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Egalitarian Paradise or Factory Drudgery? Organizing Knowledge Production in High Energy Physics (HEP) Laboratories

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ABSTRACT
The organization of cutting-edge HEP laboratories has evolved in the intersection of academia, state agencies, and industry. Exponentially ever-larger and more complex knowledge-intensive operations, the laboratories have often faced the challenges of, and required organizational solutions similar to, those identified by a cluster of diverse theories falling under the larger heading of organization theory. The cluster has either shaped or accounted for the organization of industry and state administration. The theories also apply to HEP laboratories, as they have gradually and uniquely hybridized their principles and solutions. Yet scholarship has virtually ignored this linkage and has almost exclusively focused on the laboratories' presumably unique egalitarian organizational aspects. Guided by the principles developed in the organization theory cluster, we identify the basic organizational features of HEP laboratories in relation to their pursuit of narrow and broad epistemic goals. We also provide a set of criteria and methods for assessing the efficiency of the identified organizational features in achieving such goals.

KEYWORDS
Organization theory; scientific knowledge; scientometrics; high energy physics laboratories

1. Introduction

High Energy Physics laboratories have been cutting-edge scientific institutions in terms of the experimental work performed and the scientific knowledge produced, not to mention the extent of the funds multiple states have invested in them, and the employment opportunities they have provided for physics researchers. They are unique scientific institutions in terms of the organizational structures they harbor, and their scientific success largely depends on these structures.

As HEP laboratories have been around for approximately 75 years and receive vast sums of public money, it is surprising that their organization and management are not more widely scrutinized. Of course, this is true of the scientific field more generally; although 'the division of labour and its management in science have become more important since the sizes of research teams have increased, this aspect of the management of science has not yet been addressed by research' (Maruyama, Shimizu, and Nirei 2015, 864). Furthermore, '[e]ven though the literature on the economics of science has grown … the study of the management of science has been quite limited. The management of science has not yet been well investigated in management studies' (Ibid.). It isn't just the study of management that is lagging behind: 'Organizational studies have largely ignored scientific inter-organizational collaborations as objects of inquiry' (Chompalov, Genuth, and Shrum 2002, 750).

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Even though it has never received a systematic theoretical treatment, the organizational optimization and efficiency of scientific institutions was already a practical concern during WWII when the symbiosis of the military and physics led to the rise of Los Alamos HEP laboratory in the concerted effort to design an atomic bomb. And over the years after the WWII, the assessment of the performance of HEP laboratories has gradually become a requirement of governments, their main funders.

But exactly what does 'performance' constitute? Is it how much knowledge has been produced or does it also have to do with issues of efficiency? If the latter is the case, how does one organize a large laboratory in order to achieve its optimal performance in the production of relevant knowledge? Or more precisely, what organizational principles will ensure optimal performance of a HEP laboratory in the achievement of a particular set of goals? These questions cannot be answered, unless there are clear criteria of performance as it applies to knowledge production. Such criteria are also the basis for understanding how generating scientific knowledge in the setting of HEP laboratories compares to performance in more traditional settings.

In other words, organizational principles are inextricably tied to the examination of performance criteria. And performance criteria depend on the institution's primarily epistemic goals. For instance, does the laboratory need to fulfill larger public goals (e.g. educational goals or development of new technologies), vague scientific goals set by the funders (i.e. by government agencies), the goals set by the designers of the laboratory, the usually narrow scientific goals (e.g. testing of particular hypotheses) set by the in-house team, or the goals of external research groups working on the in-house experiments, who battle for funding? As we will see, measuring performance in the accomplishment of each of these goals requires different methods and metrics, and each goal is served best by a particular organizational structure.

A helpful starting point is organization theory. This is not really a single theory – it is more like a cluster of diverse theories. In its various iterations, it has dominated both the actual development and the theoretical study of organization in industry and administration. It is not so easily applied to HEP labs, however. A HEP laboratory typically embodies a hybrid collection of organizing principles, often at odds with each other, and realized across laboratories. However, as we will argue, the common thread is that each typically exhibits organizational features identified by the principles of organization theory, making this theory valuable to any analysis of performance.

Philosophers, anthropologists, and science policy experts (Martin and Irvine 1984a, 1984b, 1985; Galison and Hevly 1992; Cetina 1999; Perović et al. 2016) have analyzed some aspects of the organization of HEP labs, yet studies of the explicit connections between the organization theory, on the one hand, and the organization and management of large scientific institutions, on the other, are lacking. As I see it, such studies are essential to understand the workings of modern HEP laboratories.

The aim of the analysis, then, is to comprehensively identify the basic general features of the organization of HEP laboratories in relation to their epistemic goals by making use of organization theory and to determine the possibility of assessing their performance – i.e. efficiency in knowledge production in relation to those features – thus motivating further quantitative and qualitative studies. In Section 3, we identify the basic organizational features and their variations with the help of distinctions in organization theory; we consider the way they are related to projected epistemic goals. We also identify what several authors deem unique features of organization of HEP laboratories (its egalitarian aspects) as actually rather common aspects of large, bureaucratized and knowledge-intensive institutions. In Section 4, we provide general criteria for assessing the efficiency of knowledge production, referring specifically to identified organizational features.

2. Preliminaries: The relevance of Organization Theory to HEP laboratories

2.1. The Rise of HEP Laboratories

After the quantum revolution in the 1920s, physics' new insights into the structure of matter required particle collisions at substantially higher energies than could be achieved in table-top experiments with fairly simple experimental apparatus. Hence, the rise of big labs. More specifically, HEP laboratories were constructed to test the latest hypotheses on the structure of subatomic matter (particles and forces); a collection of these hypotheses is known as the Standard Model of particle physics and dates back to the 1970s. Since then, HEP laboratories have extended the Standard Model in unexpected ways.

The final intended product of these laboratories – i.e. their immediate epistemic goal – has been the results of experiments typically published in relevant journals, with internal laboratory publications playing an increasingly significant role, because tasks and team members often overlap across the laboratories.[1] In our analysis of the organization of HEP laboratories and the epistemic goals they pursue, we will rely on the available official records of laboratories, as well as historical, sociological, anthropological, and scientometric accounts of those laboratories that were cutting edge at their inception. Such laboratories could potentially deliver novel experimental knowledge about the structure of matter at the highest available energies at the time and were designed, constructed, and commissioned with that purpose in mind.[2]

In particle accelerator technology, particles are accelerated in an electromagnetic field and then smashed against a fixed target. This technology was initiated in Ernest Lawrence's laboratory. It was, in effect, the first HEP laboratory to be run as a small industrial enterprise due to the size and complexity of the apparatus. Already in the late 1950s, physicists realized that they would need an unprecedented scale of funding to probe matter at ever higher energy levels (Greenberg 1970, 209). Thus, the energies at which particles have been collided have grown exponentially (see Kragh 2002, 303 for exact data on the growth). The size and the cost of the apparatus, as well as the number of physicists and engineers who design and run it, have also risen. Particle beam energy has increased by seven orders of magnitude since Lawrence's laboratory produced the first beams (Panofsky 1994, 128). While the cost of energy production in accelerators per energy unit has decreased by five orders of magnitude, the overall cost of accelerators able to produce the required energies in particle collisions has increased by 10–100 times (Ibid). To this, we need to add the cost of human resources. Early HEP laboratories employed a dozen, or a few dozen researchers; in contrast, Fermilab, one of the major HEP laboratories, presently employs 1750 regular staff, with hundreds of external collaborators working on projects in the laboratory.[3] Between three and five thousand authors are cited in recent CERN papers reporting discoveries and measurements related to the Higgs boson.[4]

This gives a clear idea of the extent to which HEP laboratories have grown since their inception. Growth was fast in the first two decades after the WWII, but it slowed when the cost of laboratories soared. In fact, the first fixed-target phase of the growth before the introduction of the particle colliders that collide accelerated beams inside a detector can be characterized as big-science HEP, similar in scale and structure to some other large laboratories in other fields. With the rise of colliders at the end of the 1960s, however, the size and the cost of individual colliders marked a new unprecedented phase of mega-laboratories,[5] characterized by a reduction in the number of laboratories producing cutting-edge physics to a handful: from a dozen lepton colliders and six hadron colliders that could achieve substantially higher energies[6] to only one, the Large Hadron Collider (LHC) at CERN. Although the organizational and epistemic issues we will discuss were apparent even at the inception of HEP laboratories before the WWII, they have fully come at the forefront in this particular phase of the development.

2.2. Development of Organization of HEP Laboratories – an overview

The organizational development of HEP laboratories[7] around and after WWII can be divided into three phases. The first phase comprises the years of WWII, with the Manhattan project for the construction of the atomic bomb being the major research work of the period and the Los Alamos laboratory the place where major research for the project was done. (Hoddeson 1993) A fact crucial for understanding the first phase is the sheer number of leading experimentalists, including future directors of HEP laboratories, such as L. Alvarez, R.R. Wilson, L. Lederman, A. Weinberg, and others, who were closely involved in the Manhattan project. In fact

> [i]t would be perhaps easier to list those [physicists] who did not [work in the project], for it included most of the Western world's most brilliant physicists from legendary figures like Bohr to young and up-and-coming physicists like Richard Feynman. (Kragh 2002, 268)

The organization of the project and Los Alamos laboratory was a novel symbiosis of the military and the scientific community operating in a university setting (Greenberg 1970; Hoddeson 1993).[8]

Also important in the first phase was the founding of CERN (Conseil Européen pour la Recherche Nucléaire). Conceived as a multinational institution, it was deliberately organized in a top-down fashion with a directing committee established to closely control all phases of the operation to balance the interests of participating nations (Hermann et al. 1987). In addition, various measures of organizational efficiency were introduced into US military projects during the war and developed with the help of simulations and modeling; this, as we will see shortly, laid the foundations for the Rational Modern strand of organization theory (Beer 1959).

Thus, the first directors and managers of major HEP laboratories learned their craft in an environment that combined the organizational principles on which state and military organizations were based, and they were trained in the need to measure and improve their efficiency. Despite these commonalities, they went on to establish quite diverse organizational structures in the HEP laboratories of the 1950s.

During the second phase, the early 1960s–1980s, laboratories exponentially increased in size and complexity, becoming, as we have noted, mega laboratories. Various organizational principles and management styles converged with those developed in industry and state administration. The very ambitious projects realized in the laboratories required close cooperation with industry, necessitating mutual organizational adjustment. This was true even for the first mega laboratories in the 1950s, but the trend grew in importance. For example, when discussing a CERN project recently, one commentator said, 'The construction of ATLAS [one of two major detectors at the Large Hadron Collider at CERN] is an industrial-scale undertaking, and the collaboration therefore has to turn to industry for help' (Boisot et al. 2011, 4). Despite the specificity of the environment of mega laboratories compared to industrial enterprises, their directors have faced some of the same challenges and have come up with similar responses.

At the same time, the state was channeling ever-increasing funds toward the big laboratories, understandably raising questions about whether the public money was being spent wisely. By 1964, US Congress had already expressed doubts about whether scientists were the best kind of personnel to manage and run big scientific projects (Marburger III 2015, 47). The fact that the state was the major funder resulted in the assimilation of organizational principles dominant in state institutions, thus adding another layer to an already hybrid structure.

Outside the labs, a fully professionalized management class was successfully running large industrial projects by then, while state institutions had been run by professional administrators for quite some time. And this new management class was educated in various forms of organization theory.

During the third phase, the 1980s to the present, the rise of large colliders substantially increased the complexity of a few laboratories that could deliver cutting-edge results. These laboratories overshadowed the rest in terms of the capacity for the experiments at the highest collision energies available. Concomitantly, a class of professional managers with MBA and related degrees (e.g. project management) emerged.[9] In addition, a formal management system was introduced in the US by Department Of Energy for large projects, the largest ones being high energy physics laboratories (Marburger 53). At this point, managers outnumber researchers in some departments of HEP laboratories and often micromanage their tasks.[10]

The large industrial and state projects, on the one hand, and HEP laboratories, on the other, share some obvious interests but they also share certain key constraints. They are continuous balancing operations where decisions are made in the face of pressures exerted by funders, constraints of human limitation that have to be made up for (e.g. a need to constantly and exponentially increase computational capabilities crucial for research), limits of cooperation of large numbers of professionals, and physical limits (e.g. collaboration across multiple geographical locations) (Barnard 1938; Peltonen 2016, 74).

They also have similar evolutionary trajectories. In the economy in which small businesses dominate, the fate of a business is not decided by ingenious ways of handling the division of labor, as it is in the setting of industrial mass production. The transition in physics laboratories followed the same trajectory as twentieth-century industry when laboratories started to evolve from handling logistical operations performed by one or two researchers at the beginning of the twentieth century (with occasional exceptions in the history of physics) to employing dozens, hundreds, and recently thousands of scientists and technical staff.

Recent forensic analyses of the failed SSC project (Marburger III 2015; Riordan, Hoddeson, and Kolb 2015) reveal crucial similarities between the environment in which planning and design of large laboratories takes place and the environment in which large industrial projects are realized. The accounts of managers of the laboratories are especially useful sources to explore such similarities,[11] as are detailed histories of laboratories (e.g. Hoddeson, Kolb, and Westfall 2008). Finally, in longitudinal studies, anthropologists embedded in the HEP community report some typical aspects of the organizational challenges we find in industry (Traweek 2009). In any case, the development of HEP laboratories represents a symbiotic linking of corporate, state, and scientific organizations and their goals. Consequently, the general features of organization and management in HEP laboratories reflect those of their partners.

2.3. Is Organization Theory Applicable to Understanding the Organization of HEP Laboratories? Or Are They A Special Case?

Organization theory refers to a cluster of theories that emerged out of industrial practice and academic and professional management studies of organization of industry and state administration.[12] The theories within the cluster can be grouped into classical organization theory, cultural modern theory, rational modern theory, structural contingency theory, and a sociological strand of classical organization theory that started with Weber. We will demonstrate that these various strands of the theory offer a powerful tool for understanding the way modern laboratories performing experiments in particle physics of high energies are organized.

The organization and the goals of production are always intrinsically related in organization theory: certain organizational principles are implemented to provide a desired form of production (e.g. steady production or production boosting short-term profits). Similarly, a key concern in the organization of a HEP laboratory is its epistemic goal (which, as we will see shortly, can be either narrow or broad). Put otherwise, the organization and the goals related to the production of knowledge in a laboratory are necessarily connected.[13] The principles that shape the organization will, in turn, shape its production of knowledge, and its epistemic goals will shape the way it is organized. In what follows, we use organization theory to identify and understand the key organizational features of HEP laboratories as they have been developed to fulfill particular epistemic goals, especially considering how the goals and organization have affected each other.

Yet before we turn to identifying the elements of organization common to HEP laboratories, industry, and state institutions, it is instructive to look at an instance of the self-reflection on the part of HEP management community on this issue. How does that community see itself in relation to the influence of the state as the funder and industry as a major partner and perhaps a prototype of organization and management of large projects? At a workshop held at CERN and sponsored by ATLAS management and its project leaders, a group of professional physicists-managers put together an exhaustive analysis, a self-assessment of sorts, of the organizational structure of HEP (CERN in particular) and its adequacy to achieve set goals (Boisot et al. 2011, 3). The general impression was fairly optimistic in terms of the capability of handling organizing tasks by pursuing autonomous management approaches (albeit from state and industry principles).

The group never explicitly invoked organization theory but rather aimed at developing particular models to understand the organizational setting and challenges of HEP.[14] One crucial specificity of the organization of large HEP laboratories, they pointed out, is shared with other knowledge-intensive organizations in industry and government – the business of research and development (R&D). In fact, the goals and structures of R&D departments in industry closely resemble those of HEP laboratories. Typically, these organizations evolve in somewhat unpredictable ways; they rely on research and innovation and, thus, continuously deal with organizational uncertainties (Boisot et al. 2011, Ch.5).

This rather rare insight into the relationship between industrial organization and organization of HEP laboratories is only a good and limited starting point, however, because the design, commissioning, and performance of HEP laboratories is so broad that it encompasses all the stages of a modern industrial project and its organization, not just its R&D department. We will argue that despite the somewhat justified attitude that 'the managers of knowledge-intensive organizations may have more to learn from how Big Science projects such as ATLAS are developed and run than the other way around' (Boisot et al. 2011, 25), the organizing principles of HEP labs are, to a large extent, deeply entrenched in the practices of industry and state, even though they have hybridized them. In fact, it is difficult to see how we can fully understand the organization of HEP laboratories without considering how organization theory has been applied in industry and government.

It should be noted right away before we turn to our analysis that the dominant notion of the exceptionalism of HEP laboratories in particle physics as uniquely egalitarian scientific institutions with little or no hierarchy (Krige 1993; Galison and Hevly 1992; Cetina 1999; Chompalov, Genuth, and Shrum 2002) is often spelled out too generally and it may be misleading. There is certainly such an aspect to the organization of HEP laboratories, and this has been explored in depth from various angles.[15] The reasons for its emergence are fairly clear:

> 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. (Chompalov, Genuth, and Shrum 2002, 751)

Yet these laboratories are much more complex institutions than the last sentence of this passage and other similar accounts suggest.[16] And as Section 3.3 goes on to show, this egalitarian aspect is a regular occurrence in large institutions with a vast administrative structure – it's just that HEP laboratories are a rare example of it in experimental physics and science in general. Thus, this organizational aspect is only a moderate loosening or flattening of a complex hierarchical organizational structure, the features of which we will go on to identify with the help of organization theory. This is a regularly occurring epiphenomenon of complex bureaucratized institutions; it inevitably eventually emerges as they get bigger and, thus, should not be deemed a central and unique organizational feature of HEP laboratories. Moreover, the hierarchical organization of all knowledge-intensive institutions, including HEP laboratories, is characterized by features that loosen or mitigate it; a tendency often deemed an impediment to their efficient performance. (Kärreman and Alvesson 2004)

As we will see, in many important aspects, the laboratories are far from being egalitarian paradises. Once we analyze their organizational structure with the help of insights in organization theory, it may not be too surprising that, in fact, a number of leading figures in the HEP community, including D. Glaser, L. Alvarez, A. Weinberg, and R.R. Wilson (Krige 1993, 235) thought of a HEP laboratory as an industrial factory-like environment that stifles creativity. The organization of HEP laboratories may be somewhere between an imagined egalitarian paradise and factory drudgery – exactly the position of the organization of most sophisticated knowledge-intensive industrial projects. The authors arguing for exceptionalism tend to contrast the environments of the laboratories with a caricatured image of similar operations taking place in industry. Thus, for instance, Krige (1993, 243) praises the mutual respect of professionals in the HEP labs as a mark of egalitarianism, even though, as we have noted, such respect is customary in industry as well. Exaggerating the egalitarian aspect may conceal the actual structure, which can be particularly detrimental if we believe in an egalitarian norm of organizing science. In fact, such rather hasty conclusions show deficiencies of the analysis that overlooks the key organizational features we will identify with the help of organization theory. We contend that the use of the theory supplements existing studies, creates a richer framework, and paints a more nuanced picture.

3. The Application of Basic Principles of the Organization Theory Cluster to the Organization of Major HEP Laboratories

3.1. Classical Organization Theory; Industrialization of Knowledge Production in HEP Laboratories

Classical organization theory focuses mainly on the organization and division of labor in industry, but emerging analysis from the sociological perspective expands this to a wider range of modern Western institutions. The former analysis was developed out of practical necessity by industry practitioners as a normative tool for industry, and taken up by professionals specializing in the field of organizational tasks. The latter was a result of academic reflection on existing organizational and administrative structures. They converge on a number of issues, however. First, they both analyze institutions as organizational wholes and focus on identifying their various key functions. Second, they study various styles of management and their impact on the efficiency of institutions. Third, they track the influence of a wider social and economic environment on the organization. Finally, and more importantly for present purposes, they both provide criteria to assess institutional performance for policy purposes.

Classical organization theory was conceived around the goal of optimizing productivity. A major insight in terms of raising productivity was that workers should not choose their tasks but perform tasks pre-planned by management; in this view, full work effort is best achieved through top-down management of smaller specialized tasks (Taylor 1919). This approach advocates a strict division of labor between workers and management, with managers requiring specialized skills different from those of the workers involved in the production. Thus, the rise of productivity crucially depends on establishing a hierarchy with a distinct skilled class of managers. Further development of the theory (Fayol 1949) suggests that the way to optimize the managerial work itself is to split it into segments and essentially treat it as production.

Taylor applied his ideas in Bethlehem Steel Works where he worked as a consultant (Taylor 1919). Gantt's (1974) subsequent development of Taylor's work was famously applied by Ford in his Detroit car manufacturing plants. Fayol managed a mining company using the same principles (Cohen 2003). The principles of classical management proved successful in these initial applications[17] and have been relied on in similar contexts across industries.

Production increased exponentially with the widespread implementation of the new organizational principles, and the theory had to grow to accommodate the expanding operations:

> As the organization grows, and as the operations become diversified, the informal organizational model built around the entrepreneur will experience external pressure. The entrepreneur can no longer control all of the information. They can no longer be familiar with all members of staff, as the organization increases in size. Operations expand geographically, and direct contact with various offices is no longer possible like it used to be. (Peltonen 2016, 50)

Thus, optimal operation requires a closely knit and well organized hierarchical network of managers and administrative staff following the basic principles of organizational theory.

Over time, the success of industrial organizations led to their expansion globally, but multinational corporations require a more flexible organizational and management structure; a matrix, as opposed to a strict hierarchy, can provide efficient communication and coordination of relatively loose groups and adequately position the organization in a large, diverse and often volatile international environment. An extended operation has to be recognizable and visible for marketing purposes; it needs to acquire a logo and other recognizable features in various domains.

The introduction of a strict division of labor to increase productivity in repetitive activities, as specified by classical organization theory, has not been confined to industry. With the exponential increase in tasks and staff, it was introduced in HEP laboratories and grew in importance over time. For example, the scanning of data was initially done manually, a technique pioneered at the LBL, where a large number of 'scanners' were, in fact, highly specialized technicians. (Alvarez 1969; Swatez 1970; Galison 1985) This gradually transformed into the need for specialists in various aspects of the computer analysis of data. The tendency toward specialization became a fact of life with the rise of large particle colliders in the late 1960s; staggering amounts of data were now recorded and processed, and the vastly increased complexity of detectors called for dedicated specialists. Experiments performed on the colliders are much larger and more complex than those on fixed target machines. Even those who say the organization of HEP laboratories is egalitarian admit that the design of detectors bears a resemblance to the factory-like division of labor (Krige 1993; 243–4). And for a typical experiment, '[a]lthough most members gained some knowledge of systems for which they had no direct responsibility, they typically did not understand the entire detector' (Hoddeson, Kolb, and Westfall 2008, 276). In addition, the colliders are not dismantled for long periods of time, and they service far fewer long-lasting experiments that engage a majority of the researchers and technical staff available (Hoddeson, Kolb, and Westfall 2008). This necessarily led to the change of tenure requirements at universities, with doctoral degrees awarded for very specialized topics serving the collider needs.

Styles of managing such large research groups varied from one laboratory to another, but they all had to establish hierarchical management of one sort or another. The LBL in the 1960s is perhaps the best example of organization managed in accord with classical organization theory; management was firmly in control of each stage of the design, commissioning, data production and analysis, and the laboratory employed a number of highly specialized 'scanners' and other specialized staff, who were managed top-down (Krige 1993). The design and commissioning phases, usually taking up a great portion of a HEP laboratory's lifetime, were organized as a typical industrial project along the principles of the division of labor in classical organization theory. Often the director of the lab was, in effect, an acting executive. For its part, CERN was run by a distinct management class from the very beginning, for the reasons mentioned above. As part of the ongoing movement toward the division of labor and labor specialization, managers with specialized degrees (MBA, project management, human resources) manage various departments.[18] Their tasks and the tasks of managers with physics degrees gradually evolved toward the micromanagement of researchers who work on very specialized tasks in detection and data analysis.

Even as their focus narrowed and became specialized, the research staff working on experiments in large colliders formed a network connecting universities around the world. Just as global expansion required industries to develop a more flexible organizational style, so too the coordination of a diverse matrix combining university affiliates with in-house staff and management required innovative management and communication technologies. Organization became a combination of formal, informal, and patrimonial approaches (discussed in the next section). The most famous response to this requirement was the precursor to the World Wide Web developed at CERN. HEP laboratories also had to establish PR units, design lab logos, and other recognizable features as they increasingly turned into social and state mega projects.

State-funding agencies have increasingly exerted external pressure on universities and HEP laboratories (Marburger III 2015). US laboratories initially had substantial autonomy as the government perceived them as a strategic asset in the cold war (Greenberg 1970). This virtually free creative period subsided with the economic crisis of the 1970s when oversight became stricter; feedback on performance was gradually introduced and finally formalized in the 1990s. (Marburger III 2015) The DOE, the main financing agency of HEP in the US, understood its role as that of a contractor, with universities the supporting units (Ibid. 61). Thus, the increased collaboration among universities and their ever-closer interdependence within large HEP projects led to the transfer of many organizational and management functions from academia (Ibid. 61-3).

Finally, the key goal of industry according to classical organization theory should be stability of the product in terms of quality and availability (Taylor 1919; Peltonen 2016). The explicitly set goals (i.e. the research products) of HEP laboratories initially varied across laboratories. As a rule, however, they shaped their epistemic goals in a broad, long-term fashion, facilitating stability of knowledge production. This initially involved projecting tests of a cluster of hypotheses, optimally distributed over a longer period of time.

As their size increased, the laboratories projected their epistemic goals as even broader long-term strategies, leading to a general tendency to structure national laboratories in such a way as to provide

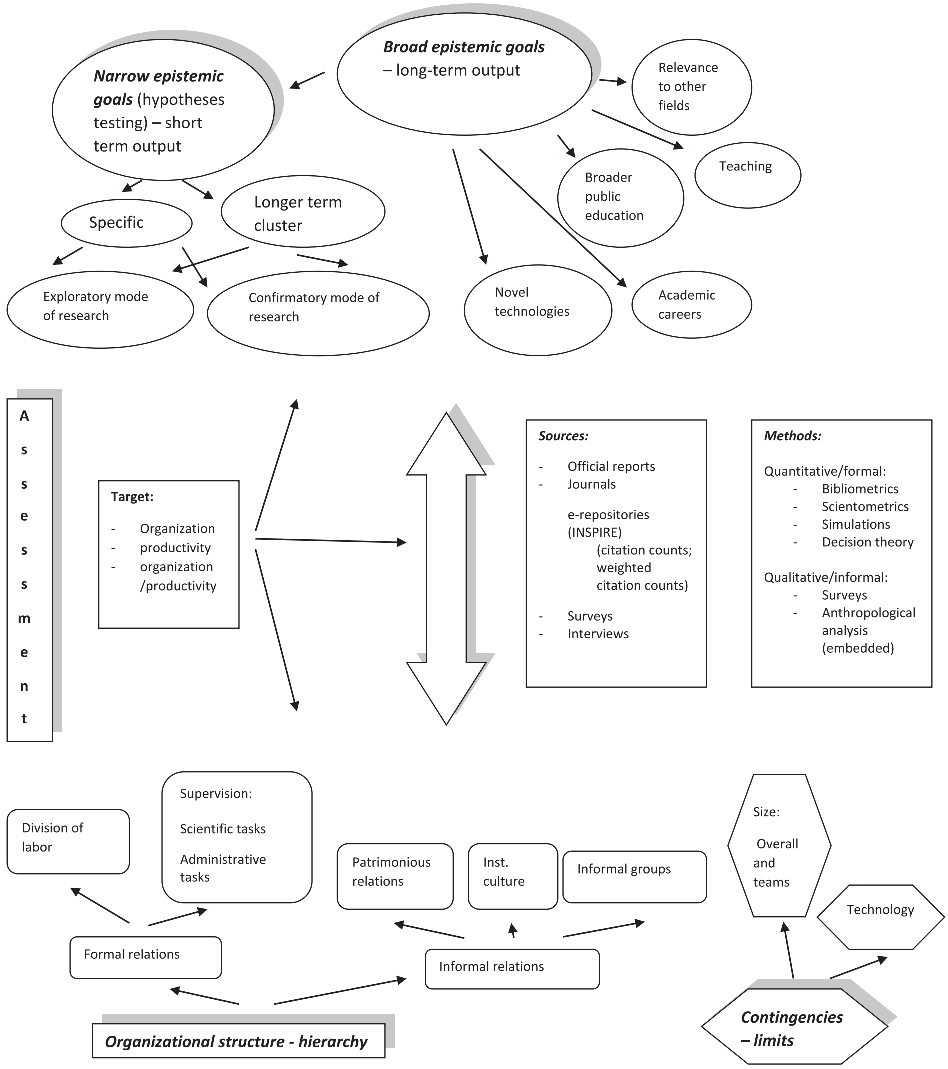

Figure 1. The basic elements of the organization and epistemic goals of HEP laboratories, and the tools for assessing them and their relationship.

stable outputs in the long term, rather than organizing around short-term tasks (Hallonsten and Heinze 2012; Westfall 2012). More specific tasks (e.g. a search for a specific particle) and their organization (selection of projects, scientists, and staff to pursue them) are now assimilated into a broader long-term strategy of pursuing larger epistemic goals.

Even at the start, CERN took a stability-first approach to mitigate its international complexity; in contrast, US laboratories such as the LBL or SLAC retained a narrow goal-oriented mission focused exclusively on testing specific hypotheses. Currently, the LHC at CERN is organized as an experimental complex to provide a steady stream of diverse experimental results and technological innovations and as a platform for broad educational achievements. (Boisot et al. 2011)[19] (See Figure 1)

3.2. Sociological Stream in Classical Organization Theory; Administering and Bureaucratizing Knowledge Production in HEP Laboratories

Quite early on, the sociological perspective on organization theory pointed to the astronomical increase in the size of institutions as the main incentive for bureaucratization and ensuing symbiosis with the state. The sheer number of organizing tasks made this inevitable. A bureaucratic structure was expected to enable the optimum performance of organizations (both state and industrial) under the pressure of contingencies, such as the increase in size (pertinent in HEP laboratories). Thus, in agreement with classical organization theory, '[b]ureaucratization offers above all the optimum possibility for carrying through the principle of specializing administrative functions according to purely objective considerations' (Weber 1958, 215). Such a structure is open to quantitative efficiency assessments of its goals, that is, assessment of internal efficiency (Ibid.). Technical superiority of bureaucracy over other forms of organizing is the main reason for its imposition. Resources, precision, and speed are optimized thanks to the bureaucratic organization and the professionalization of the class that organizes the institution. A bureaucracy can be contrasted with a collegial organization of work which is less precise, slower, and prone to conflicts. Thus, in general '[t]he larger the organization the more formalized its behaviour. … The more regulating the technical system … the more formalized the operating work and the more bureaucratic the structure of the operating core'. (Mintzberg 1989, 338)

Yet Weber points out a downside of this process. The professional inevitably becomes an overly specialized cog in the mechanisms of large institutions, be they industrial or scientific. This gives rise to another set of negative effects in large bureaucratized institutions. For one thing, the work atmosphere changes; 'normal bureaucracy' providing optimal organization turns into 'pathological bureaucracy'. Weber was one of the first, if not the first, to recognize the inevitability of the tendency toward bureaucratization in scientific institutions in the business of knowledge production. He identified its emerging downside as the following:

> In the field of scientific research and instruction, the bureaucratization of the always existing research institutes of the universities is a function of the increasing demand for material means of management. Liebig's laboratory at Giessen University was the first example of big enterprise in this field. Through the concentration of such means in the hands of the privileged head of the institute, the mass of researchers and docents are separated from their means of production in the same way as capitalist enterprise has separated workers from theirs. (Weber 1958, 225)

As the size of the HEP laboratories increased, fund administration, human resources, engineering projects, facilities, public relations, and other segments of large institutions were delegated to professionals in those areas, or to formally educated physicists who spent their careers managing and specializing in similar tasks. In fact, departments for experimental and theoretical physics in current laboratories are only two of many specialized departments. The physicists' work is often supervised by multiple supervisors affiliated with various projects; the tasks delegated to the physicists are structured in project-related collaboration across departments. It is not unusual for a physicist to have his or her work managed by multiple supervisors affiliated with different departments and projects.

As pointed out earlier, HEP laboratories feature an informal, patrimonial bureaucracy (Boisot et al. 2011, Ch. 11). Many or most of the participants in projects are affiliated with universities around the world, not with the laboratory *per se*. This makes establishing a formal hierarchical structure impossible, even one resembling a structure from the university setting. The hierarchy is not based on a legal but on an informal, largely unregulated, web of power.

Moreover, there is a struggle between two types of hierarchy, a formal one coming from the state funders and collaborating industry and an informal one emerging from the university affiliated participants who derive their professional standing from the university setting. The two systems jostle for position in the laboratories, with negative consequences all round. Despite their dramatic and desperate tone, the following two passages clearly list the downsides:

> The enormous size of Big Science projects requires constant oversight by administrative bodies …. The true risk is excessive bureaucratization of large scientific projects. Public authorities, which have the fair duty of monitoring the expenses incurred by large projects, can impose decisions based on purely financial considerations, neglecting

their scientific and technical aspects. Administrators are accustomed to operate quite different than scientists, and can even inadvertently destroy the special vitality that thrives in a research environment. (Giudice 2012)

The sheer size of the undertaking, the micromanagement by DOE, and the intensity and frequency of external oversight all led to a bureaucratic internal culture at the laboratory. In the name of cost control, technically needed changes and design trade-offs were discouraged. Decisions on technical alternatives were distorted by 'political acceptability' and were at times made late or not at all … Key scientific and technical people were generally placed low in the decision chain. (Panofsky et al. 1994)

In any event, the administration of the laboratories has varied widely, from mechanistic bureaucracy to flexible and patrimonial. As noted previously, CERN was organized top-down to reconcile the multiple national interests of those participating in the project (Hermann et al. 1987). This inevitably led to a more complex hierarchical organization. But the negative effects of such bureaucracy appeared fairly quickly, with experimenters complaining about the 'Barons of CERN' (Ibid.) who imposed tasks on them. When there is coordination across institutions, a patrimonial, informal, model of administrating becomes necessary, as the management does not have formal administrative levers to impose tasks on the external collaborators who are affiliated with various universities and institutes. This patrimonial structure is, unsurprisingly, quite similar to the collaboration within multinational corporations working on a single project and embodies the matrix organizational structure (Chompalov, Genuth, and Shrum 2002, 765; Boisot et al. 2011). While the administration is formal, the organizational structure controlling research, data, and publication of results becomes informal but tight.

Moreover, in knowledge-intensive institutions in general, the formal organizational structure tends to loosen up because of the fairly dynamic and unpredictable nature of the tasks and the focused expertise of most employees that cannot be supervised directly as supervisors lack detailed knowledge of the process (Ditillo 2004; Kärreman and Alvesson 2004; Von Nordenflycht 2010). The loosening of the organizational and managerial structure in such contexts may not be avoidable and may result in decreased efficiency (Alvesson and Sveningsson 2003). In any case, this trend is certainly not a unique feature of HEP laboratories.

Finally, the flattening of economic and social differences is unavoidable in centralized bureaucratized institutions (Weber 1958). Mintzberg summarizes this tendency:

The more complex the technical system, the more elaborate administrative structure, especially the larger and more professional the support staff, the greater the selective decentralization (to that staff), and the greater the use of liaison devices to co-ordinate the work of that staff. Essentially, if an organization is to use complex machinery, it must hire staff experts who can understand that machinery – who have the capability to design, select, and modify it. And then it must give them considerable power to make decisions concerning that machinery, and encourage them to use the liaison devices to ensure mutual adjustment among them. (Mintzberg 1989, 338)

This is true of HEP laboratories as well. The equalization of authorships in knowledge production and catering to tenure are marks of this tendency. As we have pointed out earlier, many authors have focused on this egalitarian aspect in their studies of the organization in HEP laboratories in order to hail their supposed organizational uniqueness. Yet this feature of organization is not an exceptional occurrence in any large institution; in fact, it is a complex epiphenomenon of all bureaucratized institutions, not a unique and necessarily epistemically beneficial feature of HEP laboratories.

A positive take on exponential growth has been articulated as the economy of scale (see e.g. Brinkman and Leslie 1986): centralizing production ultimately decreases the logistic costs. Another argument in favor of such an approach is that large institutions are a kind of environment that gathers human and financial resources around goals that could not be pursued without such institutions. In the case of HEP laboratories, the expectation has been that 'this produces very fertile ground that is naturally open to innovation well beyond the planned objectives of the project' (Giudice 2012, 110). (See Figure 1 – the broad epistemic goals) Some empirical research, however, suggests the opposite is true: innovation is eventually stifled by over-centralizing (Agrell and Gustafson 1996) and various atmospheric effects of gathering large numbers of scientists into a single project or a tightly knit set of projects, and result in a variety of crippling effects (Torrisi 2014). An early warning of this came from Weinberg (1963), 255), who also pointed out that the internationalizing of laboratories acts as a counter balance to this negative effect as it stabilizes funding for political reasons. The multinational nature of large expensive scientific projects works in their favor:

> [t]he International Space Station was estimated to cost more than three times that of the LHC, its cost was continually rising and the scientific motivations for its construction were rather weak. The international element and prior agreements with foreign countries certainly worked in [its] favor. (Giudice 2012, 103)

The tremendous, often multinational, investments in HEP laboratories quickly turned them into institutions that were too big to fail. Thus, '[c]olliding beams detectors are so large and costly that no one even thinks of dismantling them at the end of the run; the experiments are effectively unending' (Hoddeson, Kolb, and Westfall 2008, 281). They become social projects and a scientific activity in which the entire society was engaged one way or another and, thus, virtually impossible to dismantle.

This inevitably defines its epistemic goals in broad terms, as pointed out earlier. Yet bureaucratization and its hierarchy often go hand in hand with the centralization of funding. Large industrial projects and military organizations alike required such centralization in the first half of the twentieth century, with the government-funded Manhattan project a case in point. The change in the attitude of the state as the funder of HEP laboratories was a result of a rather usual developmental trajectory of the oversized institutions, identified by Weber early on. The costs paid for from the funds borrowed from the public will rise tremendously in the case of big centralized organizations even if their productivity is constantly improving (i.e. if they are well organized). The industrial projects that grow fast are inevitably, at least partially entrusted to the state for financial reasons. This financial help can be beneficial for the execution of the project when vast funds are needed, but the state eventually assimilates the project's organizational as well as financial scheme into the state bureaucracy as it seeks accountability as the major funder. Thus, in the case of HEP laboratories, initially

> society was willing to buy … argument, up to a point, that good science is the bottom line and that the legalistic mechanisms of accountability being implemented elsewhere were an expensive luxury whose marginal benefit to society could not balance the reduction in scientific output necessary to create it. (Marburger III 2015, 78)

In other words, the physicists were allowed to organize their laboratories on their own even though the state was the funder. The development of the laboratories in the US during and a few decades after the WWII was predicated on a belief of the state agencies as the funders that explicit justification of the organizational scheme of the laboratories was not required as the scientists knew best how to do it. Yet eventually, there was a change in the attitude of the state as the funder, a result of the funding trajectory identified by Weber.

As Weber (1958) points out, an increase in bureaucracy and secrecy eventually go hand in hand. Barring exceptions of national security agencies, the goals and methods of publically funded institutions should be public. Yet obstacles to this eventually emerge in HEP laboratories. For example, traditional peer review is not possible in current HEP mega laboratories; it becomes an internal process as almost all the scientists working in the field are engaged in the project. In addition, the highly specialized science does not help the wide dissemination of results; publications of discoveries are simply short summaries with little content, while all the relevant publications are internal. There is also a default resistance to external critique; the presumption that it will be suspicious is almost inevitable, since all the acknowledged experts are working on the mega lab's project. This contrasts to the traditional culture of universities and can have negative epistemic consequences. All this is evocative of a phenomenon identifiable across professional institutions, one Von Nordenflycht (2010) labels the 'opaque quality' of services.

3.3. Cultural Modern Organization Theory; Informal and Decentralized Organization in HEP

In his work on organization theory, Merton (1940) focused on organizations as social systems. He advocated the view that informal characteristics of organizations are far more important than the transparent and deliberately introduced formal 'facade' (Merton 1940). Thus, the analysis of an organization ought to focus on the relationship between individual and organization, as the status of the individual and the positive culture of the institution are more important to productivity than is an imposed top-down organizational structure. Normatively speaking, it is far more effective if managers are embedded in the community of specialized workers, mediating between them and the goals, rather than top-down micromanaging as a removed class. In what became known as cultural modern organization theory, Merton and others argued that the work atmosphere plays a decisive role in increasing the productivity, even though it is an informal aspect of organization. The human and social characteristics of the organization are primary movers of the organization, and informal cliques are more important than the transparent structure and formal division of labor. If this is indeed the case, applying the rules of classical organization theory in a HEP laboratory context can be harmful, as it stifles or even dissolves informal community.

A comprehensive multi-year study in Hawthorn factory tested outcomes in the productivity of various organizational structures, considering the social composition – formal and informal – of teams (Roethlisberger and Dickson 1964). Automatically recorded data on the movement and productivity of workers demonstrated that flat and loose management structures were substantially more productive. Organizational adjustment should not be confined to the social composition and culture of the people in the organization; it should extend to the wider economic environment, especially, the wider community and its social and cultural composition. Early case studies of a regional development in Tennessee (Selznick 1949) and a gypsum plant (Gouldner 1954) assessed the latter kind of adjustment and its results. The case studies, discussions, and analysis focusing on the 'climate' or 'atmosphere' in organizations (Blake and Mouton 1964) evolved into research addressing 'organizational cultures' in the late 1970s (Pettigrew 1979; Hofstede et al. 1990). Another line of research looks at the role of the broader environment in managing organizations (Nystrom and Starbuck 1981).

Fermilab's first director, R.R. Wilson, organized the first major US national laboratory in the early 1970s by deliberately placing individual scientists and their needs at the center, in contrast to the formal, hierarchical and closely-knit organization of the in-house specialists at LBL and CERN, which makes his management style exemplary of cultural modern organization theory. He was not alone in this thinking; as we have mentioned earlier other prominent figures in the physics community reacted to what they perceived as the increasingly industrial organization of the research process in particle laboratories, and the factory-like conditions that undermined creativity. They objected to seeing physics going down the road of industrial organization as conceived by classical organization theory. Some left the field altogether to pursue small-scale research in biology, but Wilson stayed and built an alternative vision at Fermilab:

> He expressed his vision of research as performed ideally by lone, independent scientists … Hoping to redeem what the Manhattan Project had wrought upon the world, Wilson … planned a utopian laboratory intended as a place of beauty … and contributing to cultural and social advancement. (Hoddeson, Kolb, and Westfall 2008, 6)

Under Wilson's directorship, the laboratory was a place for assembling experiments by outside groups, not a centralized in-house run institution (Hoddeson, Kolb, and Westfall 2008). Moreover, the in-house physicists were assigned administrative work to prevent them from gaining too much power in performing experiments (Hoddeson, Kolb, and Westfall 2008; Traweek 2009, 137). The dependence on external groups led to the management to oversee the budget and tightly schedule activities (Marburger III 2015, 54), unlike the centralized laboratories that vastly over-spent often just because they could, and lowered their financial expectations to have their proposals accepted.

Wilson's vision within the HEP context called for the removal of the rigid hierarchy, a focus on individual intellectual and other needs of scientists, and the introduction of an informal structure of administrating the laboratory and experiments. Yet eventually the lab was beaten by CERN in a few break-through discoveries; this resulted in a major organizational overhaul that led to centralization and the establishment of long-lasting in-house experimental groups. (Hoddeson, Kolb, and Westfall 2008, Ch. 7)

The factor of 'work atmosphere' played a key role in organizational change as well.[20] In the 1970s and 1980s, the main issue in the debate among physicists on 'the best environment for physicists'

(Traweek 2009, 126) centered on the relations between in-house and outside groups (Hoddeson, Kolb, and Westfall 2008; Traweek 2009). This was not surprising, as the '[r]elations among the groups [were] highly, though informally, structured' (Traweek 2009, 127). The in-house groups were typically long-lasting and closely knit, but they also had to work with groups from outside. The formal and informal relationships between the in-house and outside research groups became the crucial organizational point. The physicists themselves often perceived failures to compete with other labs, or the fact they missed discoveries that technically could have been made at their lab but instead were made at another one, as stemming from a type of organization that favored outside groups (Ibid. 130). The in-house groups at SLAC emphasized their technical superiority over outside groups (Ibid. 128), and the lab director ultimately re-established the 'lab's traditional decision-making structure' (Ibid. 129).

The epistemic goal of laboratories was focused on facilitating a flexible structure for explorative searches expected to bear cutting edge results. It was not defined in terms of an immediate knowledge product – i.e. results of specific tests of a chosen set of hypotheses. This led to a focus on flat, informal organizational structures and collaboration with the wider particle physics community. The job of crafting short-term tasks was delegated to a wider community of external research groups hosted in the laboratory, with each using its own way of organizing to complete its task.

Barnard's cooperative theory (Barnard 1938) is another instance of the cultural modern organization theory. It addresses 'non-logical' thinking, or pragmatic thinking under pressure. In fact, the pragmatic, rather than the principle-based reasoning formalized in either decision theory or theory of rational choice we will discuss shortly, may be crucial in decision-making in HEP laboratories (Staley and Rehg 2008). If so, formal decision theory cannot be a major guide to organizing an institution, a view held by the proponents of the rational modern approach (next section). Nor is transparent formal organization the reason for the stability of the production process. We ought to focus on building the common goals, ideology, and culture of the organization, not on providing direct financial or career-success incentives. This may be true of HEP labs as well; according to Corley, Boardman, and Bozeman (2006), in physical sciences '[m]ethodological or epistemic norms within a discipline often define the 'rules' that the discipline uses to deal with a variety of work-related issues', while 'the cultural status of the discipline is entangled in the shared epistemology between the members of the discipline' (977).

3.4. Rational Modern Organization Theory; Formal Streamlining of Knowledge Production Processes in HEP

The operational analysis of rational systems and choices resulted from the military need for efficient rational management systems and decision-making in WWII (Hoddeson 1993; Edwards 1997; Johnson 1997). Mathematical modeling, simulations, and quantitative optimization were developed to address these needs in quantifiable, transparent, and applicable ways. The methods were meant to be applied widely in industry after the war.

The symbiosis with the systems theory of Bertalanffy and others resulted in a rational–scientific epistemology of organization (Peltonen 2016, 91) whose goals include the identification of operating principles and their optimization, as well as optimal decision-making procedures of individuals. Beer (1959) developed a thorough theoretical account of 'a cybernetic factory' based on a set of computational principles. H. Simon's decision-making theory (Simon 1947) detached operational analysis from qualitative studies by Weber and other sociologists by focusing on models of operations that identify and analyze relevant variables. This gradually resulted in the separation of the sociological study of organization from MBA studies. The onus in the latter work is on optimizing hierarchical, vertical structures in order to break the hierarchical bureaucracy. Rationality is treated as bounded, within the operational framework of the organization. Thus, prioritizing and evaluation, that is, considerations of consequences, are always part of operations. For instance, various predictions, contingencies such as power of technology or size of the operation, or politics of funding are taken into account during the planning phase. The approach has been developed as computational organization theory. (Carley and Wallace 2001)

This approach became a feature of the planning and organization of HEP labs early on, especially in CERN. Physicists built on the experience of early organizers of the Manhattan Project, especially the organization of Los Alamos Laboratory (Hoddeson 1993), and the organizers' discovery that linking military organization and science benefited from their methods. Anticipation of technological advances and estimations of the capacity of the existing and planned technology have always driven decisions on the long-term development of HEP laboratories; for example, the development of the LHC instead of the lepton linear collider was largely predicated on such estimates. (Panofsky 1994) And in accord with the rational modern approach, laboratories also introduced quite early on an operational self-assessment in the form of citation metrics based on the INSPIRE archive of HEP papers. Simulations and modeling have been part of the scientific process in HEP laboratories since the beginning. The laboratories were on the leading edge of the development and use of such techniques.[21]

In any case, a clear epistemological goal shapes assessments and organizations. The organization is seen as a formalized network of nodes and their relations; the assessments of the scientific network are implemented top-down to optimize the network's operation, given its desired product, whether wider knowledge-production or narrow hypotheses testing.

3.5 Structural Contingency Organization Theory; The Size Matters in Organizing HEP

The structure of each unit and technology implemented in the production process requires a specific, usually hierarchical, division of labor, and situational contingencies such as the size of the organization or the phase of its development inevitably frame the organizational structure. The goal of organizational analysis, according to structural contingency theory (Woodward 1958; Thompson 1967), is to find an optimal form of organization by assessing operating methods with respect to these contingencies. This represents a shift from the study of general organizational systems to the study of the internal contingent organizational structure. A range of different types of organizations can be included, from bureaucratized hierarchical organizations to flexible organic organizations, as can a range of contingency factors, from size, to technology, environment, and business strategy (Peltonen 2016, 116). The treatment of each contingency has to be contextualized, measured against many other factors – and each can benefit or harm the organization depending on the context.

Thus, for instance, an increase in the size of an institution will generally lead to a substantial increase in bureaucratization. Early empirical studies from the Aston school (Pugh et al. 1969), as well as more recent studies (Wang, Thijs, and Glanzel 2015) demonstrate that an increase in size also leads to increased specialization and structural diversification. (Blau 1970; Peltonen 2016, 120) In fact, this issue is central to understanding the organizational challenges faced by HEP laboratories. The downside of increasing the size of research institutions across sciences, including physics, has been analyzed using a number of parameters (Katz 1982; Von Tunzelmann et al. 2003; Carillo, Papagni, and Sapio 2013). The results show that the initial advantages of size eventually bring about diminishing returns, so the ways of restructuring laboratories and their priorities in the research process are crucial. The question is to what extent this applies to the HEP laboratories and how.

The focus on building a favorable local context rather than establishing a coherent general system of organization may be another essential component of the organizational development of HEP laboratories. Japan and the US have developed different models: Japan's model is that of a household where mutual agreement is key, while US labs are tightly managed top-down, much like sports teams (Traweek 2009, 149). As is generally acknowledged, the Japanese industrial management practices based on the 'household' turned out to be superior to the US model in the car industry. Japanese factories were strategized around properly timing multiple autonomous and the level–field partnerships. Given the failure of the US model in the auto industry, some questioned its ability to manage big laboratories (Marburger III 2015, 50)

Thus, instead of a full-blown assessment and optimization of the network, akin to Beer's 'cybernetic factory', optimization of the network in this case required the identification of the limits of its key contingencies, e.g. size/efficiency relations. Whatever the actual goal in terms of knowledge production (broad or narrow, long- or short-term), the contingencies will affect it, so understanding its limits is crucial.

4. Conclusions: Organizational Features of HEP Laboratories and Their Epistemic Efficiency

4.1. Conclusions

The organization and epistemic goals of HEP laboratories shape each other. The principles of organization theory point to the following key features of this interrelation (Figure 1):

(1) The organizational hierarchy, strict division of tasks, and specialization promoted by classical organization theory as the foundation of efficient industrial production emerged early in the development of HEP laboratories.
(2) Classical organization theory argues for long-term stable production as the goal of an organization. With the increase in size of the laboratories, the initial short-term epistemic goals of testing specific hypotheses (hypotheses-confirmatory goals) steadily became only a part of the longer term, broader epistemic goals of continuous wide knowledge production (long-term, optimally timed testing of a cluster of hypotheses, education of wider public, granting degrees, developing new technologies, etc.).
(3) The egalitarian feature of the organization of HEP labs that some authors see as an exception and a unique organizational feature is simply flattening and loosening a complex administrative and organizational structure already identified by the sociological strand of classical organization theory in all large institutions, especially knowledge-intensive ones.
(4) The anti-industrial reaction to the premises of classical modern organization theory that identified and promoted a focus on informal and flat organizational structures as the essential features of institutions was echoed in deliberate decentralization and matching open exploratory (as opposed to centralized confirmatory) epistemic goals in early phases of Fermilab and some other HEP laboratories.
(5) The organizational dynamics engendered by the size of laboratories – i.e. bureaucratization and hierarchy resulting from the increased size – is the key contingency in HEP laboratories in the optimization knowledge production.
(6) The rational modern (operational research) organization theory approach that emerged with the Manhattan project promoted formally based assessment and optimal operation of organizational structures; either overtly or covertly, this has been a steady feature of the development and operation of HEP laboratories.

4.2. The Organizational Features of HEP Laboratories and their Epistemic Efficiency

The interrelated basic organizational features and epistemic goals of the laboratories are presented in Figure 1. The diagram also identifies formal and informal methods of assessment of these features and their relationship with the epistemic goals – i.e. the assessment of the efficiency of knowledge production depending on various organizational features employed in the organizing laboratory. The goal of the assessment is to identify the adequacy of an organizational structure and its various aspects (as defined by different strands of organization theory), with respect to a particular kind of epistemic goal and to point out possible trade-offs. As we have seen, some methods of assessment have been applied (bibliometrics, embedded anthropological and sociological studies), but an analysis based on organization theory provides a comprehensive framework for a concerted effort of this sort.[22]

An organization's epistemic efficiency, i.e. its ability to meet its knowledge production goals can be assessed quantitatively or qualitatively, that is, along the lines of either rational modern or cultural modern organization theory. The narrow scientific hypotheses-driven goals can be analyzed through the lens of rational modern organization theory. Any scientific research has an internal measure of its efficacy. The self-assessment of productivity through the comprehensive HEP archive of papers and citations Inspire established and run by the HEP community (mentioned above) is a good model for measurements of this sort and can be applied across other scientific fields.

In contrast, classical organization theory focuses on the stable continuous production of results, not on narrow short-term goals. CERN is managed as a continually updating and evolving stable long-term operation aiming to satisfy a number of broadly defined goals. Performance defined in this way focuses, broadly speaking, on a comprehensively satisfying use of large public funds. In fact, all large colliders should be assessed against such broader considerations. One such broad consideration is the usefulness of experimental results to other similar enterprises and other scientific fields. Another is that the laboratory can be expected to provide a constant output of innovative technologies. And it is a place where a generation of physicists is educated, thereby providing a platform for their success in university careers and their achievements of teaching goals. These broader criteria are harder to quantify, and the analysis must rely, at least in part, on qualitative assessments of the larger social and cultural context of the laboratory.

The organization can be also assessed as a transparent administrative structure, following classical organization theory, focusing on the intricate division of labor, the role of the management class and its relationship with the research and technical staff. Following cultural modern theory, however, the work atmosphere and informal groups are equally essential to well-organized operation (). Finally, various contingency factors, especially the size of the laboratory are main considerations identified by structural contingency and sociological theory, respectively.

The efficiency of each of these aspects of the organization identified with respect to the production of narrow and broader goals can be tested quantitatively and qualitatively. Computer simulations, decision theoretic analysis, assessments based on scientometric criteria, and certain sociological and anthropological methods can measure the effectiveness of various aspects of the organizational structures in terms of the efficacy of achieving both narrow and broader goals. These existing methods should be comprehensively applied and developed. The production of experimental knowledge in the laboratories can be traced surprisingly accurately by tracking the production of papers and citation counts (Martin and Irvine 1984b; Perović et al. 2016). The HEP archive of papers and citations INSPIRE was established in the early 1970s. These citation counts are as accurate a measure of productivity as we can get in a scientific field. On the one hand, missing relevant work is virtually impossible, since only a handful of labs collaborate. On the other hand, the papers are not cited to any significant extent outside the narrow field of particle physics, so citation counts indicate expert opinion alone. Put otherwise, they trace the agreement between experts on the validity and fruitfulness of results. These can be compared to the organizational features. The perception of the role of various organizational factors in the performance of the laboratory by researchers or policy-makers themselves can also be surveyed and concrete solutions offered.

The US Government gradually introduced accountability, along with substantial penalties for infractions, into large scientific projects, including large colliders (Marburger III 2015, 53, 54). In fact, this was the basis for the cancelation of the SSC funding. In Europe, this type of oversight was present from the very beginning, and CERN developed in a different social and political context than the US HEP laboratories. The US trend toward close oversight emerged after the end of the cold war. Although the funding agencies (i.e. government) began to request feedback on the performance of the laboratories, the HEP communities and policy-makers did not make a concerted effort to define their goals and the corresponding metrics. Of course, a major obstacle to performance analysis in science is that advocacy, rather than thoughtful policy, usually leads funding decisions, but efficiency metrics are the basic level of any science policy: funders, policy-makers, and often scientists themselves should require them.

Notes

1. Broader epistemic goals have emerged with the substantial increase in the size of the laboratories, involving the education of a wider public, teaching, granting degrees, etc.
2. A number of HEP accelerators have been constructed for industrial purposes.
3. For the number of physicists working in HEP labs in previous decades see Martin and Irvine (1984a, 192) and pp.193–4 of the same publication for the estimated cost of each major laboratory.
4. See http://www.sciencedirect.com/science/article/pii/S037026931200857X and https://journals.aps.org/prd/abstract/10.1103/PhysRevD.93.072004#authors
5. This sound distinction was drawn by Hoddeson, Kolb, and Westfall (2008)
6. For a list and location of major HEP laboratories producing collisions at energies in excess of one billion electron-volts, see Panofsky (1994, 93). For an exhaustive list of laboratories prior to the Large Hadron Collider at CERN, see Martin and Irvine (1984a, 1984b, 1985). For a comprehensive list of all HEP-related institutions, see http://slac.stanford.edu/spires/institutions/major.shtml. For a complete list of HEP cutting-edge laboratories, see https://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics.
7. In the US most prominently: Lawrence Berkeley National Laboratory (LBL), Stanford Linear Accelerator Center (SLAC), Brookhaven National Laboratory (Stoney Brook), Fermilab. In Europe: CERN (Switzerland), Frascatti (Italy), and HERA (Germany). KEK in Japan and JINR in Dubna in Russia/USSR.
8. In his classical theory of state bureaucracy to which we will turn later on, arguably the most influential work in the sociological strand of organization theory, Weber (1958) accounts for the basic elements of the administrative structure and organization of the military later employed in the Manhattan project, showing how it overlaps with the principles guiding large private enterprises.
9. See Section 3.2; see also, e.g. affiliations and education of authors in Boisot et al. (2011).
10. This insight is based on recently conducted interviews with the physicists of various seniority at Fermilab and CERN. See Section 3.2.
11. For example, see the accounts of Alvarez (1968), Marburger III (2015) and (Hoddeson, Kolb, and Westfall 2008) for an exhaustive list of R. R.Wilson's accounts.
12. In dividing and grouping various theories of organization, I rely on a wonderful and informative review of organization theory and its history by Peltonen (2016). There are many excellent historical accounts and classifications of organization theory each focusing on particular strands. But I focus on those relevant to the organization of HEP mega laboratories; in this sense, Peltonen's classification is helpful and comprehensive. It is certainly possible that other work may be relevant, but this is a preliminary account meant to motivate further studies.
13. See Torrisi (2014) for an in-depth discussion of various criteria of productivity in science.
14. Another telling example of an overly optimistic view of the management of mega laboratories is the unconditional perception of open-science, especially resource aggregation as benefiting research. The limits of aggregation have been extensively studied, and the results suggest that aggregation can fairly quickly start affecting performance negatively for a number of reasons. (Agrell and Gustafson 1996; Carayol and Matt 2004).
15. See especially Chompalov, Genuth, and Shrum (2002) where extensive interviews are conducted with researchers across physical science, including those working in HEP laboratories. The results show a loose administrative structure in HEP laboratories compared to other sub-fields, but this, as we will see shortly, does not necessarily mean the patrimonial organizational structure of research is as loose.
16. There are also substantial differences between the organizations of various laboratories, as well as differences in different phases of their development. They started as either temporary establishments organized around multiple projects or as centralized in-house run laboratories, but they all evolved into long-term standing institutions.
17. For critical assessments of Taylor's accounts of his early experiments, see Wrege and Perroni (1974).
18. See Section 3.2.
19. See also https://home.cern/topics/large-hadron-collider.
20. The cultural modern approach to organization has ongoing relevance, with policy analysts in industry and science seeking to explain variations in the efficiency of institutions. This sort of research is rare in its explicit connection of organization theory and organization in science; it is on the right track and stands to shed useful analytical light on the HEP laboratories.
21. Yet these techniques have only recently been used to assess the capacity of various organizational structures in scientific institutions (Zollman 2007; Perović et al. 2016). The last section returns to this issue.
22. The author is collaborating on three ongoing different projects of this sort.

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