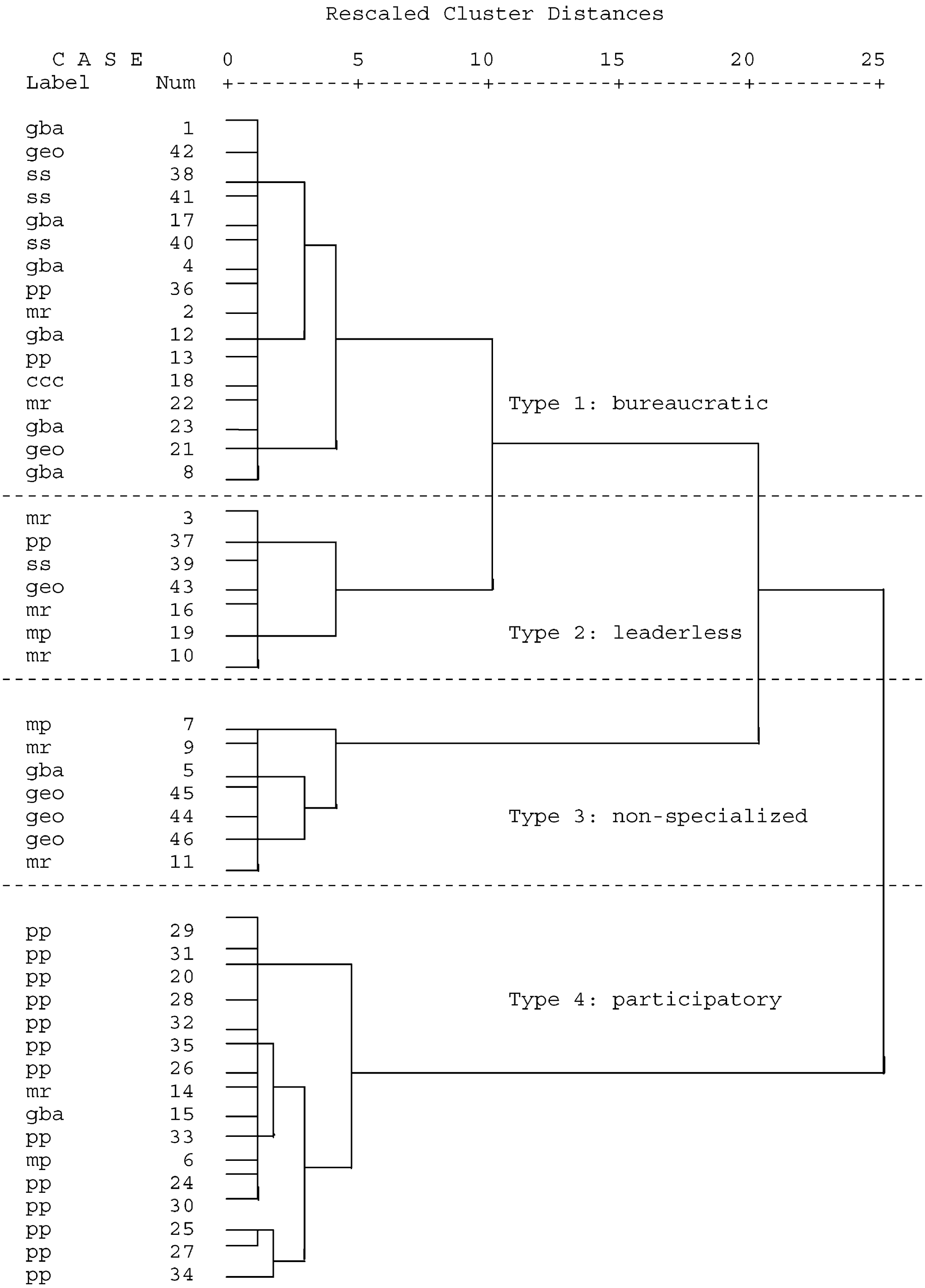

Fig. 1. Organization and management dendrogram using Ward's method: pp = particle physics; ss = space science; geo = geophysics; mr = materials research; gba = ground-based astronomy; mp = medical physics; ccc = computer centered collaborations.

Table 2
Characteristics of project organization and management types[a]

	Formalization		Hierarchy		Scientific leadership		Division of labor	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Type 1: bureaucratic ($n = 16$)	0.88	0.16	2.02	0.41	1.25	0.45	1.00	0.00
Type 2: leaderless ($n = 7$)	0.74	0.15	1.64	0.66	0.00	0.00	0.93	0.19
Type 3: non-specialized ($n = 7$)	0.66	0.37	1.66	0.40	1.14	0.69	0.07	0.19
Type 4: participatory ($n = 16$)	0.21	0.20	1.10	0.37	1.12	0.62	1.00	0.00
Total ($N = 46$)	0.59	0.36	1.59	0.58	1.00	0.67	0.85	0.35

[a] The "formalization" index has a minimum value of 0 (low) and a maximum value of 1.20 (high). The "hierarchy" index ranges from a minimum of 0.75 to a maximum of 2.50. "Scientific leadership" ranges between 0 and 2 (more than one leader), and division of labor was coded 0 = unspecialized and 1 = specialized.

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 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.

3.1. Bureaucratic collaborations

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 dominate the collaboration, but it also befits multi-organizational collaborations whose scientists can sharply distinguish the collaboration's "engineering" from its "science". In these cases, collaborators can pursue science autonomously 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 embarked on a venture to build a novel telescope and observatory concepts that could yield as much as 100 times the observing power they currently enjoyed and would vault them into the vanguard of optical observing power. They endorsed an idea, championed by Jerry Nelson of Lawrence–Berkeley Laboratory (LBL), of an optical telescope with a segmented 10-m 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 US$ 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 while Caltech found William Keck, who insisted on giving the money needed for a complete observatory and having it named for him. The University

[8] By "leaderless" we mean collaborations without a scientific leader, not without an administrative leader. As a matter of fact, most of the projects belonging to this type had an officially designated administrative leader.

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 US$ 140 million. 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. 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.

3.2. Leaderless collaborations

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–Northwestern–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.

The authority structure made for a well-understood system of responsibilities and reporting. The DND Board, like Keck's Board, controlled the budget.

However, 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 SSC 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. 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.

3.3. Non-specialized collaborations

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). 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 World Climate Research Program (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 and then have each team follow a standardized procedure based on that algorithm. Thus, 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. 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 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 datasets 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.

3.4. Participatory collaborations

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 specialty. 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. In that sense, collaborative HEPP experiments are set apart by the extraordinarily broad coverage of activities that their members collectively engage in.

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. No administrative or engineering leader for the collaboration was needed in the context of a well-understood division of labor. The experiment did have a designated scientific leader, whose title was spokesperson (Peter Cooper of Yale), but it had no hierarchy of scientists. 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 unrestrained, 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.[9] 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.

Fig. 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 dataset 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.

Construction of instrumentation closely follows the design of instrumentation and does not generate much differentiation among the three organizational types that designed instrumentation. In subcontracting, 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 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 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 subcontract 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

[9] Of course, we do not wish to imply that there is a causal relationship between organizational features and the production of scientific knowledge. We simply claim that the two are related. It could alternatively be argued that it is the technological aspects of collaborations that shape their manner of organization.

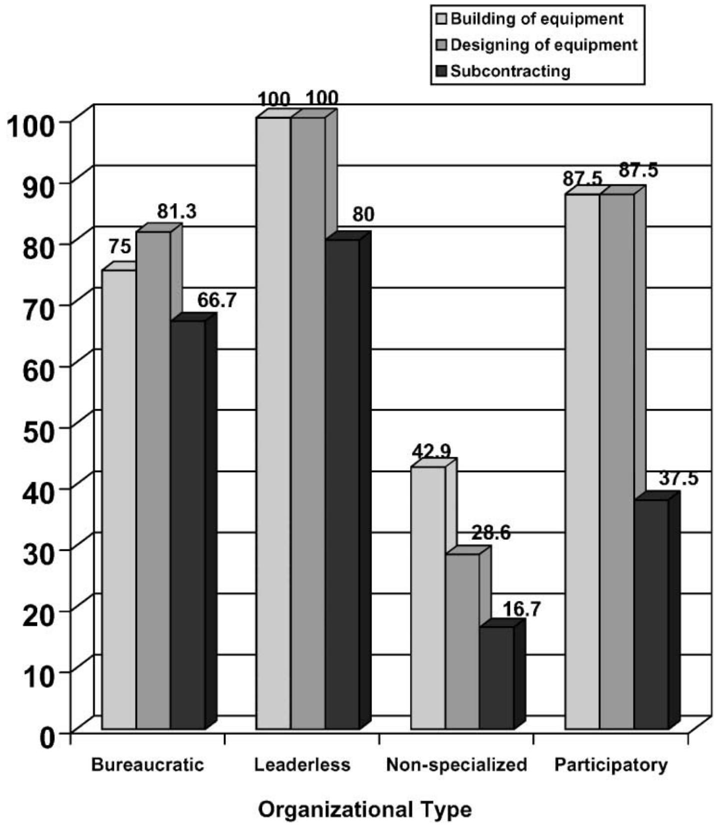

Fig. 2. Cross-tabulation of organizational type by building of equipment, designing of equipment, and subcontracting.

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.

Fig. 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 two 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

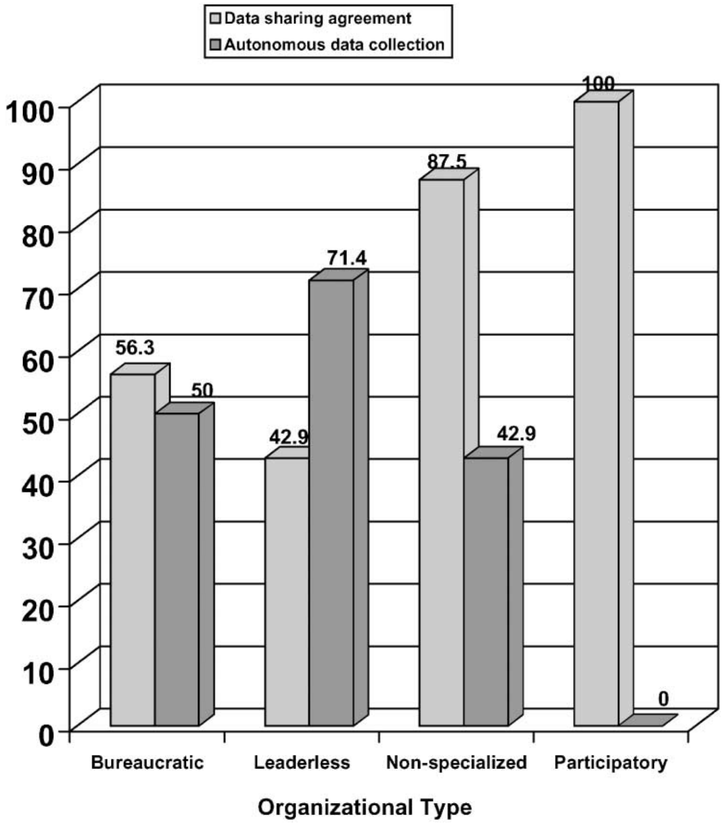

Fig. 3. Cross-tabulation of organizational type by data sharing agreement and data collection.

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. 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. Participants had to take data collectively, as well as co-ordinate 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

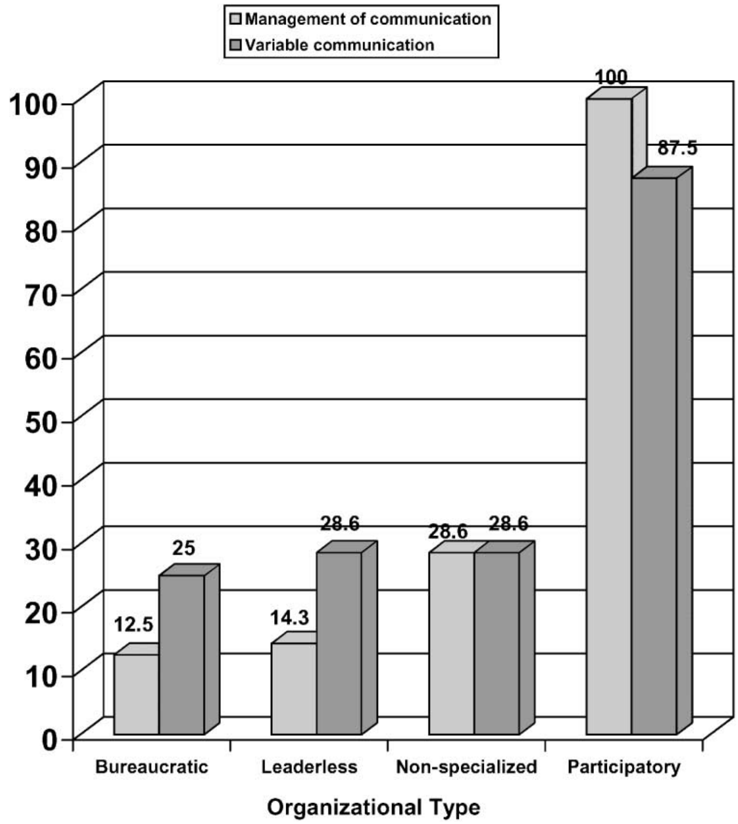

Fig. 4. Cross-tabulation of organizational type by management of external communication and communication pattern.

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". Such an integrated approach to taking data led the PIs to share data automatically; the purpose of collaborating was to merge the data streams to see whether a particle's behavior violated accepted theory.

Fig. 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 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 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 SSC. The latter had regular monthly meetings. However, the collaboration as a whole provided no support for 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. Communication was variable depending on the phase of the project. During the preparatory stage, it was not very intense and consisted mainly in co-ordination 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. 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.

To recapitulate, our findings indicate that the patterns of organization of R&D collaborations are associated with particular features of knowledge production. What matters most is the link between the leadership structure and the degree of formalization, on the one hand, and the interdependence of knowledge generating practices, on the other. In obtaining instruments to conduct scientific research, the designation of an influential administrative leader contributed to significant subcontracting, as exemplified by the bureaucratic and leaderless types of collaboration. In data acquisition and analysis, the integration of activities invariably led to less formalization and distributed leadership manifested most notably in participatory projects. This arrangement, which is typical of particle physics, carries over to dissemination of results where variable communication throughout the different phases of the experiment and collective, collaboration-wide authorship are the norm.

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, non-profit 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 (Hagstrom, 1964). 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 (Krige, 1993; Zabusky, 1995; 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, 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 (Galison and Hevly, 1992; Krige, 1993; Knorr Cetina, 1999), 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 co-ordinate 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 it's 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 it's 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. In the United States a number of federal legislative acts that stimulated R&D collaborative ventures were passed in the 1980s. At the same time, a trend of greater accountability and more frequent assessment of results, most notably embodied in the Government Performance and Results Act of 1993, affected the major funding agencies which support scientific co-operative research (NSF, NASA, DOE, DOD). Consequently, reporting and evaluation requirements for government sponsored collaborative projects have increased, thus creating favorable conditions for greater bureaucratization. This has heightened the tension between the need for better management and the academic culture of intellectual autonomy. Therefore, science policy makers should be sensitized to the fact that changing funding environments have forced and are forcing R&D collaboration teams to look beyond the simple divide between bureaucracy and consensus and resort to alternative intermediary forms of organization that are often better suited to the participants' interests and common goals, as well as the technological and logistical challenges of working together.

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