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The Social Structure of Experimental Strings at Fermilab; A Physics and Detector Driven Model*

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The Social Structure of Experimental Strings at Fermilab; A Physics and Detector Driven Model[1]

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Introduction

For all the empirical certainty and mathematical rigor of experimental high-energy physics (HEP), its sociology remains somewhat of an enigma to those outside this scientific community. Writing a sociological account of HEP demands that experiments be studied within the institutional contexts where they are performed and not as closed systems divorced from the dynamics of laboratory activities. In addition, social factors cannot be separated from the "experimental" aspects of HEP - detectors, particle beams, and computing architectures. By analogy with the approach taken by Human Factors engineers, those who would study the sociology of experimental HEP must approach it as a people-experiment process.[2] Also, accounts

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[1] An earlier version of this paper was published as Fermilab TM-1706 on December 12, 1990. This work is part of my Ph.D. dissertation research at the University of Chicago, under the direction of D. Garber and W. Wimsatt of the Philosophy Department and B. Winstein of the Enrico Fermi Institute. This research was made possible because of the help of the members of the E-516, 691, 769, and 791 collaborations (J. Appel, S. Bracker, B. Denby, R. Morrison, T. Nash, K. Stanfield, and D. Summers), who in interviews and/or by reading drafts provided guidance on the technical details of the paper. I would like to thank my Fermilab colleagues, A. Malensek, J. Morfin, who read multiple drafts of the paper and made many helpful comments. I would also like to thank G. Fraser, Editor, *CERN Courier* for providing valuable insights from the CERN perspective and F. Nebeker (Rutgers-The State University of New Jersey) who provided helpful comments from a historical perspective. Special thanks go to P. Galison (Stanford University) whose comments helped to strengthen a number of my arguments. Finally, I would like to thank my colleagues L. Hoddeson, C. Westfall, and A. Kolb for helpful comments on multiple drafts under the auspices of the Fermilab History Collaboration. Fermi National Accelerator Laboratory (Fermilab) is operated by Universities Research Association Inc., for the United States Department of Energy.

[2] The major objective of Human Factors Engineering (Ergonomics) is the study, design, and development of systems in terms of the capabilities and limitations of the people who operate, maintain, and manage them. My point here is that much like Human Factors engineers study systems with the assumption that the human organism is a crucial element which must be integrated into an overall people-system design, social factors in scientific activities must be viewed as part of the experimental process itself. For details on Human Factors Engineering see B.H. Kantowitz and R.D. Sorkin, *Human Factors: Understanding People-System Relationships*, (New York: John Wiley & Sons, 1983), E. J. McCormick and M.S. Sanders, *Human Factors in Engineering and Design*, 5th ed., (New York: McGraw-Hill, 1982), and E. Grandjean, *Fitting the Task to the Man*, 3rd ed., (London: Taylor & Francis Ltd., 1980).

that claim to characterize the nature of *experimental* practice must focus primarily on experiments not the conceptual development of the theoretical models of HEP. But when experimental case studies are used as the basis of accounts, they should be representative of the majority of HEP experiments within a defined time period. Accounts that focus solely on the limited set of so-called "discovery" experiments help to perpetuate the misguided image of high-energy physics research being dominated by a continuing series of crucial discoveries. The account must also be sufficiently fine-grained to describe what collaborations of experimentalists actually *do*, but anchored to the larger institutional context of laboratory life. Writing a sociological account also demands the identification of "unifying devices" that help to organize the data that are presented. But such devices should emerge from the actual practice of experimentalists and not be taxonomies which are artificially imposed on the data.[3] Finally, the sociological researcher should take the views of the experimental researcher seriously, but not uncritically, subjecting them to the constraints described above.

In this paper, I present a case study of four high-energy physics experiments performed at Fermilab between 1976 and 1991. I begin by describing the institutional context of Fermilab in terms of a number of distinct, yet inter-related, resource "economies" within which experimental collaborations must trade for the resources needed to perform experiments. I then show how the case study suggests a physics and detector driven model of the social structure of collaborations. I also define the experimental process as a people-spectrometer system in which social factors are a crucial part of all phases of the experiment from detector design through the publication of physics results. I try to demonstrate how the physics and detector driven model can be extended to describe "strings" of experiments which have a complex and definable social structure that spans a 15 year period. In addition to describing the copiousness of experimental strings at Fermilab, I suggest that they are motivated by experimentalists' attempts to avoid the *physics* uncertainties involved in building new experimental detectors, the *sociological* uncertainties of securing resources from the laboratory, and problems of forming new collaborations to perform follow-up experiments.[4] Finally, I suggest that experimental strings are unifying devices which emerge from the actual practice of HEP and are not ad hoc taxonomies that are imposed upon experimental activities.

Resource Economics at Fermilab

Presently, Fermilab operates the highest energy particle accelerator in the world. The laboratory's five stage accelerator complex produces 800 billion electron volt (GeV) proton beams which can be used to produce different types of particle

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[3] The importance of identifying "unifying devices" was recently pointed out by Lillian Hoddeson in a review of J.L. Heilbron's and R. W. Seidel's book *Lawrence and His Laboratory: A History of the Lawrence Berkeley Laboratory*, vol. 1 (Berkeley, CA: University of California Press, 1989). Hoddeson explains how "Writers of institutional history are typically plagued by too many achievements, too many structures, too many events, and too many people to analyze or even identify carefully. This overabundance of content calls for the invention of unifying devices to prevent disintegration of the histories into kaleidoscopic chronicles." See Lillian Hoddeson, "Roots of Big Science", in *London Times Higher Education Supplement*, (London: The London Times, Summer, 1990).

[4] In her recent comments for the Panel on Big Science at the 1990 Annual Meeting of the History of Science Society in Seattle, Lillian Hoddeson pointed out that the large investments that collaborations make in their experimental apparatus and the professional relationships they form with members of the group are other important motivations for experimental strings.

beams by colliding them on fixed targets and selecting secondary particles from the collision products.[5] Currently, there is no other accelerator laboratory to which experimentalists can go to obtain particle beams of this high an energy and, consequently, competition for use of these beams is intense.[6] In order to gain access to a particle beam, experimentalists must navigate a number of inter-related technical and sociological uncertainties within a well-defined institutional structure headed by a single scientist, the Director, who has ultimate authority in all matters scientific and otherwise.[7] Proposed experiments are subject to a complex review process that is embedded in the social structure of the laboratory.[8] While the technological and scientific factors associated with proposing an experiment are more quantitative, the social factors involved in the process of beginning, running, and ending an experiment are much less quantitative and are more difficult for experimentalists to control systematically. While descriptions of these social factors find little or no place in the written accounts of high-energy physicists, for those who are familiar with the actual practice of laboratory life it is clear that they are at least as important as anything "experimental."[9]

The increasing high cost of building larger, higher energy, accelerators and increasingly large and complex experimental detectors are important factors in the overall development of HEP. The financial investment in Fermilab during its 22 year history is over two billion dollars, with a typical fixed target detector costing between

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[5] An electron volt (eV) is the unit of measurement used to describe the acceleration of charged particles like protons and electrons through a one volt potential. Fermilab's accelerators can also be used to produce beams of protons and antiprotons which are circulated and then collided together in the center of large collider detectors, but I will limit the majority of my discussion to fixed-target counter experiments performed at Fermilab.

[6] For example, over the 22 year history of the laboratory, 817 experiments have been proposed by collaborations of experimentalists, but only 345 have been selected, begun, and completed. See Roy Rubinstein (ed), *Fermilab Research Program 1990 Workbook*, (Batavia, Ill: Fermi National Accelerator Laboratory, 1990), p 2. Totals are as of April, 1990.

[7] The Director appoints a Physics Advisory Committee (PAC) composed of scientists from universities and other high-energy physics laboratories to advise him on the nature, scope, and priorities of the physics program. This is similar to the organizational structure of CERN. See the *CERN User's Guide*, (Geneva, Switzerland: CERN, 1988) for details.

[8] For a description of the proposal and review procedure required by the laboratory see the *Fermilab Procedures for Experiments*, (Batavia, ILL: Fermi National Accelerator Laboratory, 1991). CERN has similar proposal and review processes which it requires of experimental proposals submitted to the laboratory. See the *CERN User's Guide*, (Geneva, Switzerland: CERN, 1988) for details.

[9] My own familiarity with the actual practice of laboratory life at Fermilab is based upon ten years of observations as a member of the Fermilab staff, most recently in the Fermilab Directorate. Also, I will limit the scope of this paper by not discussing the philosophical issues associated with anti-realism or the reduction of the theoretical and experimental aspects of scientific practice in high-energy physics to purely "social interests." For an example of this type of "social constructionist" account see Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics*, (Chicago: The University of Chicago Press, 1984). For an account which offers a number of cogent arguments against the social constructionist view, see Peter Galison, *How Experiments End*, (Chicago: The University of Chicago Press, 1987), pp 10-13.

three and five million dollars.[10] The magnitude of the financial investment and the fact that these funds are provided primarily by the United States Department of Energy, also introduces a number of political problems when securing financial resources. While these financial factors are crucial to the study of the development of "big science," I will focus on three less understood, and inter-related "economies," (proton economics, experimental real estate, and physicist economics), which are based upon a number of definable "commodities" (protons, experimental halls, and physics expertise).[11] These economies are of course predicated on the assumption that financial resources can be secured by Fermilab, but my analysis reveals a complex social system within which collaborations of high-energy physicists must trade in order to participate in the process of generating scientific knowledge about the sub-nuclear structure of the physical world.[12]

Within the economy of proton economics, protons are the commodity needed to perform HEP experiments and for which collaborations of experimentalists must

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[10] Fermilab typically operated 15 or more fixed-target experiments simultaneously, and alternates fixed-target operation with two large collider detectors (The Collider Detector at Fermilab (CDF) and the D0 detector) which cost over $60 million each.

[11] The phrase "Big Science" was originally coined by Alvin Weinberg, see Alvin M. Weinberg, *Reflections on Big Science*, (Cambridge, MA: M.I.T. Press), 1967. Since that time, a number of historians and sociologists of science have made extensive studies on Big Science and the development of particle physics a major focus of their research activities. For example see L. M. Brown and L. Hoddeson (eds.), *The Birth of Particle Physics*, (New York: Cambridge University Press, 1986); L. M. Brown, M. Dresden, and L. Hoddeson, "Pions to Quarks: Particle Physics in the 1950's" in L. M. Brown, M. Dresden, and L. Hoddeson (eds.) *Pions to Quarks; Particle Physics in the 1950's*, (New York: Cambridge University Press, 1989), p 13 ff; J. L. Heilbron and R. W. Seidel, *Lawrence and His Laboratory; A History of the Lawrence Berkeley Laboratory*, vol. 1 (Berkeley, CA: University of California Press, 1989); A. Pickering, *Constructing Quarks: A Sociological History of Particle Physics*, (Chicago: The University of Chicago Press, 1984); P. Galison, *How Experiments End*, (Chicago: The University of Chicago Press, 1987); Peter Galison, "Bubbles, Sparks, and the Postwar Laboratory," in L. M. Brown, M. Dresden, and L. Hoddeson (eds.) *Pions to Quarks; Particle Physics in the 1950's*, (New York: Cambridge University Press, 1989); D. Kevles, *The Physicists: The History of a Scientific Community in Modern America*, (New York: Knopf, 1978); A. Hermann, J. Krige, U. Mersits, and D. Pestre, *History of CERN*, vol. 1, (New York: Elsevier, 1987); A. Hermann, J. Krige, U. Mersits, and D. Pestre, with L. Weiss, *History of CERN*, vol. 2, (Amsterdam: North Holland, 1990); A. Needel, "Nuclear Reactors and the Founding of Brookhaven National Laboratory," in *Historical Studies in the Physical Sciences*, 14 (1983), 93-122; S. Traweek, *Beamtimes and Lifetimes; The World of High Energy Physicists*, (Cambridge, MA: Harvard University Press, 1988); B. Latour and S. Woolgar, *Laboratory Life; The Construction of Scientific Facts*, (Princeton: Princeton University Press, 1986); B. Latour, *Science in Action*, (Cambridge, MA: Harvard University Press, 1987); Michael Riordan, *The Hunting of the Quark*, (New York: Simon and Schuster, 1987); S. Schweber, "Some Reflections on the History of Particle Physics in the 1950's," in L. M. Brown, M. Dresden, and L. Hoddeson (eds.) *Pions to Quarks; Particle Physics in the 1950's*, (New York: Cambridge University Press, 1989); and C. Westfall, "Fermilab: Founding the First U.S. 'Truly National Laboratory,'" in F.A.J.L. James (ed), *The Development of the Laboratory: Essays on the Place of Experiment in Industrial Civilization*, (London: Macmillan Press, 1989), pp. 184-217; C. Westfall, "The Site for Fermilab," in *Physics Today*, 42, January 1989, pp. 44-52.

[12] The annual Fermilab budget for operating and equipment expenses is currently about one third of the entire high-energy physics budget in the United States, or about $200 million.

compete when submitting experimental proposals.[13] Competition for protons is intense because the magnitude of the overall proton economy is limited by the accelerator's ability to produce a given number of protons (beam intensity). Sociological and beam-management parameters arise when the laboratory Directorate must decide how to utilize the protons, choosing which types of particle beams to produce in view of the submitted proposals.[14] But beam management decisions are further constrained by the cross section for secondary and tertiary beam production.[15] For example, because the cross section for neutrino production is 10^{-36} cm^2 and the pion cross section is 10^{-27} cm^2 the decision to approve experiments that use incident beams of neutrinos is already a major decision which affects proton economics.[16] A neutrino beam is much more costly than a pion beam in terms of the number of protons needed to produce it, especially if a large sample of particle events is necessary for an experiment.

Proton economics and beam-management decisions are also constrained by the cross sections for particle production in the experimental target. Prior to proposing an experiment, the collaboration performs a Monte-Carlo study of the number of potential events to be detected in the experimental spectrometer with a given secondary beam intensity. Knowing the secondary beam intensity, the repetition rate for beam extraction from the accelerator, the nuclear properties of the target, the geometric acceptance of the spectrometer, and the cross section for the interaction to be studied, the collaboration can calculate a reaction rate for that particle event type. The experiment must also determine the number of events that will provide adequate statistics in their data sample, given the size of data samples accumulated by previous experiments. When writing the proposal, the collaboration begins by calculating the size of the event sample and works back through the process to determine the number of incident protons needed on the primary production target. Upon completing these calculations, they include this number as a "beam request" in the experimental proposal they submit to the Fermilab Directorate.[17]

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[13] I refer to "proton" economics only because I have limited the scope of this article to Fermilab. For example, at the Stanford Linear Accelerator Center (SLAC) where electrons and positrons are accelerated for experiments, one would refer to "electron/positron" economics with the commodities being "electrons and positrons." One could extend this notion to all accelerator facilities, independent of particle type, by referring to "beam" economics, with the generic commodity of particle beams.

[14] At Fermilab, the Director appoints a Program Planning Office in the Directorate which oversees beam-management and other issues associated with performing and scheduling experiments. Similar organizational structures exist at CERN. See the *CERN User's Guide*, (Geneva, Switzerland: CERN, 1988) for details.

[15] When the proton beam is directed toward a fixed-target, the protons interact with the nuclei in the target in a variety of ways producing many different types of secondary particle products. The probability that a particular type of secondary particle will be produced is normally expressed in terms of the cross section (σ) per nucleus for each type of interaction. The cross section is traditionally expressed in units of area measured in units of the "barn" (10^{-28} m^2).

[16] The pion cross-section is roughly constant for energies above two GeV at about 40 millibarns. The neutrino cross section is not constant, but is linearly proportional to the energy. For Fermilab, a reasonable neutrino energy to use is 100 GeV, which would give a cross section of about 0.7 picobarns.

[17] For example, at the time of this writing, a rough summation of all the maximum beam requests for experiments proposing to run during the 1993 fixed-target run at Fermilab is about $5X10^{13}$

The second type of economy is experimental real estate, the commodity of which is obtaining possession of an experimental hall at the end of one of the particle beamlines to house the collaboration's apparatus. Given the size and complexity of HEP detectors and the long lead times needed to assemble and operate them, then analyze the data they accumulate, collaborations of physicists who *are* given beam time move into the hall with the explicit goal of performing that experiment, and the implicit goal of not moving out. The detector configurations are often based on the use of general purpose equipment provided by the laboratory, with only portions of the spectrometer being built by the collaborating universities. Often, an apparatus can be modified to do a series of different experiments.[18]

Collaborations obtain experimental real estate in a number of ways, all of which aim at "holding their place in line" and preventing competing collaborations from gaining control of a specific piece of real estate. For example, incumbent experiments try to convince the laboratory of the importance of their proposed physics measurements with the goal of securing more laboratory resources for a follow-up experiment. The resources are more than just beam time, but usually involve the resources needed to upgrade the experimental detectors themselves. If they succeed, they can leave the major components of their detector in place, upgrade portions of the apparatus, and gain additional access to the beam. If the above strategy fails and other experimental groups threaten to displace them by submitting a proposal which uses that beamline and experimental hall, the next best trading strategy is for the incumbent to try to convince the laboratory (and the competition) to use portions of their detectors (something which the competing group often argues against). Doing this enables the incumbent to partially hold his place in line, and increases the probability that the laboratory will allow them to do subsequent experiments. In generating their arguments against giving up the experimental real estate, the incumbent collaboration uses the data from the previous run and the promise of new results to show that the experiment is "more important" to the study of HEP than the proposed results of the experiment seeking to displace them. Sometimes this strategy works, and other times it fails because within the economy of experimental real estate, the laboratory Director must ultimately decide which experiments gain access to a particular piece of experimental real estate.

The third type of economy is physicist economics, the commodity of which is the physicists themselves with their specific areas of expertise. Larger and more complex detector configurations demand that collaborations contain larger numbers of physicists having a distribution of experimental expertise. The number of high-energy physicists that can commit themselves to perform experiments at Fermilab is constrained by the total number of physicists *available* at a given point in time and the rate at which Ph.D. graduates are produced. Consequently, physics expertise has become a valuable commodity within the resource economies of Fermilab.[19] In

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protons. The accelerator is currently capable of producing about $1.5X10^{13}$ protons, a factor of three less than current requests. The constraints of proton economics will limit the total number of experiments which will actually be approved to run by the Director or the scheduling of experimental running periods.

18 The practice of using Fermilab provided, general purpose equipment, became more common as experimental configuration increased in cost, size, and complexity. An early example that I will focus on in the case study, is the Tagged Photon Magnetic Spectrometer which is located at the Tagged Photon Lab.

19 The issue of physicist economics is a crucial part of evaluating the direction of presently operating and future accelerators (like the Superconducting Super Collider) with their associated

addition to defining the physics measurements to be made and the detector design, one of the most important factors of whether an experimental proposal will be approved by the Fermilab Directorate, is the "people design" of the collaboration. Within the scientific proposal, the collaboration must demonstrate to the laboratory that they have a sufficient number of physicists committed to carrying the experiment through to the final stage of publication.[20] This also means that an adequate number of graduate students will be sponsored by the university-based contingencies of the collaboration. The people design described in the proposal must also show that the collaboration has the appropriate distribution of expertise needed to design, fabricate, install, commission, and operate the apparatus. In addition, it must account for the expertise needed to develop the computing systems and the software programs used to reconstruct and analyze the particle events recorded with the detector.

Collaborations that propose experiments are often formed around a core group of physicists who have specific physics interests. One of the most common ways members of the core group recruit collaboration members is by making presentations to their colleagues in the hope of attracting them to join the experiment. Most times the presentation consists of a description of the physics measurements to be made, a technical description of the detector sub-systems, and a "shopping list" of "job openings" which normally involves assuming responsibility for one or more of the detector sub-systems of the overall experimental apparatus.[21] The notion of the "people design" is important because it is a heuristic which points to a method for characterizing the basic social structure of HEP experiments and the higher-level social structures that are required by the laboratory Directorate.

A Physics and Detector Driven Sociology: a Case Study

The history of the development of the detectors used for HEP moved along two definable but orthogonal axes (size and complexity), both directly resulting from the physics measurements being made. Along the first axis, detectors increased in size, but not necessarily in complexity. An example highlighted by Peter Galison, was the development of the table-top sized spark chamber by J. Cronin and G. Renninger in 1960, and its expansive extrapolation by Melvin Schwartz and Leon Lederman into a detector that was large enough to use surplus naval cruiser deck plates weighing

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experiments. For example, A recent study of the HEP research program for the 1990's performed by the High-Energy Physics Advisory Panel, under the auspices of the United States Department of Energy, included a detailed demographic study of "manpower considerations" during the time period under study. See the *HEPAP Subpanel on the U.S. High Energy Physics Research Program for the 1990's*, U.S. Department of Energy Office of Energy Research Division of High Energy Physics, DOE/ER-0453P, April, 1990, pp 68 ff.

20 In addition to teaching responsibilities, university-based physicists often divide their research time between more than one experimental activity, while Fermilab-based physicists can devote 25-50% of their time to performing experimental research which is considered a part of their laboratory responsibilities. Consequently, the number of physicists committed to an experiment is often expressed in terms of the number of full-time equivalents (FTE's), with experimentalists devoting only a portion of their research time to an experiment. In other words, five physicists who devote 20% of their time to a single experiment are counted as a single FTE for the collaboration.

21 Another common way that experimentalists recruit collaborators is by individually contacting colleagues who they know have technical expertise in a particular area.

between two and three thousand tons.[22] The scale of this type of counter detector increased rapidly. Within ten years, experimentalists had moved from the table-top to the mammoth spark chambers used by the Fermilab based E-1A experiment. What is important to note about the scale of the E-1A detector is that its size was driven by the fact that the E-1A collaboration was searching for experimental evidence of neutral currents using *neutrino* interactions.[23] It was the cross section for neutrino interaction that necessitated a target mass measured in tons and the increased requirements for shielding the fiducial volume of the detector from background events. Consequently, the design of such experiments was inextricably tied to the physical properties of the neutrino cross section and the cross sections of the hadrons and leptons that composed the background for the events E-1A chose to study. But because the signature for detecting neutral currents only involved detecting the absence or presence of a muon track protruding from the cluster of hadrons produced in the incident neutrino collision, the E-1A detector (for all its size) was a relatively uncomplex detector, having only 46 spark chambers. Growth in the size of detectors also meant an increase in the cost of experiments like E-1A, which made collaborations more dependent upon Fermilab for the financial resources needed to construct these mammoth experimental configurations.

Along the orthogonal axis of complexity, many varieties of detector types were combined to form increasingly complex spectrometers composed of a variety of detector sub-systems. These complex spectrometers enabled experimentalists to record more complex physical interactions and measure an increased number of physical parameters simultaneously. The Tagged Photon Magnetic Spectrometer (TPMS) used for experiment E-516 at Fermilab was an early example of a spectrometer that grew substantially along both axes simultaneously, being large in size and very complex.[24] The goal of experiment E-516 was to do precise studies on charmed particles using a photon beam as incident on an experimental target of liquid hydrogen.[25] When the incident photon beam interacted in the experimental target,

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[22] This detector was used in 1961 to demonstrate that there were two distinct types of neutrinos, the muon and electron neutrinos. L. Lederman, J. Steinberger, and M. Schwartz later shared the 1988 Nobel Prize in Physics for this discovery. See Peter Galison, "Bubbles, Sparks, and the Postwar Laboratory," in Laurie M. Brown, Max Dresden, and Lillian Hoddeson (eds.) *Pions to Quarks; Particle Physics in the 1950's*, (New York: Cambridge University Press, 1989), pp 235-237.

[23] The issues associated with the first axis of detector development, "The Scale of High Energy Physics", are discussed by Peter Galison in reference to experiment E-1A and the Gargamelle bubble chamber at CERN. Galison also provides a detailed account of the E-1A experiment and carefully describes the collaboration's search for evidence of neutral currents. I will not reiterate these details here. See Peter Galison, *How Experiments End*, (Chicago: The University of Chicago Press, 1987), pp 197 ff and Peter Galison, "How the First Neutral Current Experiments Ended" in *Rev. of Mod. Phys.*, 55 (1983): 477-509.

[24] See the Tagged Photon Magnetic Spectrometer; Facility Design Report, May 9, 1977 for the technical details of the spectrometer's design. Other less sophisticated examples at Fermilab were the Multi Particle Spectrometer used for experiment E-557 and the spectrometer used for experiment E-400 in the Broad Band Photon Beam Line.

[25] Charmed particles contain at least one charmed quark. They were originally discovered independently in 1974 by S. Ting et al at Brookhaven National Laboratory and B. Richter et al at the Stanford Linear Accelerator Center using different experimental techniques. Ting and Richter shared the 1975 Nobel Prize in Physics for the discovery. For an account of this discovery, see Michael Riordan, *The Hunting of the Quark*, (New York: Simon and Schuster, 1987). The formal name of E-516's original proposal was "Proposal to Study Photoproduction of Final States of Mass

it produced numerous secondary particles, some of which were charmed particles that would subsequently decay into other types of particles. The Tagged Photon Magnetic Spectrometer was designed to detect the 8-12 decay products and allow the E-516 collaboration to record, reconstruct, and analyze properties like the charmed particle production cross sections and particle mass.

The E-516 spectrometer was an array of individual detector sub-systems designed to function as a unit, with events selected at a higher level by a specially designed computing architecture.[26] Because the decay products of charmed particles were more numerous than simply detecting the absence or presence of a muon track for E-1A, the number of data measurements needed to record and reconstruct the multiple final states demanded that the spectrometer be a significantly more complex apparatus. The E-516 spectrometer was divided into six detector regions: the experimental target/recoil detector, the tracking system, the Cerenkov counters, the electromagnetic calorimetry, (which consisted of the segmented liquid scintillation shower counter (SLIC) and the outriggers), the hadron calorimeter, and the muon system (a diagram of the spectrometer is shown at the end of this article).[27] The complexity of the particle interactions to be detected was reflected in the complexity of the spectrometer which had 7,000 interaction points distributed over the six detector regions.[28] Each interaction point was connected to a channel of electronics and fed into the trigger processor and finally the on-line computing system. The design of the E-516 spectrometer demonstrates the relationship between the complexity of the physics interactions to be measured and the complexity of the detectors needed to detect and measure those interactions. It also shows that the cost of building such spectrometers substantially increased by virtue of both size and complexity, because obtaining more interaction points and channels of electronics meant obtaining more money.[29] When spectrometers became as large and complex as

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Above 2.5 GeV with a Magnetic Spectrometer in the Tagged Photon Lab" which was submitted to the Fermilab Directorate on October 1, 1976 by J. Appel, P. Mantsch, and T. Nash (Fermilab), R. J. Morrison (University of California, Santa Barbara), and G. Luste (University of Toronto).

[26] Experiment E-516 used a computerized trigger processor which allowed the collaboration to trigger the spectrometer on interesting events by programming the trigger requirements into the computer. It was specially designed by T. Nash and S. Bracker and was described in the May, 1983, issue of *Physics Today*.

[27] The target/recoil detector was used primarily to trigger the spectrometer, the tracking system was used to analyze the trajectories and momenta of charged particles that penetrated the apparatus, the Cerenkov counters were used to identify particle type by measuring particle mass, the electromagnetic calorimeters (SLIC and outriggers) measured the energy of photons and electrons, the hadron calorimeter was used to measure the energy of uncharged hadrons, and the muon system was used to measure the presence and trajectories of muons that penetrated the most forward region of the spectrometer. For the technical details of the detector sub-systems see the Tagged Photon Magnetic Spectrometer; Facility Design Report, May 9, 1977.

[28] Physicists normally refer to an "interaction" point as a point at which particles interact in the experimental target. What I am referring to are points within the detector sub-systems where the decay products from particles produced in the experimental target interact, for example, the cell of a drift chamber in the tracking system, or a wire in a proportional wire chamber in the target/recoil detector.

[29] A rough rule of thumb for estimating the expense of complex spectrometers is to quantify cost in terms of dollars per channel of electronics. K. Stanfield, who designed the drift chambers for the E-516 tracking system, claims that one of the major factors in determining the number of wires/channels for the tracking system was taking the dollar amount of the E-516 budget for tracking and dividing by the cost per wire and channel of electronics (private communication).

the E-516 spectrometer, the institutions that composed the collaboration not only became more dependent upon the laboratory for financial resources, they also became more interdependent upon one another for bearing their share of the cost of the experiment. The comparison between E-1A and experiment E-516 suggests that the nature of the physics measurements made by these experiments powerfully drove the physical architecture of the detector design. For those familiar with the experimental practice of HEP, this claim ought not be surprising.

But what may be surprising is the claim that the physics driven explanation of detector designs does not stop at the detectors, but extends to the social structure of the collaboration itself.[30] In other words, the "people design" of the E-516 collaboration was built around the physical structure of the E-516 spectrometer. In the initial organization of the collaboration, each of the six regions of the spectrometer became the domain of a particular institutional group in the collaboration and represented that group's hardware contribution to the overall experiment. The recoil detector was built by the University of Toronto, the SLIC and outriggers were built by the University of California at Santa Barbara, the Cerenkov counters were built by the University of Colorado at Boulder, and the tracking system, hadron calorimeter, and muon system were built by Fermilab scientists (see the diagram of the spectrometer at the end of this article for details).[31]

The basic social structure of experiment E-516 emerges from the drawing of the E-516 spectrometer when the universities and institutions responsible for the design and construction of the detector sub-systems are identified. Add to this the fact that each of these institutions had an institutional representative, and the basic social structure of E-516 begins to take shape. The complexity of the physics interactions determined the physical structure of the spectrometer, and the people who planned to carry out the experiment organized (taxonomized) themselves around

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30 Discussion about whether high-energy physics is "driven" by theoretical or experimental developments, while important to the conceptual development of HEP, would lead far beyond the scope of offering a fine-grained account of the experimental activities in my case study. What is at stake here philosophically is understanding the role that experiment plays in the overall development of HEP. These issues are typically discussed in terms of the Positivist and post-Positivist tendency to make a clear distinction between observation and theory and the Kuhnian and post-Kuhnian tendency to make little or no distinction between observations and theoretical or sociological background assumptions. But whether the experimentalists of E-516 believed that "physics" was driven by theoretical developments, social interests, or experimental advances, I claim that the account presented here still obtains. Consequently, I will continue to abstain from discussing these philosophical issues in what follows. For discussions on the Positivist view see A.J. Ayer (ed), *Logical Positivism*, (New York: The Free Press, 1959). For discussions on a recent reformulation of Positivist notions see Bas C. van Fraassen, *The Scientific Image*, (Oxford: Clarendon Press, 1980) and Paul M. Churchland and Clifford A. Hooker (eds), *Images of Science; Essays on Realism and Empiricism, with a Reply from Bas C. van Fraassen*, (Chicago: The University of Chicago Press, 1985). For a discussion of the Kuhnian view see Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 2nd ed. enlarged, (Chicago: The University of Chicago Press, 1970). For a discussion of the post-Kuhnian "social constructionist" view see Andrew Pickering, *Constructing Quarks; A Sociological History of Particle Physics*, (Chicago: The University of Chicago Press, 1984) and B. Latour, *Science in Action*, (Cambridge, MA: Harvard University Press, 1987). For discussions on the importance of the role of experiment in the development of science in a non-Positivist/post Positivist and non-Kuhnian/post-Kuhnian framework see Ian Hacking, *Representing and Intervening*, (New York: Cambridge University Press, 1987) and Peter Galison, *How Experiments End*, (Chicago: The University of Chicago Press, 1987), pp 6-13.

31 The trigger processor and the on-line computing systems were collaborative efforts between Fermilab and the University of Toronto contingents of the collaboration.

this structure by institution and area of expertise.[32] Because the E-516 spectrometer was a complex array of detector sub-systems, it was carved up into smaller, more manageable pieces, which suggests how the phenomenon of technical specialization for experimenters emerged with the advent of large and complex experimental configurations. Those who are interested in characterizing the basic social structure of experiments like E-516 must begin their analysis with a diagram of the apparatus itself. In a well defined and predictable way, the increased complexity of the physics measurements led to an increased complexity in spectrometer designs, which in turn meant more complex social structures for collaborations. The descriptive ability of the physics and detector driven model can be extended even further to describe most aspects of the E-516 experiment up to and including the data analysis and publication phases.

In the design, construction, and installation phases, the technical and financial demands of getting the spectrometer built and operating forced the collaboration members to focus most of their attention on that region of the spectrometer for which they were responsible. Because many of the detector sub-systems were constructed at home institutions then shipped to Fermilab for installation, there tended to be less social interaction between the members of the collaboration in the earlier phases of the experiment.[33] The amount of social interaction within the collaboration significantly increased when they came together as a group at the laboratory during the installation phase of the experiment. From this point on, the social interaction of the collaboration continued to increase through the actual data taking phases of the experiment. But the E-516 spectrometer had even more profound effects on the nature of the collaboration's social interaction in the later phases of the experiment.

During the actual running of the experiment, the detector-based social taxonomy defined the way in which technical problems and challenges were addressed by the collaboration. Problems in the operation of the segmented liquid scintillation shower counter (SLIC), for example, were within the domain of the University of California, Santa Barbara contingent of the collaboration which designed and constructed it. Problems with the Cerenkov counters were considered the purview of the University of Colorado at Boulder part of the collaboration. Various members of the collaboration gained a limited knowledge of the detector sub-systems for which they had no direct responsibility. But throughout the operation phase of the experiment, the major repositories of expertise for running the experiment were taxonomized and distributed along the lines shown in the diagram of the E-516 spectrometer.

The phase of the experiment in which the collaboration wrote the computer software programs needed to reconstruct particle events (and the process of

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[32] It is interesting to note that the social structure of Fermilab itself is organized in a similar way. The Fermilab organizational chart shows that the 2,200 people employed by the laboratory are taxonomized and distributed around the accelerators, devices, and support systems needed to produce the particle beams for experiments. I attribute this largely to the fact that the upper level management positions at Fermilab are held primarily by high-energy physicists who tend to define the laboratory's social structure much like an experimental collaboration would.

[33] There were of course design meetings and reviews performed both within the collaboration and in the context of the laboratory, but the fact that detector components were constructed at home institutions and subsequently shipped to Fermilab limited the amount of social interaction within the collaboration during the earlier phases of the experiment.

reconstructing them) was spread over a three year period.[34] During the reconstruction phase, there seemed to be a relaxing of the well-defined distribution of hardware expertise, as various members who had responsibility for one specific detector sub-system wrote software reconstruction packages for other regions of the spectrometer. In fact, multiple reconstruction packages were written for some of the detector sub-systems.[35] During the reconstruction phase the boundaries that organized the collaboration around the spectrometer's hardware were more easily crossed as one group member attempted to extend his area of expertise to detector sub-systems which were the responsibility of another group in the collaboration. While the collaboration's social structure was anchored in the spectrometer design throughout all phases of an experiment, the example of E-516 shows that these taxonomies became less rigid and less defined in the later phases of the experiment when tasks involved the development and use of software rather than hardware.[36]

In the final phase of the experiment, data analysis and final publication, the collaboration faced a more intimate type of social interaction which was strongly related to the distribution of expertise around the spectrometer. Problems associated with the final calibration of data recorded with the SLIC were addressed mainly by the University of California, Santa Barbara group that designed and built the detector, while problems with the final calibration of data recorded with the Cerenkov counter were considered within the domain of the University of Colorado, Boulder group.[37] What is interesting *sociologically* about this experimental phase is that in the same way all of the physical components of the TPMS had to work together as a unit in order to produce the evidence that would support the data in the publications, the human components that were distributed around the detector sub-systems were also forced to work together as a unit. In the same way the six spectrometer regions had to work together as a unit in order to analyze the multiple decay products of charmed particles, the collaboration had to work together as a people-spectrometer unit in order to come to agreement on the final form of the publications.[38] While the "human" aspects of individual personalities were

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34 The reconstruction and running phases of E-516 overlapped substantially in time. This is not always the case with even large and complex experiments, but depends on the level of software expertise in the collaboration, the "real-world" constraints of getting the hardware portions of the detector up and running properly, the complexity of the physics events and the spectrometer, and the level of competition within the collaboration in regard to which individuals write which software packages. In regard to dates, the first shakedown run of E-516 was in the Summer of 1979, with the first data run beginning in the late Fall of 1979. The final data run began in early 1981 and ended at the accelerator shutdown in June, 1981, with the data reconstruction process continuing into the early part of 1983.

35 For example, there were three separate reconstruction packages generated for the tracking system, and two packages generated for the SLIC.

36 This is partially due to the inability of the collaboration to secure the resources necessary to design and construct multiple hardware detector sub-systems. The resources needed to produce software are much easier to obtain because they only involve the time and expertise of the students and physicists on the experiment which are directly under their control and have little or no financial impact.

37 Evidence from the minutes of collaboration analysis meetings during this phase of the experiment supports this claim.

38 The two major papers from the experiment were submitted for publication in the Fall of 1983. They appeared in the journal *Physical Review Letters* in early 1984. See D.J. Summers et al, "Study of the Decay D^0-$K^-\pi^+\pi^0$ in High-Energy Photoproduction", in Phys. Rev. Lett. Vol. 52, No. 6,

manifested throughout all phases of the experiment, they were evidenced more powerfully in the more intimate social negotiation needed to produce physics results.[39]

In addition to the spectrometer-based social structure, there was a higher-level social structure that is important to characterize. The Fermilab Directorate requires experimentalists to appoint a spokesperson that acts as the liaison between the laboratory and the collaboration in all aspects of the experiment. The "management" style of the spokesperson is also an important element in the social negotiation that occurs both within the collaboration and between the experimentalists and the Fermilab Directorate. Almost without exception, the spokesperson and the laboratory Directorate are the major players in what might be characterized as the Director-experiment relationship. While the spokesperson's organizational and interpersonal skills are important to the "management" of the collaboration, they are far less important to defining the group's basic social structure. Whether the management style of the spokesperson is autocratic, democratic, bureaucratic, etc., the underlying spectrometer-based social structure is the foundation upon which these higher-level social structures are predicated.[40] For example, shortly after the follow-up experiment to E-516 was approved by the Fermilab Directorate, there was a rotation of spokespersons for the collaboration.[41] But, the basic social structure of the collaboration and the repositories of expertise remained taxonomized around the physical design of the spectrometer even after this change of leadership.[42]

The example of how the detector sub-systems working together forced the collaboration to work together as a unit shows how the practice of HEP is an interactive people-spectrometer system from which sociological factors cannot be removed. Descriptions of how scientific knowledge in HEP is produced must be characterized in terms of the experimentalists and their detectors working together to produce the data that constitutes the evidence presented in scientific publications.

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6 February, 1984, pp 410-413, and B. Denby et al, "Inelastic and Elastic Photoproduction of J/Ψ (3097)", in Phys. Rev. Lett. Vol. 52, No. 10, 5 March, 1984, pp 795 ff..

39 The written correspondence between members of the E-516 collaboration shows that the collaboration experienced significant inter-group problems determining when the data results had stabilized and were dependable enough to publish. Galison characterizes this type of negotiation in HEP experiments as occuring along two axes: increasing directness of the measurement and growing stability. See Peter Galison, *How Experiments End*, (Chicago: The University of Chicago Press, 1987), p 259 ff.

40 The issue of the "management style" of collaboration spokespersons was recently pointed out in reference to the spokespersons for experiments competing for approval to run at the Superconducting Super Collider Laboratory. The management style of two of the spokespersons, S. Ting (L* experiment) and G. Trilling (SDC experiment), are described respectively as "autocratic" and "bureaucratic." See Robert Crease, "Choosing Detectors for the SSC" in *Science*, Vol. 250, 12 December, 1990, pp 1648-1650.

41 T. Nash, spokesperson for E-516, rotated the position of spokesperson with another member of the E-516 collaboration, M. Witherell, in order to devote his time to the development of new low-cost high-power parallel processing computers which he had proposed to the laboratory a year earlier. See "A Program for Advanced Electronics Projects at Fermilab" by Tom Nash, May 11, 1982. This proposal eventually developed into the Advanced Computing Project (ACP) under the leadership of Nash.

42 For some Fermilab experiments, like E-665, the role of spokesperson is a fixed time-period (much like the chairman of a university department), after which another member of the collaboration assumes that role.

This example also reveals another crucial sociological phenomenon that extends the descriptive ability of the physics and detector driven model beyond a single experiment to "strings" of experiments, revealing even more complex, definable, and long-lived social structures.

The Nature of Experimental Strings

I will now describe how experiment E-516 and its follow-up experiment (E-691) met at a transition-like interface where the first experiment seemed to transform into a second one.[43] Most physicists in HEP understand this transformation process intuitively and can even identify experimental strings which consist of four or five individual experiments. But such intuitions have yet to be concretized in a systematic way.[44] Key to describing this transformation is the ability to characterize the continuities between the individual experiments in such strings. The evidence that I will present below suggests that these continuities are constituted by the physics goals, the spectrometer configuration, the physicists in the core group of E-516, E-691 and their progeny, and the collaboration's ability to work together effectively as a people-spectrometer unit in a continuing program of physics studies that yields successful results.

The configurations of the Tagged Photon Magnetic Spectrometer for E-516 and E-691 were almost identical. The one important difference was the use of a Silicon Microstrip Detector (SMD) instead of the recoil detector and more loosely defined trigger processor assumptions.[45] The SMD allowed E-691 to reconstruct the decay vertices of charmed particles in the upstream portions of the spectrometer and project the tracks of particle decays to the detector sub-systems located downstream. In contrast, experiment E-516 triggered the spectrometer with the upstream recoil

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[43] Follow-up experimental proposals which require a change in experimental configuration are once again subjected to the Fermilab review process and, if approved by the laboratory Directorate, are assigned a new experimental number. In this case, the follow-up experiment for E-516 was designated as E-691. Experiment E-691 was formally proposed to the laboratory on February 4, 1981 *before* the end of the final data run of E-516. Much like E-516, the goal of E-691 was to study the photoproduction of charmed particles using an incident photon beam with the Tagged Photon Magnetic Spectrometer. But experiment E-691 ran with a proton beam of 800 GeV from the newly completed Tevatron accelerator which raised the the energy of the incident photon beam to the experiment from about 160 GeV to about 300 GeV.

[44] I am aware of similar, but independent, work in process at the Center for the History of Physics of the American Institute of Physics (AIP), headed by J. Warnow-Blewett. While the AIP group's overall research goals are to describe multi-institutional collaborations at a number of laboratories, J. Genuth's and F. Nebeker's work discuss the existence of experimental strings at Fermilab. For example, Nebeker's research focuses on experiments E-70, 288, 494, 605, 608, 772, and 789.

[45] While both E-516 and E-691 triggered the spectrometer on charmed particles, E-516 used the recoil detector in combination with tightly defined trigger assumptions to look for the charm signature of a recoil proton. E-691 used more loosely defined trigger assumptions with portions of the forward region of the spectrometer to trigger the spectrometer. It is interesting to note that the configuration for E-691 was so similar to the one used for E-516, that the collaboration simply attached a copy of the original Tagged Photon Magnetic Spectrometer: Facility Design Report produced in 1977 for E-516 to their proposal and described the differences between the two configurations in the text.

detector and projected the particle tracks back toward a vertex that could not be as carefully defined by the recoil detector. The use of the Silicon Microstrip Detector was the only major hardware change, revealing a strong spectrometer-based continuity between the two experimental configurations.[46] This modification to the spectrometer was adopted as an additional "job" by a specific part of the collaboration which meant that the spectrometer diagram shown at the end of this paper continued to define the basic social structure of the collaboration in a predictable way.[47]

The physics goals described in the original proposal of E-516 already included an ambitious physics program for the spectrometer that transcended the studies proposed by the first experiment. The plans for using the spectrometer in the E-691 configuration were already explicitly stated as early as 1976.[48] The proposal states,

> "In fact, although this is by no means a proposal for the Energy Doubler, this spectrometer will be ideal - and unique - for studying photoproduction when the Doubler comes into operation. It is probably the only existing P East facility that will be able to operate at 1000 GeV. The extra proton energy will be used either to increase photon intensity in the 70-140 GeV range or to double the photon energy. The latter would involve no modification of the electron beam which is capable of 300 GeV."[49]

When this statement is compared with the actual history of E-516's progeny, it is clear that the outline for what was later submitted as the proposal for E-691 was already anticipated by the collaboration five years earlier.[50] But the original E-516 proposal also described a program of study that extended beyond the boundaries of a second experiment by saying,

> "The electron beam can also be used to transport pions into the Tagged Photon Lab.... Thus, one can imagine a future proposal to use the spectrometer at the TPL for direct comparison of photoproduction and hadron production with systematic errors caused by using different detectors eliminated. This

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[46] The discontinuities between the two configurations included the addition of two banks of drift chambers to the tracking system (which enabled them to have greater redundancy in resolving the trajectories of particles penetrating the spectrometer), and the significant addition to the on-line computing capabilities (using a VAX 11/780 for data monitoring and a PDP11/55 solely for the acquisition of data from the detector sub-systems). For E-516, the PDP11/55 was used for both data acquisition and data monitoring.

[47] Responsibility for the design, construction, and installation of the Silicon Microstrip Detector was given to the University of California, Santa Barbara group. The additional on-line computing was a collaborative effort between the University of Toronto and Fermilab.

[48] E-691 was formally proposed in February, 1981, but not approved by the laboratory until November, 1983.

[49] The name "Energy Doubler" described a (then proposed) new ring of superconducting magnets designed to increase the energy of the accelerator proton beam from 400 to 1000 GeV. This accelerator ring eventually became known as the Tevatron, because the design goal was to produce proton beams of 1000 GeV, or one trillion electron volts. See the Proposal to Study Photoproduction of Final States of Mass Above 2.5 GeV with a Magnetic Spectrometer in the Tagged Photon Lab, submitted October 1, 1976 by J. Appel, P. Mantsch, and T. Nash (Fermilab), R. J. Morrison (University of California, Santa Barbara), and G. Luste (University of Toronto), pp 2-3.

[50] I have also confirmed this claim in private communications with T. Nash (E-516 spokesperson), R. J. Morrison, and other members of the E-516/691 collaboration.

emphasizes the flexibility and long range benefits to the Proton East program that the spectrometer we propose would bring."[51]

The dual statements about converting the beamline to a pion beam and using the spectrometer to do hadronically produced charm studies reveal a plan for exploiting a continuing program of physics measurements with what was at the time only a proposed facility. The primary beam was eventually converted to transport pions, enabling the collaboration to study hadroproduction of charmed particles (submitted as the proposal for E-769), and then hadronic decays of charmed particles (submitted as the proposal for E-791).[52] A listing of the names on the proposals for the four experiments reveals that there was a distinct continuity in the core group of physicists that proposed the subsequent experiments.[53] In addition, an analysis of the components of the spectrometer configurations for experiments E-516, 691, 769, and 791 shows that the majority of the detector sub-systems remained intact and that all substantial changes were simply additions to (or modifications of) the basic structure of the spectrometer.[54]

This case study provides support for a physics and detector driven model, with the first major continuity, the physics goals of the four experiments, already outlined in the original E-516 proposal as a continuing program of measuring the properties of charmed particles using both photoproduction and hadroproduction techniques. Two other major continuities of this experimental string are the spectrometer configuration and the core group of physicists who proposed the

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[51] See the Proposal to Study Photoproduction of Final States of Mass Above 2.5 GeV with a Magnetic Spectrometer in the Tagged Photon Lab, submitted October 1, 1976, p 3. The proposal refers to a study performed by R. Rubinstein that supports the feasibility of converting the TPL beamline to a pion beam.

[52] *The iterations from one experiment to another show how collaborations attempt to* "hold their place in line" within the resource economy of experimental real estate. While there were no competing experimental collaborations attempting to displace E-516 during this time period, it is interesting to note that the E-516 collaboration originally obtained the real estate at the Tagged Photon Laboratory by displacing experiment E-152. In attempts to resist this take over, the spokesperson for E-152, C. Heusch, proposed to the Fermilab Directorate that the two experiments share "portions" of the E-152 spectrometer, hoping to partially hold his place in line in the experimental hall. See Heusch to Goldwasser, June 2, 1977. The proposal for experiment E-769 was submitted to the laboratory in November, 1985, approved in December, 1985 and completed in February, 1988, having a substantial time overlap with its predecessor, E-691. The proposal for experiment E-791 was formally submitted to the laboratory in November of 1987, approved in June, 1988, and is currently scheduled for a second running period early in 1991.

[53] A sample of the core group listed on the proposals is T. Nash (E-516, 691, 769, 791, Fermilab), J. Appel (E-516, 691, 769, 791, Fermilab), W. J. Spalding (E-516, 691, 769, 791, University of Toronto and later Fermilab), P. Mantsch (E-516, 691, 769, 791, Fermilab), S. Bracker (E-516, 691, 769, 791, University of Toronto), and D. Summers (E-516, 769, 791, University of California at Santa Barbara and later the University of Mississippi). Another issue that is beyond the scope of this present study is the relationship between the names listed on the formal correspondence with the laboratory and the actual level of activity of these individuals over the course of the experiment.

[54] As with the E-691 proposal, the spectrometer configuration for experiment E-769 was so closely based upon the design of the original E-516 configuration, that the collaboration included a diagram of the E-516 configuration of the spectrometer with the experimental proposal and simply explained the modifications in the text. The E-791 proposal did not even contain a copy of the spectrometer design, it had become so well known to the community of physicists at Fermilab.

experiments. The case study suggests that there are social and experimental continuities that transcend a single experiment and can provide a method for understanding what appears to be more complex social structures and research programs that exist for more than 15 years.[55] Each experimental configuration in this string displays a more complex iteration of the original spectrometer which leaves the fundamental design of the detector sub-systems largely intact. Analysis of yet other experiments performed at Fermilab reveals that evidence for the existence of experimental strings is manifested copiously and provides a unifying device for characterizing the entire experimental history of Fermilab.[56] Most importantly, the evidence for experimental strings emerges from the actual practice of scientists and is not an ad hoc taxonomy imposed on the experimental program for the purpose of organizing the sociological and experimental factors of laboratory life.

To this point, the physics and detector driven model has provided a basis for understanding the major continuities that link individual experiments into a string of experiments, but I have not fully described what appears to be one of the deeper motivations for the emergence of such strings. In other words, I have described *what* the continuities are, but not *why* they persist through successive iterations of

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[55] I have purposely limited my discussion to fixed-target counter experiments and not discussed the experiments performed with large bubble chambers like the Fifteen Foot Bubble Chamber at Fermilab. As a brief comparison with our case study, the major continuity between experiments performed with the Fifteen Foot Bubble Chamber (E-28A, 31A, 45A, 53A, 155, 172, 180, 202, 234, 341, 343, 380, 388, 390, 502, 545, 546, 564, and 632) seems to be the chamber itself. In a less defined way, there were some continuities in the target substances with which the chamber was filled. But the social structures of these collaborations were different from the one described in the case study. Bubble chamber spokespersons seemed to draw upon the expertise of the international community of bubble chamber physicists each time they formed an experimental group and consequently the collaborations did not exhibit the same type of well-defined core-group structure found in large, complex fixed-target counter experiments. My preliminary studies show that the relatively uncomplex social structure of these *collaborations* results from the existence of a Fermilab-based *Bubble Chamber Department* devoted solely to the operation and maintenance of the complex systems of the chamber, independent of the experimental collaborations that used it. When a major system was added to the chamber, it did become the domain of a particular portion of either the collaboration or Fermilab (External Muon Identifier, holography, etc). This type of heterogeneous Fermilab/collaboration social structure is not evidenced in even the largest fixed-target counter experiments at Fermilab, but it is interesting to note that a similar phenomenon does appear with the advent of the mammoth collider detectors like the Collider Detector at Fermilab (CDF), and the D0 detector. I will discuss this further in the final section of the paper.

[56] For example, there are similar continuities revealed in the E-82, 226, 383, 425, 486, 584, 617, 731, 773 string, the E-531, 653 string, the E-8, 440, 495, 555, 620, 619, 756, 800 string, the E-21A, 262, 320, 356, 616, 770 string, the E-594, 733 string, the E-98, 365, 665 string, the E-1A, 310 string, the E-95, 537, 705, 771 string, the E-70, 288, 494, 605, 608, 772, and 789 string, the E-87, 358, 400, 401, 402, 687 string, and the E-497, 715, 761 string. These experiments display the general characteristics of the physics and detector driven model in the sense that more complex physics measurements demanded a more complex detector design, which gave rise to a more complex social structures for the collaborations. But the inverse was also true. Experiments studying less complex physics measurements, had less complex detector designs which resulted in a less complex social structures for the collaborations. My preliminary studies show that similar experimental strings are also found at laboratories like the European laboratory CERN. In regard to photoproduction experiments at CERN during the time periods of E-516 and E-691, there were experiments NA1 (1980 run), NA1 (1983 run), NA14, NA14/2, as well as experiments WA4, WA57, WA58, and WA69.

experiments within the context of the resource economies mentioned earlier. As I already indicated, the sociological problems of gaining resources within the economies of proton economics, experimental real estate, and physicist economics can be more difficult to navigate than technical matters because collaborations cannot systematically control them. I will now explain how the case study of experiments E-516, 691, 769, and 791 suggests that experimental strings are one way that physicists attempt to remove many of the physics and sociological uncertainties of performing experiments within the institutional context of Fermilab.

In regard to the removal of physics uncertainties, using the tagged photon beamline for all four experiments meant that the properties of the beamline transport system were well-known factors, eliminating the need for designing, constructing and commissioning a new beamline for each experiment. As indicated earlier, even the design for converting the secondary beam from an electron to a pion beam had been established for almost ten years prior to the proposal for E-769. In addition, using the Tagged Photon Magnetic Spectrometer as the basis for all four experiments made the detector a well known experimental tool which could be built upon by the collaboration without facing the experimental problems of understanding the systematic errors inherent in commissioning a new spectrometer.[57] Because the vast majority of the detector sub-systems remained intact throughout all four experimental configurations, much of the software that the E-516 collaboration wrote for reconstructing the particle events which occurred in the spectrometer could be reused for the subsequent experiments with simple modifications to the computer code. When the collaboration listed the "job openings" for each new experiment, the major task of writing new software for constantly changing detector configurations and geometries did not have to be included. In the case of E-691, the collaboration's ability to produce physics results shortly after the end of their data run was a direct result of a conscious decision not to modify the majority of the components of the spectrometer from the E-516 configuration.[58] Finally, rather than proposing new, unrelated, physics measurements for each new experiment and increasing the risk of rejection by the Fermilab Directorate, this string chose to focus on a continuous program of studying photoproduction then hadroproduction of charmed particles. The data from each subsequent experiment was an extrapolation that built upon the previous data and forged ahead into new areas of charmed particle measurements, accumulating larger and larger samples, increasingly precise statistics, and more fine-grained measurements.[59]

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[57] In the original E-516 proposal, the collaboration stressed the importance of minimizing the systematic errors of the spectrometer and used this as a justification for viewing the Tagged Photon Magnetic Spectrometer as a "facility" for performing an on-going series of experiments, rather than simply as a single "experiment." See the Proposal to Study Photoproduction of Final States of Mass Above 2.5 GeV with a Magnetic Spectrometer in the Tagged Photon Lab, October 1, 1976, p 3.

[58] In addition to the evidence of the continuities evidenced in the configuration of the detector sub-systems of the two experiments, and the statement of this intent in the written text of the E-691 proposal, I confirmed this in a private communication with R. J. Morrison, a member of both experiments.

[59] The success of experiment E-691 is evidenced by the fact that they accumulated 10,000 fully reconstructed photoproduced charmed particle events and made the most precise measurements of charmed particle lifetimes in the world at that time. E-769 accumulated 6,000 fully reconstructed hadronically produced charmed events which was also the largest hadronically produced sample of charmed particles produced in the world at that time. Experiment E-791 plans to accumulate 100,000 fully reconstructed hadronically produced charmed particle events

But experimental strings also remove many of the sociological uncertainties associated with institutional HEP. The scientific practice of transforming one experiment into another *before* the first experiment is fully completed helped the collaboration maintain possession of the Tagged Photon Laboratory real estate, thus reducing the probability of being displaced by competing groups. In addition, the fact that the spectrometer was utilized with only modifications to the original E-516 design meant that only the new portions of the experimental configuration were subjected to the most rigorous aspects of the institutional review process prior to approval of the follow-up experiment. While the size and complexity of the Tagged Photon Magnetic Spectrometer powerfully affected the original cost of building the experimental set-up, the spectrometer proved to be a good investment of laboratory resources, given the physics results produced.

From the perspective of the collaboration "as a group," the accumulation of expertise for the original "people design" and the fact that this core group participated in the follow-up experiments, allowed them to draw upon these repositories for the expertise needed to carry out the subsequent experiments. From the perspective of the collaboration "as individuals," participating in an on-going program of successful experiments meant they had a base of operation that assured each physicist continuing future research opportunities.[60] In a similar way, the continuity of the institutional affiliations was crucial for the professors and university physics departments that needed access to high-energy particle beams to train graduate students. The importance of the pedagogic function of experiments ought not be underestimated given the resource constraints of physicist economics.[61] In the competitive context of institutional HEP, the longevity of experimental strings can help university-based physicists to publish results more regularly and attract top-notch graduate students to their universities.[62]

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during the current running period at Fermilab which will surpass even the samples accumulated by experiments using the photoproduction mechanism which involves much lower background rates.

60 In a private communication, my colleague Catherine Westfall pointed out that it is important to note why some physicists decide *not* to continue as part of the core group. She cites two possible reasons for this. On one hand, sometimes the risks involved in joining another experiment *are* acceptable to experimentalists if they believe it will pay-off in terms of physics results that are of major significance. On the other hand, physicists can simply "lose interest" in that program of physics goals. Two examples from E-516 which support her claims are D. Summers and B. Denby who decided to join the CERN-based UA1 collaboration because of the high probability that UA1 would be the first to detect experimental evidence for the (then) elusive W and Z vector bosons. UA1 did in fact discover these particles for which the 1984 Nobel Prize in Physics was awarded to C. Rubbia and S. van der Meer. Upon the completion of his work with UA1, Summers returned as a collaborator on the final two experiments in our case study (E-769, 791), while Denby eventually became a staff scientist at Fermilab and decided to focus his research on what he believed were the more "interesting" physics goals of the Collider Detector at Fermilab collaboration rather than return to this string of experiments (private communication with B. Denby).

61 Two related motivations for the continuities of experimental strings are the tendency for high-energy physics graduate students to continue to work in a related area of research long after they have received their Ph.D. and the maintaining of professional ties with the university professors who supervised their thesis research.

62 R. J. Morrison of the University of California, Santa Barbara claims that he was still "putting students through" with the very large data sample accumulated with E-691 (private

But this experimental string also had a subtle but real effect upon the Fermilab community's perceptions of the collaboration. With each successive iteration of the spectrometer, the collaboration was viewed by its colleagues as a more competent group which developed a "track record," demonstrating that they could make good on their experimental promises to the Fermilab Directorate.[63] Because the collaboration lowered the risk factor associated with each new experiment, the laboratory not only granted them additional resources more easily, but would also assign them a higher priority than the more "risky" experiments in the design, installation, and commissioning phases of each experiment. This also had a powerful effect on the beam-management decisions involved in proton economics for each experiment. When the Directorate and the Physics Advisory Committee (PAC) had to decide how to distribute the fixed number of protons from the accelerator, this successful string of experiments which proposed to extend their studies, was more likely to receive the laboratory's support. The ability to "come through" gives an experimental string an advantage over collaborations that cannot appeal to a long experimental tradition in support of their requests. In fact, at the E-791 proposal presentation to the PAC, the first overhead used by the collaboration had a large picture of a slow-moving turtle on it with a caption that referred to the Tagged Photon Magnetic Spectrometer as "Old, Slow, and Successful."[64]

Conclusions and Preliminary Thoughts on Collider Detectors

By describing this case study within the context of the distinct, yet inter-related, resource economies of proton economics, experimental real estate, and physicist economics, I have tried to emphasize that the nature of experimental practice in high-energy physics must be studied within the larger social context of laboratory life. By abstaining from the temptation to describe experiments as closed systems which can be divorced from the laboratory context, I have tried to capture some of the most salient aspects of the actual practice of high-energy physics. Using a physics and detector driven model for social structure, I attempted to show how experimental HEP is an inter-related "human-factors-like" system

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communication). J. Appel of Fermilab claims this is also true of the data taken with experiment E-769 (private communication).

63 The ability to do what they promised was inextricably bound to requests for more and more resources, especially in terms of on-line and off-line computing. Thus, while the collaboration *could* produce valuable physics results, this heightened the competition with other experiments for laboratory resources.

64 S. Bracker who was a member of E-516, 691, 769, and 791 claims that the attributes of "Old, Slow, and Successful" were coined by theorist J. D. Bjorken who at that time was Fermilab's Associate Director for Physics Research. During the era of Fermilab's first Director, Robert Wilson, there were multiple examples where although experimental risk factors were high, the laboratory still assigned the proposal a high-level of priority because of the promise of important and unique physics results (for example, experiment E-1A). But the collaborations which proposed these more risky experiments had to remove as many of the physics and sociological uncertainties as possible. As pointed out in Galison's account of E-1A, this collaboration failed to do this. During the post E-516 era of Fermilab's second Director, Leon Lederman, there was a decided shift toward larger and more complex experimental "facilities" as part of the Tevatron II Project which upgraded the fixed-target experimental areas to 800 GeV capabilities. With the development of increasingly large, complex, and costly detectors, substantial experimental risks became less acceptable to both collaborations and the Fermilab management.

consisting of physics measurements, spectrometer designs, and people designs working together as a unit. The physics and detector driven model also explains why the sociological factors which are noticeably absent in scientists' accounts of science cannot be ignored if the goal is to describe what physicists actually *do* in experimental halls. By using a case study which is representative of many HEP experiments within the time period of 1976-1991, I have tried to offer an alternative to the image of high-energy physics research being dominated by a continuing series of crucial discovery experiments. While the data produced by E-516, 691, 769, and 791 did not substantially influence the overall conceptual development of HEP, I claim that the account presented here *is* very typical of what most scientists actually do at Fermilab.

I have also argued that the physics and detector driven model can be used to describe strings of experiments which are motivated partially by experimentalists' attempts to avoid many of the uncertainties of proton economics, experimental real estate, and physicist economics. Experimentalists must learn to trade with the *commodities of protons, experimental halls, and physics expertise because* currently there is no other way to participate in accelerator-based high-energy physics research. I attempted to support my claim that the formation of experimental strings is an established scientific practice by demonstrating how copiously they appear throughout Fermilab's entire research program. Moreover, using experimental strings as a unifying device which emerges from the actual practice of scientists shows how crucial the experimentalists' role is in writing a veridical account of scientific practice; that is, if the goal of such accounts is to describe what high-energy physicists actually *do* in the laboratory.

My preliminary research shows that the physics and detector driven model and the existence of experimental strings in fixed-target counter experiments may also be suggestive about the sociological and experimental factors associated with large Fermilab collider experiments like the Collider Detector at Fermilab (CDF) and the D0 collider detector.[65] Within the constraints of the resource economies mentioned previously, the model would predict that more complex physics measurements would demand a corresponding increase in the size, cost, and complexity of the detector designs, which would give rise to more complex social structures for these collaborations. One would begin such a study with a diagram of the overall detector and a list of the institutions responsible to design and construct the detector sub-systems. If the claims presented thus far are correct and if they can be extended to collider detector collaborations, this exercise should define the basic social structure of the more than 250 physicists in the CDF collaboration. Analysis of the early phases of CDF (design and construction) shows that the expertise of the collaboration was in fact taxonomized and distributed along the lines drawn in a diagram of the CDF detector (track chambers, calorimeters, muon systems, and electronics), with the institutional responsibilities for the detector sub-systems remaining the repositories of expertise throughout all phases of the experiments performed with the CDF detector.[66]

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65 Fermilab's accelerators can be used to produce beams of protons and antiprotons which are circulated then collided together in the center of large collider detectors like CDF and D0.

66 For the details of which institutions assumed responsibilities for the CDF detector sub-systems see *The Collider Detector at Fermilab; A Compilation of Articles Reprinted from Nuclear Instruments and Methods in Physics Research-A*, (Amsterdam: North-Holland Physics Publishing, 1988).

My research also shows that the complexity of the physics measurements to be made drove the size, cost, and complexity of the CDF detector to a level that far exceeded the experiments noted in our case study ($60 million, 2,000 tons, 100,000 channels of electronics).[67] One would subsequently expect that a far more complex higher-level social structure would be superimposed on the basic social structure by the laboratory in order to manage the detector facility and the collaboration. The history of the CDF collaboration shows that this was evidenced in two major ways. First, Fermilab insisted that CDF's higher-level management structure be headed by co-spokespersons; one physicist from a university in the collaboration and one physicist who was a Fermilab scientist. With a detector of this size, complexity, and cost, the risks that might otherwise be taken with moderately sized fixed-target counter detectors became absolutely unacceptable to the Fermilab management and the experimentalists. This heterogeneous mixture of spokespersons was one way that the laboratory could maintain control over all aspects of the CDF collaboration's activities.

A second way that Fermilab maintained some control over CDF was by forming a Fermilab-based CDF Department devoted solely to the operation, maintenance, and upgrading of the detector. With the formation of the CDF Department, we see the emergence of an even more complex and heterogeneous social structure which adds a new dimension to the physics and detector driven model described thus far. Because even the largest and most complex fixed-target counter experiments at Fermilab did not have dedicated support departments, one might initially conclude that this represents a novel sociological development in HEP. But closer examination shows that the formation of the CDF Department has organizational links to the dedicated support departments which operated and maintained large bubble chamber facilities like the Fifteen Foot Bubble Chamber at Fermilab.[68] While the existence of a laboratory/university social structure is evidenced in both cases, the formation of these support departments appears to be motivated by different issues. The emergence of dedicated support departments for large bubble chambers was motivated (primarily) by the safety problems associated with using liquid hydrogen in the chamber and (secondarily) by the size and complexity of the chamber.[69] The formation of the CDF department appears to have been driven primarily by the size, complexity, and cost of the detector, not by issues of safety.

The previous discussion of experimental strings would also predict evidence for continuities between multiple experiments performed with the CDF detector; the physics goals, the detector design, and the ability of the core group of physicists to work together as a unit in a continuing program of successful physics studies. To-date, four experiments have been proposed using the CDF detector (E-741, 775, 775A, and 775B), all of which display many of the properties of

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67 For the technical details of the CDF detector see the *Design Report for the Fermilab Collider Detector Facility*, (Batavia, Ill: Fermilab, 1981).

68 For a description of the history of the operation of the Fifteen Foot Bubble Chamber, see M. Bodnarczuk (ed), *Reflections on the Fifteen Foot Bubble Chamber at Fermilab*, (Batavia, Ill: Fermilab, 1989).

69 Galison points out how important safety issues were when L. Alvarez decided to use liquid hydrogen in his seventy-two-inch bubble chamber. Given the volume of liquid hydrogen need for Fermilab's Fifteen Foot Bubble Chamber, these safety related problems became enormous. See Peter Galison, "Bubbles, Sparks, and the Postwar Laboratory," in L. M. Brown, M. Dresden, and L. Hoddeson (eds.) *Pions to Quarks; Particle Physics in the 1950's*, (New York: Cambridge University Press, 1989), p 220.

an experimental string.[70] Analysis of the respective experimental proposals shows that each experiment was a successive iteration of upgrades to the basic detector sub-systems and associated computing systems.[71]

But the physics and detector driven model and the notion of experimental strings may also be suggestive about the next generation of collider detector collaborations like the Solenoidal Detector Collaboration (SDC). If fully approved, SDC will begin running at the Superconducting Super Collider Laboratory around the year 2,000. As the model would predict, the complexities of the proposed physics measurements to be made with the SDC detector have demanded that its design be among the largest, most costly, and complex devices ever designed for any scientific activity.[72] This would suggest that an extremely complex "people design" for the collaboration would have to emerge in order to carry the experiment through to completion and that it would be based upon the basic structure of the detector sub-systems - and so it is. The basic social structure of the SDC collaboration is composed of nine Technical Steering Committees (The Calorimetry, Muon Systems, Superconducting Magnet, Tracking, Computing and Analysis Software, Electronics and Data Acquisition, Detector Integration and Experimental Facilities, and Physics and Detector Performance Committees), each headed by a Chairperson from the collaboration. In other words, the SDC collaboration's organization chart is a *sociological representation* of the list of detector sub-systems in the experimental apparatus. The physics and detector driven model would also predict an increase in the complexity of the higher-level social structure needed to manage this collaboration. Currently, the collaboration's physicists number about 600, with the higher-level social structure consisting of 1 Spokesperson, three Deputy Spokespersons, a Technical Manager, and a 13 member Executive Board.[73] The SDC collaboration has written and ratified a Governance

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70 Experiment E-741 was approved by the Fermilab Directorate in April, 1982; E-775 was proposed in May 1986 and approved in July 1986; E-775A was proposed in June 1988 and approved in January 1989; E-775B was proposed in September 1988 and received Stage I approval from the laboratory in January 1989.

71 Another area of research that is beyond the scope of this paper involves instances where experimental strings seem to be *transmitted* from fixed-target counter to large collider detector experiments. It has been pointed out by G. Fraser at CERN that a major factor in the formation of the core group for the Aleph collider detector at CERN's Large Electron Positron (LEP) Collider was the admiration and loyalty that experimentalists had for spokesperson, Jack Steinberger. In this case, Steinberger *himself* became a major continuity around which the core group for Aleph was built. Although there were almost no continuities between the physics interests/detector designs of the fixed-target neutrino counter experiments at CERN's Proton Synchrotron in the 1960's and this LEP experiment, Fraser claims that Steinberger and a core group of physicists from these neutrino experiments were the continuity around which the larger Aleph collaboration was formed. See G. Fraser, "Aleph" in *CERN Courier*, vol. 31, no. 1, January/February, 1991, pp 1-4.

72 Current estimates by the SDC collaboration describe a detector that will cost $500 million (in 1990 dollars), weigh 10,000 tons, and have 20 million channels of electronics. For details, see the *Solenoidal Detector Collaboration Expression of Interest*, 24 May, 1990.

73 The higher-level social structure of CERN's Delphi experiment at LEP, has been referred to as a "parliament." The collaboration consists of over 500 physicists, and is headed by a Collaboration Board which is responsible to reconcile potential conflicts of interest between participating institutions and overview the final production of physics results. In addition, a collaboration Executive Committee is responsible to make technical recommendations for the

Document which describes the organization and management of the group and the rules for admitting additional members into the experiment.[74]

It is interesting to speculate about the present trend toward the use of collider detectors and away from fixed-target counter detectors. Currently, fixed-target counter experiments are beginning to play less of a role in the overall research of HEP. If this trend continues into the SSC era, the social structure of U.S. HEP might be defined by the number of interaction regions in the world-wide network of accelerators, the distribution of the majority of high-energy physicists into the collaborations that propose collider detectors, and a social structure for these collaborations based upon the model I have described above.[75] This type of localization of the majority of high-energy physicists into a small number of large collider experiments, might even suggest that the size, cost, and complexity of these detectors may become a self-limiting factor in the sociological make-up of U.S. HEP.

In regard to the model's prediction that such detectors would be used to perform strings of experiments, even in the early design phase of the SDC the collaboration is trying to anticipate the need for upgrading the capabilities of the detector to do subsequent experiments. This is partially due to the SSC laboratory's proposed plan to eventually upgrade the accelerator's ability to produce particle interactions (luminosity) and the collaboration's plan to pursue a continuing program of physics goals that spans multiple experiments.[76] In addition, when detectors become as large, complex, and costly as the SDC, the importance of removing the uncertainties mentioned in our case study is crucial. With SDC, the failure to eliminate as many of the risks as possible is absolutely unacceptable to the experimentalists and the SSC laboratory management because the failure of the detector to perform as intended could adversely affect a major portion of the

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experiment which must be subsequently ratified by the Collaboration Board. See G. Fraser, "Delphi," in *CERN Courier*, vol. 30, no. 8, November, 1990, pp 1-5.

74 For details, see the *Solenoidal Detector Collaboration Expression of Interest*, 24 May, 1990, p 93 ff..

75 Currently, one Expression of Interest has been submitted to the SSC Laboratory for a 20 TeV Super Fixed Target Beauty Spectrometer (SFT) which is estimated to cost about $24 million (in 1990 dollars). Because the physics measurements to be made with the SFT are far more complex than those described in our case study, the spectrometer design exhibits a corresponding increase in cost, complexity, and size. The various components of the SFT include two large analysis magnets, a silicon microvertex detector, several stations of PWC wire and pad chambers, a Ring Imaging Cerenkov Counter, and electromagnetic detector, and a muon detector. These detector sub-systems are distributed over a spectrometer which is 70 meters long and 10 meters wide at the downstream end. Based on my analysis thus far, one would also expect that the complexity of the social structure of this collaboration would also increase substantially. Currently, there are about 140 physicists affiliated with this experiment, and even in this early design phase, they are organizing themselves around the lines drawn in the SFT spectrometer diagram. See *An Expression of Interest in a Super Fixed Target Beauty Facility (SFT) at the Superconducting Super Collider*, May 25, 1990.

76 Luminosity is a measure of how effectively a collider induces collisions between the two circulating beams of particles. It is the product of the number of particles per second circulating in one beam and the average number of intercepted particles per unit transverse area in the other beam. When multiplied by the cross section for a given reaction, it gives the average number of events per second for that reaction. For a brief account of the physics goals of SDC and the technical details of the anticipated luminosity upgrade, see D. Green, *SDC at High Luminosity*, Fermilab-Conf-90/110.

U.S. high-energy physics community for a decade or more.[77] While it may not be clear exactly how a collaboration like SDC will function throughout the lifetime of the detector, the notions of proton economics, experimental real estate, physicist economics, the physics and detector driven model of social structure, and experimental strings *together* may provide a useful way to characterize the nature of institutionalized scientific practice in high-energy physics into the next millennium.

[77] Current estimates claim that approximately 50 per cent of the HEP community in the U.S. will be involved in some aspect of the two collider experiments at the SSC Laboratory, with 50 per cent participating in research at other U.S. laboratories like Fermilab and SLAC. For details see the *HEPAP Subpanel on the U.S. High Energy Physics Research Program for the 1990's*, U.S. Department of Energy Office of Energy Research Division of High Energy Physics, DOE/ER-0453P, April, 1990, pp 68 ff.