From Materials Science to Nanotechnology: Interdisciplinary Center Programs at Cornell University, 1960–2000

ABSTRACT

During the last several decades, interdisciplinary research centers have emerged as a standard, powerful tool for federal funding of university research. This paper contends that this organizational model can be traced to the “Interdisciplinary Laboratories” program funded by the Advanced Research Projects Agency in 1960. The novelty of the IDL program was that it created a peer group of university laboratories with sustained funding to ensure their institutional stability. The Cornell Materials Science Center, one of the first three Interdisciplinary Laboratories, served as a breeding ground for a new community of engineering faculty members, who subsequently helped establish a series of interdisciplinary research centers at Cornell, including the National Research and Resource Facility for Submicron Structures (or National

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The following abbreviations are used: AEC, Atomic Energy Commission; ARPA, Advanced Research Projects Agency; CCMR, Cornell Center for Materials Research records, #53-24-3676, Division of Rare and Manuscript Collections, Cornell University Library; CHESS, Cornell High Energy Synchrotron Source; CIS, Center for Integrated Systems; DOD, Department of Defense; DOR, Cornell University College of Engineering Dean’s Office records, #16-2-2156, Division of Rare and Manuscript Collections, Cornell University Library; DRC, Dale R. Corson papers, #3-11-1665, Division of Rare and Manuscript Collections, Cornell University Library; ERC, Engineering Research Center; FRP, Frank H.T. Rhodes papers, #3-12-1795, Division of Rare and Manuscript Collections, Cornell University Library; IDL, Interdisciplinary Laboratories; LASSP, Laboratory for Atomic and Solid State Physics; MIT, Massachusetts Institute of Technology; MRL, Materials Research Laboratories; MRSEC, Materials Research Science and Engineering Center; MSC, Materials Science Center; NNI, National Nanotechnology Initiative; NNIN, National Nanotechnology Infrastructure Network; NRRFSS, National Research and Resource Facility for Submicron Structures; NSB, National Science Board; NSEC, Nanoscale Science and Engineering Center; NSF, National Science Foundation; VLSI, very large-scale integration.

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Submicron Facility) in 1977. The Materials Science Center and National Submicron Facility provided explicit models for the expansion and coordination of networks of interdisciplinary centers, both within single universities (such as Cornell) and across multiple campuses (through programs such as the National Nanotechnology Infrastructure Network and the Nanoscale Science and Engineering Centers). The center model has proved both flexible and durable in the face of changing demands on universities. By examining the Materials Science Center and the National Submicron Facility, we show that recent institutional developments perceived as entirely novel have their roots in the high Cold War years.

KEY WORDS: materials bottleneck, relevant research, multidisciplinary, microfabrication, organizational field, laboratory buildings

On January 21, 2000, President Bill Clinton announced the National Nanotechnology Initiative (NNI). Clinton and, later, George W. Bush justified the NNI not only for its scientific merit, but also for its potential to fend off foreign competition and secure American industrial competitiveness in the emerging field of nanotechnology.¹ For American universities, the initiative meant a large influx of federal funds to conduct research on and train advanced students in nanoscale science and technology. The NNI's most visible tool in aiding academic nanoscientists has been the interdisciplinary university research center: as of July, 2012, the NNI's website lists fifty-four dedicated university nano centers funded by its member agencies, plus another six "networks" of smaller centers and seventeen National Science Foundation (NSF)-funded academic centers that are partially nano-oriented. Indeed, most of the NNI's centers and networks were funded by the NSF, primarily through its Nanoscale Science and Engineering Centers (NSECs), Materials Research Science and Engineering Centers (MRSECs), and the National Nanotechnology Infrastructure Network (NNIN).

While the fifteen NSECs, thirty-five MRSECs, and fourteen NNIN sites cover a broad range of research interests—from nanomanufacturing to nano/bio interfaces and environmental nanotechnology—they share some common institutional features. Most importantly, their operating procedure follows, in

1. The White House Office of the Press Secretary, "President Clinton's Address to Caltech on Science and Technology," California Institute of Technology, Pasadena, CA (21 Jan 2000). For an analysis of the policy battles that led to the NNI, see Yasuyuki Motoyama, Richard Appelbaum, and Rachel Parker, "The National Nanotechnology Initiative: Federal Support for Science and Technology, or Hidden Industrial Policy?" *Technology in Society* 33 (2011): 109–18.

NSF parlance, the “centers’ mode of support.”² According to the NNI’s official website, these centers “provide opportunities and support for multidisciplinary research among investigators from a variety of disciplines and from different research sectors, including academia, industry and government laboratories.”³ Multiyear contracts ensure some continuity in funding, contributing to the centers’ relative financial stability. Finally, while the NSECs, MRSECs, and NNIN sites are required to identify several “thrust areas” or central research themes, the authority to fund individual researchers or purchase specific tools is largely delegated to the executive committees at host universities. In short, interdisciplinarity, stability, and decentralization are the key characteristics of NSF-funded university research centers.

In this paper, we contend that the historical origin of the “centers’ mode of support” can be traced to the late 1950s, when the newly created Advanced Projects Research Agency (ARPA) began a funding program to support interdisciplinary materials research in response to the Sputnik crisis in 1957. We do not mean, of course, that ARPA invented organized interdisciplinary research. Industrial research laboratories have relied on avowedly interdisciplinary teams since at least the early twentieth century, while the Rockefeller Foundation funded several interdisciplinary academic research units in the 1930s.⁴ During World War II, academic scientists and engineers mobilized in interdisciplinary laboratories to develop new weapons systems, such as MIT’s Instrumentation and Radiation Laboratories, the Johns Hopkins Applied Physics Laboratory, and the University of Chicago’s Metallurgical Laboratory.⁵

The novelty of the ARPA materials research program, however, was that it created a *peer group* of university laboratories dedicated to fostering a specific field and providing sustained funding to ensure their institutional stability.

2. Dragana Brzakovic, “NSF Centers: Platforms for Innovation,” http://www.nsf.gov/od/oia/presentations/db/platforms_for_innovation.pdf (accessed 4 Dec 2011), on 5. Brzakovic’s presentation succinctly covers the characteristics of this mode of support.

3. National Nanotechnology Initiative, “Centers and Networks,” <http://nano.gov/centers-networks> (accessed 19 Jul 2012).

4. Leonard S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (New York: Cambridge University Press, 1985); Robert E. Kohler, *Partners in Science: Foundations and Natural Scientists, 1900–1945* (Chicago: University of Chicago Press, 1991).

5. David Kaiser, “Elephant on the Charles: Postwar Growing Pains,” in Kaiser, ed., *Becoming MIT: Moments of Decision* (Cambridge, MA: MIT Press, 2010), 103–21; Michael Aaron Dennis, “‘Our First Line of Defense’: Two University Laboratories in the Postwar American State,” *Isis* 85, no. 3 (1994): 427–55.

The result was the creation of a community in the field of materials science with a common institutional experience. The successful emergence of a discipline of materials science in the 1960s, with the ARPA centers as its institutional backbone, heightened the status of interdisciplinary centers as a *modus operandi* of federal funding for academic science and engineering in subsequent decades. Since the early 1970s, federal research funding agencies have almost automatically reacted to changes in national science policy priorities by fostering new peer groups of interdisciplinary academic research centers. The NNI's heavy reliance on peer groups of interdisciplinary academic centers is merely the latest example of this organizational form's continuous significance for more than fifty years.

The case of Cornell University provides a particularly useful example for illuminating the continuity and adaptability of the centers mode in the postwar era. Cornell was one of three universities—along with the University of Pennsylvania and Northwestern University—selected by ARPA in 1960 to establish the first batch of Interdisciplinary Laboratories (IDL) in materials science. The Cornell Materials Science Center (MSC), as the largest and most successful among its peers, was not only a wellspring of advanced knowledge and trained personnel, but also became an institutional exemplar for future interdisciplinary centers both within and outside Cornell University.

Nationally, the success of the MSC in the 1960s and the simultaneous formation of an interdisciplinary materials science community contributed to the survival of the centers mode despite contracting defense budgets in the early 1970s, when the ARPA program was transferred to the NSF. Locally, the MSC served as a critical resource in the establishment of other interdisciplinary centers at Cornell, particularly the National Research and Resource Facility for Submicron Structures (NRRFSS) in 1977.

The NRRFSS and other second-generation Cornell centers should be seen as products of the community of physical scientists and engineers who came of age within the MSC. The NRRFSS and other Cornell centers were also linked as peers with centers at other universities that were similarly closely tied to their campus's materials science centers. Together, Cornell's MSC and NRRFSS and their inter- and intra-university peers provided explicit models for the expansion of the “centers' mode of support” at NSF, up to and including the NSEC and NNIN programs today.

The postwar trajectory of the Cornell physical sciences community reflects the broad sociopolitical changes that transformed the American scientific

landscape. Yet Cornell's centers have, at least superficially, been remarkably stable amid those changes. Established institutional structures can be adapted to a broad range of rationales, depending on the specific needs of the time. At Cornell and elsewhere, institutions created in the high Cold War era to conduct basic research and train specialists in materials science were later adapted to serve the "relevance" agenda of the late 1960s and early '70s. Since the late 1970s, those same institutions (and their spin-offs) have served as models for successive crops of research institutions created to meet international economic competition. Through the years, the interdisciplinary center model has shown both persistence and flexibility.

We emphasize the continuity of institutional models for scientific research as both an addition and a corrective to recent scholarship on discontinuities in the role of research universities in the United States during the last half-century. Many scholars have noted that "Cold War universities" dramatically reoriented toward commercial activities around 1980, sometimes characterizing the latter mode as "postmodernity."⁶ In this narrative, new "interdisciplines," such as biotechnology and nanotechnology, emerged as key denizens of the commercialized universities.⁷ The commercialized postmodern university did not, however, arrive fully formed in the 1980s. Rather, it was built using existing institutional resources that had been in place since at least the late 1950s. In this paper, we aim to eschew the dichotomy of pre- and post-1980, and underscore the continuities of scientific research communities and institutions in the postwar decades. The case of Cornell University clearly shows that recent institutional developments perceived as entirely novel have their roots in the high Cold War years.

6. Paul Forman, "The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology," *History and Technology* 23 (2007): 1–152. Forman is not the only one that takes circa 1980 as the key turning point. Roger Geiger also points to 1980 as the point when "concerted effort was made to relate academic research more closely to the civilian economy." Roger L. Geiger, *Knowledge & Money: Research Universities and the Paradox of the Marketplace* (Stanford, CA: Stanford University Press, 2004), vii. The Bayh-Dole Act of 1980 is another reference point in the discussion over the commercialization of research universities. On the impact of the Bayh-Dole Act, see David C. Mowery, Richard R. Nelson, Bhaven N. Sampat, and Arvids A. Ziedonis, *Ivory Tower and Industrial Innovation: University-Industry Technology Transfer Before and After the Bayh-Dole Act* (Stanford, CA: Stanford University Press, 2004).

7. Some sociologists formulate this as a change from "Mode 1" to "Mode 2" research. See Michael Gibbons et al., *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies* (London: Sage, 1994).

“MATERIALS BOTTLENECK”

At the end of World War II, scientists and policymakers began to recognize the problem of procuring adequate strategic “materials” as critical for the rapidly expanding national security apparatus. For example, John von Neumann, eminent mathematician and commissioner of the Atomic Energy Commission (AEC), frequently expressed frustration at the unavailability of key materials for nuclear reactors.⁸ Newly developed weapons systems, such as long-distance ballistic missiles, jet aircrafts, and advanced electronics equipment, often required novel materials with superior properties. By the mid-1950s, the term “materials bottleneck” came into wide circulation within the Washington science policy circle to describe the lack of knowledge and personnel in materials research.

The recognition of the “materials bottleneck” was partly based on a critical reflection on materials research practices during World War II and the early postwar years. As MIT professor Arthur R. von Hippel quipped in 1956, “[t]he answers to the increasingly excessive demands for materials remain empirical; they are slow in coming and are bought in uncertain approaches at an excessive cost.” In other words, materials research had been plagued by what he called a “phenomenological approach.” As a solution to this problem, von Hippel proposed an alternative approach of “molecular engineering” based on the firm theoretical foundation of the molecular properties of matter. Utilizing the vast advances in physics and chemistry during the last fifty years, he continued, one could “build materials from their atoms and molecules for the purpose at hand He can play chess with elementary particles according to their prescribed rules until engineering solutions become apparent.”⁹

While the potential power of fundamental physical principles was widely acknowledged among scientists in the 1950s, not everyone accepted it as a remedy for the materials bottleneck. Solid-state physicist Frederick Seitz, for example, expressed more humility as he pointed out that the “present methods of theoretical analyses are far too crude to give us more than a rough grasp of the properties of even the simplest material systems.” A more realistic solution could be found, he argued, in the “symbiotic activity of several species of

8. See, for example, Frederick Seitz, “Perspectives in Materials Research,” *Physics Today* 14, no. 11 (1961): 24–28.

9. A. von Hippel, “Molecular Engineering,” *Science* 123 (1956): 315–17. For a more comprehensive articulation of Von Hippel’s vision, see his edited volume *Molecular Science and Molecular Engineering* (Cambridge, MA: MIT Press, 1959).

scientist and engineer The future development of the field [materials science] requires that means be found to enhance the interplay of various professional groups.”¹⁰ As opposed to Von Hippel’s rather grandiose vision proffering primacy to scientific principles, Seitz called for a cooperative effort among physicists, chemists, and engineers. Seitz’s vision gradually emerged as the dominant view among policymakers as federal efforts to foster materials research came to fruition in the late 1950s.

The critical impetus for a large-scale program on materials research came from the external shock of Sputnik in October 1957, which sparked widespread concerns that the Soviet scientific and technological capabilities were rapidly outstripping those of the United States. Within this context, the field of materials science quickly became one of the key theaters of the Cold War. As early as January 1958, officials at the U.S. Department of Defense (DOD) and the AEC had already begun detailed discussions on the scale and scope of the new materials program. By early 1959, the newly created Advanced Research Projects Agency (ARPA) was accepting preliminary proposals from major research universities around the country as part of its IDL program.¹¹ The program’s name reflected its underlying aim to foster interdisciplinary cooperation and collaboration among related disciplines of physics, chemistry, and metallurgy (among others). This goal was to be achieved through making available centralized spaces and shared facilities on campus, within which scientists and engineers could mingle and interact.

In July 1960, ARPA completed the review process and announced the results of the first-year contracts. From more than three dozen applicants, the agency selected Cornell University (\$6.1 million), the University of Pennsylvania (\$4.4 million), and Northwestern University (\$3.4 million), each for an initial period of four years and renewable with a four-year forward plan.¹² Nine more contracts of various sizes were awarded within the next three years, making a total of twelve IDLs around the country. The IDL program continued until 1972, when it was transferred to the NSF and changed its name to the Materials Research Laboratories (MRL) program.

10. Seitz, “Perspectives” (ref. 8).

11. Robert L. Sproull, “Materials Research Laboratories: The Early Years,” in Peter A. Psaras and H. Dale Langford, eds., *Advancing Materials Research* (Washington, DC: National Academy Press, 1987), 25–34.

12. “U.S. Aids Research in New Materials,” *New York Times*, 17 Jul 1960; Cornell University News Bureau, “Press Release,” 1 Jul 1960, DRC, Box 3, Folder 5.

PHYSICS AND ENGINEERING COMMUNITIES AT CORNELL UNIVERSITY

Cornell University was the largest beneficiary of the ARPA-IDL program throughout its twelve years of existence. Who, then, were the people behind Cornell's proposal? In the 1950s, Cornell boasted a vibrant and prestigious physics community on campus. This was made possible in large part by the arrival of Hans A. Bethe in 1935.¹³ Trained under Arnold Sommerfeld and Enrico Fermi, Bethe was a theoretical physicist with a broad range of interests in nuclear and solid-state physics. During the war, he was recruited by J. Robert Oppenheimer to lead the theoretical physics division of the Los Alamos Laboratory and made critical contributions to the basic design of the first atomic bomb. When Bethe and the other Cornell physics "veterans" returned to campus after the war, they were greeted with much fanfare. As Bethe noted later, "[r]eturning 'veterans' could make ambitious plans, [and the university] administration [was] very receptive. Government support was very likely."¹⁴ Armed with university and government support, the physics community aimed to continue their wartime research on nuclear physics at the new Laboratory for Nuclear Studies, established in 1946 complete with an electron synchrotron built with funding from the Office of Naval Research.¹⁵ Between 1945 and 1952, the size of the physics faculty grew by more than 40%—from 17 to 24—attracted by the high-profile faculty members and the new research facility.¹⁶ The Cornell physicists had a head start in pursuing an active research agenda in atomic and nuclear physics during the early postwar years.

The expansion of the Cornell physics community soon crossed the boundaries of the College of Arts and Sciences, of which the Department of Physics was a part. In 1948, Lloyd P. Smith, then chairman of the physics department,

13. Lillian Hoddeson, Ernst Braun, Jurgen Teichmann, and Spencer Weart, eds., *Out of the Crystal Maze: Chapters from the History of Solid State Physics* (Oxford: Oxford University Press, 1992), 193.

14. H. A. Bethe, "30 Years of Physics at Cornell," speech given at the Clark Hall Dedication, 20 Oct 1965, Hans Bethe papers, #14-22-976, Division of Rare and Manuscript Collections, Cornell University Library, Box 8, Folder 63.

15. S. S. Schweber, "Big Science in Context: Cornell and MIT," in Peter Galison and Bruce Hevly, eds., *Big Science: The Growth of Large-Scale Research* (Stanford, CA: Stanford University Press, 1992), 177–79.

16. Number counted from appendix of Paul Hartman, *The Cornell Physics Department: Recollections and History of Sorts* (privately published in 1984), 332–40.

successfully wrangled a deal with the university administration to establish the new Department of Engineering Physics within the College of Engineering. This was in return for Smith's turning down a deputy directorship of RCA's Laboratories Division at Princeton, the premier industrial research organization of its time with which Smith had collaborated extensively. The objective of the new department was to provide "training which is neither entirely that of the physicist nor that of the engineer"—in other words, to "break down the traditional barriers that had divided the province of science and engineering."¹⁷ By 1959, physicists in the two departments worked side by side within the Laboratory for Atomic and Solid State Physics (LASSP) housed within the university's Rockefeller Hall, a half-century-old structure built in 1906 with a quarter-million dollar gift from John D. Rockefeller.¹⁸

With the exception of the Department of Engineering Physics, the other engineering departments at Cornell were still largely populated with faculty members with a strong bias toward teaching and service, those sometimes disparagingly referred to as "old school" engineers or "cookbook materials types."¹⁹ When Dale Corson moved from chair of the physics department to dean of engineering with a mission to transform the college from being "craft-centered" to "science-centered," the composition of engineering faculty members soon emerged as a critical bottleneck. Corson noted, for instance, that at Cornell materials science seminars in the early 1960s, "even with worthwhile outside speakers . . . there was no participation or show of interest by the [engineering] faculty—they simply sat at the back of the room, mute."²⁰ The generational and disciplinary bifurcation of faculty members continued to pose a serious problem through the early 1960s. As late as 1964, Corson openly expressed his discontent toward the "old school" engineers: "There are concentrations of staff not oriented toward research or intimate with the frontiers of engineering in science. A cursory look at the present effort shows that a number of our engineering divisions . . . do little research and make small contribution to the advancement of the field."²¹

17. Paul L. Hartman, *Applied and Engineering Physics at Cornell: A History of the School with Various Asides and a Brief Look at the Department from Which It Came* (Ithaca, NY: College of Engineering, Cornell University, 1994), 8–9.

18. J. A. Krumhansl, "The Laboratory of Atomic and Solid State Physics," 12 Jan 1961, DRC, Box 16, Folder 18.

19. Hartman, *Engineering Physics* (ref. 17), 37–38.

20. *Ibid.*, 38.

21. "Cornell and Its Future in Engineering," 8 Oct 1964, DRC, Box 16, Folder 28.

Given the asymmetry in research activities between the physics and engineering communities, it was no surprise that the former took the lead when ARPA began to solicit proposals for the IDL program in early 1959. At the helm was Corson (then still chairman of physics), who assembled the “Interdepartmental Committee on Materials Research Program.” He named Henri S. Sack, professor of engineering physics, as chair of the committee with the responsibility of coordinating the effort to prepare the proposal. Other members of the committee included physicist Robert L. Sproull and two young assistant professors from the College of Engineering, Arthur L. Ruoff and Chester W. Spencer.²² As chair, Sack played an instrumental role in drafting the proposal, and between May 1959 and April 1960 he prepared four documents outlining a detailed plan for the new Materials Science Center (MSC).²³

Sack recognized that the key area of weakness for Cornell was the imbalance of research activities between physics and engineering. This was a serious problem for a center whose aim was to foster interdisciplinary collaboration among scientists and engineers. In the proposal, Sack managed to spin the weakness in the best possible light: “In Metallurgical Engineering and Engineering Materials, research has been relatively inactive until a few years ago; but a strong upsurge is taking place and the research efforts are being increased at a rapid rate.”²⁴ Sack’s remark was probably more hopeful thinking than an accurate representation of reality. In terms of the annual operating budget at the time of writing the proposal, the Department of Physics alone occupied 52% (\$385,000) of the total research activities in materials science at Cornell, while the three engineering departments of Metallurgical Engineering, Engineering Materials, and Chemical Engineering combined held a meager 14% (\$108,000). If Engineering Physics was included as part of the physics community, the unevenness became even more conspicuous.²⁵ Thus, building up a strong research community in engineering to match their physicist colleagues emerged as an urgent matter.

22. T. P. Wright (Vice President Research) to Dale R. Corson, 11 May 1959, CCMR, Box 36, Folder 11; Arthur L. Ruoff, interview with author (Choi), Ithaca, NY, 15 Jun 2009.

23. Sproull became the inaugural director of Cornell’s Materials Science Center, a post he assumed until 1963 when he became the Director of ARPA. Sack succeeded Sproull as the second director of MSC. The first draft of the proposal was entitled “Plans for a Materials Science Center at Cornell University, Ithaca, N.Y.,” 23 May 1959, DRC, Box 3, Folder 3.

24. “Plans for Materials Center” (ref. 23), 5.

25. “Additional Remarks to ‘Plans for a Materials Science Center at Cornell University’ submitted May 23, 1959,” 23 Sep 1959, CCMR, Box 31, Folder 31.

Despite the potential weakness of the Cornell team's proposal, the ARPA-IDL contract was awarded to the university in July 1960. Efforts to secure the contract were largely led by physics members of the Departments of Physics and Engineering Physics, where the bulk of research activities in materials science were taking place. In the proposal, Sack outlined Cornell's research activities in materials science, including transport phenomena, electronic properties, surface structure, magnetic spin resonance, high polymers, and metal physics. The first four topics represented work done largely by physicists; high polymers was the chemists' domain; and metal physics that of the engineers. Apart from Ruoff and Spencer, who respectively worked on diffusion and creep under high pressure and electronic properties of intermetallic compounds, there was little intercollegiate overlap of research areas.²⁶ It was eminently clear that the success of Cornell MSC as an IDL would depend upon cultivating a new community of research-oriented engineers and embracing them as equal partners in the endeavor.

"IMPACT OF THE ARPA PROGRAM"

In July 1960, the Cornell Materials Science Center officially began its operation, with Robert Sproull as inaugural director.²⁷ With the establishment of the MSC, materials research practices at Cornell University underwent slow but significant change. Henri Sack and Paul J. Leurgans (associate director of MSC) noted in a 1964 report outlining the "Impact of the ARPA Program in the Area of Materials Science" in its first five years that "it is not too early to feel already the marked impact of the Center [MSC] on graduate education and research at Cornell in general, and the area of materials in particular." In their view, the most visible changes were staff expansion and construction of a new building dedicated to the physical sciences, which was to be occupied in the following year.²⁸

As Cornell University added new faculty members in the materials area, special attention was placed on fostering a research-oriented engineering community. This, at the most fundamental level, required a generational shift:

26. "Plans for Materials Center" (ref. 23), 5–11.

27. Cornell University News Bureau, "Press Release," 24 Jul 1960, DRC, Box 3, Folder 5.

28. Henri S. Sack and Paul J. Leurgans, "Impact of the ARPA Program in the Area of Materials Science at Cornell University: The First Three Years of Operation of the Materials Science Center," 31 Jan 1964, CCMR, Box 14, Folder 23.

rather than encouraging skill-based traditionalist engineering educators to build up their research agenda, administrators brought in a new breed of engineers with experience in science-based research and training. One of the earliest of these young Turks in Cornell's College of Engineering was Arthur L. Ruoff. He was hired in 1955 as assistant professor in the Department of Engineering Mechanics and Materials, upon earning his doctorate in physics and physical chemistry at the University of Utah under the direction of Henry B. Eyring.²⁹ In addition to serving on the committee that prepared the IDL proposal, Ruoff played a leading role in developing a new materials science and engineering curriculum to replace the obsolete coursework in metallurgical engineering.³⁰ He was followed by a few other isolated cases in the Department of Chemical and Metallurgical Engineering, such as Chester W. Spencer (Ph.D., University of Wisconsin, 1952) and Herbert H. Johnson (Ph.D., Case Institute of Technology, 1957).³¹ These young engineering professors were at the core of the Cornell College of Engineering's early participation in the MSC.

Thus, though a few young, research-oriented engineering faculty were hired in the second half of the 1950s, the influx of new funding from the ARPA contract gave a much needed boost to that trend. MSC leadership went to great lengths to promote expansion in the engineering disciplines, sometimes at the expense of the sciences. In 1962, at an MSC Executive Committee meeting called to discuss "long-range plans," director Sproull recommended that "expansion for the next few years should occur mostly in [John P.] Howe's area [Engineering Physics and Materials Science] and EE [Electrical Engineering], with very little in Chemistry and Physics."³² Within a decade, more than a dozen engineering faculty members working in the field of materials science were hired in various departments with partial funding from the MSC program. As we will see below, some of the young engineering faculty members brought in during the early years of the MSC—such as Joseph M. Ballantyne (Electrical Engineering) and Boris W. Batterman (Materials Science and

29. Eyring was an eminent chemist who contributed to the study of chemical reaction rates. He was a faculty member at Princeton University until 1946, when he moved to the University of Utah as dean of its graduate school. His relocation to Utah was partly motivated by his religious faith as a Mormon. For Eyring's "life and faith," see Henry J. Eyring, *Mormon Scientist: The Life and Faith of Henry Eyring* (Salt Lake City, UT: Deseret Books, 2008).

30. Arthur Louis Ruoff, "Personal Data," copy provided to Choi by Ruoff.

31. Ruoff, interview (ref. 22).

32. "Memo for the File: Meeting of the MSC Executive Committee on 26 September, 1962," 15 Oct 1962, CCMR, Box 20, Folder 2.

Engineering)—went on to play important roles in building further interdisciplinary centers spun off from Cornell's MSC.³³

The other landmark change facilitated by the ARPA award was the construction of a new building dedicated to the physical sciences. If the Cornell physics community was at the front line pushing hard for the ARPA-IDL contract, at least part of their motivation came from the possibility of fulfilling their decades-long wish for an expanded space adequate for cutting-edge research. As Sproull repeatedly acknowledged, "A good part of the grass roots impetus for this materials program . . . arose from the feeling that the Physics and Engineering Physics groups would simply have to help themselves if they were going to emancipate themselves from the impossible conditions in Rockefeller [Hall]." ³⁴ The postwar expansion of the Cornell physics community led to extremely cramped quarters within Rockefeller Hall. Moreover, the half-century-old structure lacked the adequate infrastructure required for physics research. Therefore, heated discussions on the size and location of a new building ensued soon after ARPA announced the first three winners of the IDL contract.

From the beginning, Sproull was determined to build a "first-class research building." As early as September 1960, he made plans to visit laboratory buildings around the country. In his mind, the best models were recently built industrial and government laboratory buildings, such as the Union Carbide Parma Laboratory near Cleveland, Ohio; the IBM Research Center in Yorktown Heights, New York; the new Bell Telephone Laboratories in Holmdel, New Jersey; and the AEC Laboratory in Oak Ridge, Tennessee. Upon inspecting these state-of-the-art research facilities, Sproull strongly favored the "utility corridor" system to allow for maximum flexibility in providing services such as water, special gases, and power.³⁵ Also, the new building would be "completed air-conditioned," using chilled water from the nearby Beebe Lake.³⁶ Architects

33. Joseph M. Ballantyne, an MIT doctorate with specialties in semiconductor materials, was hired as assistant professor of electrical engineering in 1964. He played an instrumental role in establishing Cornell's National Research and Resource Facility for Submicron Structures (NRRFSS) in 1977. Boris W. Batterman, also an MIT doctorate in physics, arrived at Cornell in 1965 after years of experience at the Bell Telephone Laboratories, and became the key figure behind the Cornell High Energy Synchrotron Source (CHESS) established in 1978.

34. Robert L. Sproull, "Early History of the MSC at Cornell," Aug 1963, CCMR, Box 31, Folder 4.

35. Robert L. Sproull, "Physical Sciences Building History," 1964, CCMR, Box 31, Folder 31.

36. John E. Gerich, "Science Center . . . Univ. Constructs Largest Hall," *Cornell Daily Sun*, 3 Jan 1963.

FIG. 1. The Clark Hall of Science, ca. 1965. *Source:* Reprinted from Paul L. Hartman, *Cornell's Materials Science Center: The Early Years* (Ithaca, NY: Cornell Center for Materials Research, 2007), 76. Permission granted by Cornell Center for Materials Research.

at J. Fruchtbaum of Buffalo, New York, came up with a building design exhibiting a towering seven-story structure in the shape of an “iceberg,” with a broad base and narrower upper floors. This was intended to house most of the sensitive experimental instruments on the ground floor, so as to minimize vibration. Sproull even took care to divert undergraduate traffic away from the laboratory areas, in order to “keep the pounding of feet when classes were changed quarantined into a region of the building that did not include research labs.”³⁷

After a few months debating details, Cornell administrators and faculty members decided to make the new “Physics-ARPA Building” the largest structure on campus, with approximately twice the square footage covered by the ARPA contract. The new building would be occupied by the departments of Physics, Engineering Physics, and Astronomy; the LASSP; the Center for Radiophysics and Space Research (CRSR); a common physical sciences library; and the MSC administrative offices and part of its shared facilities. Approximately \$4 million—half of the construction cost—came from ARPA. The rest was covered by the NSF, the New York State Dormitory Authority, and

37. *Ibid.*, 15.

a \$3 million gift from Cornell alumnus W. Van Alan Clark, chairman emeritus of Avon Products, Inc.³⁸ The building, named the Clark Hall of Science in honor of the donor, was finally dedicated on October 20, 1965. At the dedication ceremony, Hans Bethe appropriately gave his blessings with an overview of “30 Years of Physics at Cornell,” summarizing his experiences at the university since 1935.³⁹

Despite all the rhetoric of interdisciplinary research, Clark Hall was meant to be home mainly to the physics community. The location of Clark Hall at the center of the campus, strategically connecting Rockefeller Hall (Physics and Engineering Physics) and the Baker Laboratory of Chemistry, symbolized the “new spirit of cooperation among the physical sciences.”⁴⁰ Towering over campus from atop a low-rising hill, the façade of Clark Hall had interesting parallels to the Greek Parthenon. Indeed, the new building was to be a modern-day temple for the physical sciences. From the Engineering Quad, where most of the engineering departments were located, however, it is a rather long and uphill walk to Clark Hall. The distance was definitely not prohibitive, but certainly could have been a factor discouraging more intimate interactions between scientists and engineers.⁴¹ While the geographical marginalization of the engineering community from the MSC headquarters at Clark Hall should not be equated with marginalization in research funds and facilities, it nevertheless reflected the unspoken power relations between the physics and engineering communities in the 1960s.

By the mid-1960s, the Materials Science Center was well on its way to becoming a prominent feature of Cornell’s campus. It had succeeded in its stated aim of convincing departments in the College of Engineering to hire a number of new faculty members from top Ph.D. programs around the country, and it had put ARPA money into supporting research done by those new hires. The impressive state-of-the-art laboratory building located right across the street from the main library served as a visible symbol of the

38. “The Physics-ARPA Building,” 22 Aug 1960, CCMR, Box 4, Folder 10; “Dedication of Clark Hall of Science and Physical Sciences Symposium,” 20 Oct 1965, Hans A. Bethe papers, #14-22-976, Division of Rare and Manuscript Collections, Cornell University Library, Box 8, Folder 63.

39. Bethe, “30 Years” (ref. 14).

40. “Clark Hall of Science,” 2 Dec 1966, CCMR, Box 4, Folder 10.

41. In a recent interview, Arthur Ruoff emphasized the distance between his department and the MSC headquarters, and added that whenever one walks between Clark Hall and the Engineering Quad “[i]t’s probably raining, in addition.” Ruoff, interview (ref. 22).

heightened status of materials research at Cornell. MSC members produced important research results in their respective fields, as well as an increasing number of graduate students who went on to do similar research at other

universities and in industry.⁴² From Cornell's perspective, things were moving along smoothly.

THE SEARCH FOR RELEVANCE

Progress was noticeably slower, however, in meeting the ARPA-IDL program's original goal: a solution to the materials bottleneck. As early as April 1964, program officers at ARPA were concerned that IDLs were not yielding enough results directly applicable to the immediate defense needs of the nation. That month, Charles F. Yost, Director for Materials Sciences at ARPA, transmitted a memorandum to the IDL directors outlining a plan to solve the "problem of translation of materials sciences to technology." The opening paragraph of the memo clearly conveyed Yost's concerns: "Although the DOD expends millions of dollars annually in effective support of new materials science and in the development of technological solutions to the materials requirements in the new systems hardware, there continues to exist a 'materials bottleneck' constituting a serious obstacle to the national goals of adequate defense."⁴³

As a solution, Yost proposed an "organizational and management mechanism" called "coupling," designed to forge links among universities, industry, and government laboratories. While the IDLs "expanded basic research and are producing new generations of trained people," these outputs were not quite enough from DOD's perspective. The dual objectives of the coupling program were "1. The exploitation of fundamental materials sciences in order to evolve new materials technology; 2. The orientation of such an exploitation toward Department of Defense needs in materials."⁴⁴

ARPA's attempt to harness fundamental science for military applications was part of a broader science policy discussion in Washington. Already in 1963,

42. Out of twenty-four PhDs who graduated through Cornell MSC in 1965, eleven of them went on to academic positions, six to industrial jobs, and four to government laboratories. "Graduate Students Who Have Received Advanced Degrees, 1964–1965," CCMR, Box 38, Folder 20.

43. Charles F. Yost to Directors, Materials Sciences Program, IDL Universities, 23 Apr 1964; ARPA Materials Sciences, "Translation of Materials Sciences to Technology: The Problem and a Possible Solution," 7 Apr 1964, CCMR, Box 1, Folder ARPA Correspondence, Jul 63–Jun 64.

44. "Translation of Materials Sciences" (ref. 43), 3. Perhaps reflecting the general response of the academic community, the reader of the memorandum made handwritten notes in the margins, putting a question mark next to the phrase "Department of Defense needs" and noting that this was "too restricted." The person who wrote the note was most likely Henri Sack, who was the Director of Cornell MSC at the time.

the DOD had begun a project to evaluate the effectiveness of its research and development contracts in attaining new weapons systems. The result of the evaluation was dismal. According to the project's final report, basic science contributed a meager 0.3% in developing the air-to-ground tactical missile system.⁴⁵

In the latter 1960s, DOD's pressure on universities to prove relevance mounted considerably. In early 1967, for example, the Office of the Director of Defense Research and Engineering (ODDR&E) sent a memo to the Director of ARPA, entitled "High Priority Problems in the DOD Materials Programs."⁴⁶ The memo outlined the most urgent materials needs for the defense establishment and derived the technological limitations as well as the basic research required to meet them. The items listed under "Priority A" were deep submergence, low cycle fatigue, sonar and anti-sonar, thermal protection, and armor. In the area of deep submergence, for example, the memo observed that existing materials, such as high-strength steel and titanium alloy, were inadequate for operations below 15,000 feet under water. Hence, the DOD called for "improvements in reinforced plastics," which required extensive basic research in polymer chemistry, amorphous surfaces, and glass-resin interactions. While the memo did not directly mobilize scientists for mission-oriented R&D, it was certainly meant to discipline the IDLs—as participating materials scientists understood loud and clear. As MSC Director Henri Sack reported upon returning from an IDL Directors' Meeting in Washington in early 1968, ARPA's emphasis was on "'relevance' to ARPA as a user (and DOD in a wider sense)."⁴⁷

The background for ARPA's search for relevance was the gradually decreasing federal budget for research and development beginning in the second half of the 1960s.⁴⁸ Then, in 1969 came the Military Procurement Authorization Act, drafted by Senator Mike Mansfield. Later known as the Mansfield Amendment, the act banned the use of DOD budget to fund "any research or study unless such project or study has a direct and apparent relationship to a specific military function or operation." For the IDLs, this decision only

45. For an early discussion of Project Hindsight, see Karl Kreilkamp, "Hindsight and the Real World of Science Policy," *Science Studies* 1 (1971): 43–66.

46. Office of the Director of Defense Research and Engineering to Director, Advanced Projects Research Agency, "High Priority Problems in the DOD Materials Programs," 6 Feb 1967, CCMR, Box 20, Folder 8.

47. H. S. Sack to Members of Executive Committee, "IDL Directors' Meeting, Washington, D.C. January 5, 1968," CCMR, Box 20, Folder 8.

48. See, for example, George C. Wilson, "War Trims U.S. Aid to Research," *Washington Post*, 27 Nov 1967.

reinforced the trend that had already been in place since the mid-1960s. In early 1970, Robert Huggins, on leave from Stanford University to serve as Program Officer at ARPA, sent an urgent telegram to all IDL Directors requesting a “short statement on the relevance of each work unit to a specific military function or operation.” These statements were to be used by the Director of ARPA to prepare “an adequate defense to any part of the DOD program that might be single [sic] out for attack.” Huggins added that the “guiding principle” for the relevance statements should be that “length and depth must be proportional to presumed vulnerability.”⁴⁹

By the fall of that year, DOD could no longer justify continuation of the ARPA-IDL program. In 1971, Congress decided to transfer the IDL program wholesale to the NSF under a new rubric: the “Materials Research Laboratories (MRL)” program. This decision greatly relieved the IDL universities, which had feared the program would simply be wiped out. During the transition period, the NSF conducted an extensive assessment of all IDLs to ensure the program’s feasibility. While the review process was largely uneventful (none of the existing centers was axed), one question baffled the NSF reviewers: did the IDL program achieve its initial goal of fostering interdisciplinary research? As one of the reviewers openly admitted, the notion of interdisciplinarity “depends largely on the individual interpretation of the meaning of the same words as used by different people. The problem is akin to that of an American and a Russian discussing democracy.” But, he continued, the review team reached a “general consensus . . . that the extent of the interdisciplinarity resulting directly from the IDL experiment has been, at most, modest.”⁵⁰ What could have been the criteria that they used to reach this conclusion?

Within the NSF in the early 1970s, the notion of interdisciplinary research was tied inextricably—indeed, by official definition—to the issue of relevance. According to an official study of the first couple of years of the NSF-MRL program, research conducted by collaborating practitioners from multiple academic disciplines did not, by itself, qualify as “interdisciplinary research.” Rather, the defining characteristic of interdisciplinary research was that the

49. Robert Huggins, “Memo to Principal Investigators of all ARPA-supported Materials Research Programs; Implementation of Section 203 of the 1970 Military Procurement Authorization Act,” 8 Jan 1970, Materials Research Lab Records, 1949–1996, Special Collection Library, Pennsylvania State University Archives, University Park, PA, Box 2, Folder ARPA Crystal Prep. Program at Penn State.

50. “Materials Research Laboratories: Where to in Materials Research,” n.d. [1971?], CCMR, Box 5, Folder 5.

“problem determines the selection of the personnel required, whereas in other [non-interdisciplinary] research the individual’s discipline determines his problem selection.”⁵¹ That is, the NSF, like many science policy stakeholders in the Vietnam era, viewed interdisciplinary research as nearly equivalent to “problem-oriented” or “relevant” research.⁵² In the eyes of the NSF’s reviewers, the IDLs lacked interdisciplinarity not because their members did not come from multiple disciplines, but because materials research activities at the IDLs were not oriented to solving problems. Hence, NSF program officers—just like their predecessors in the ARPA program—continued to push academic materials scientists to produce more practical solutions.

A CENTER OR A FACILITY?

Thus, the NSF moved to exert its influence over the MRLs’ research agenda almost as soon as the program was transferred from ARPA. In return, the MRLs reshaped the NSF by enhancing the status of engineering science and of the “centers’ mode of support” within an organization traditionally devoted to supporting individual basic researchers in the physical and life sciences. Those shifts, in turn, facilitated the NSF’s accommodation to the legislative and executive branches’ increasing desire for applied, interdisciplinary research “relevant” to civilian “human problems” such as environmental remediation, mass transit, public housing, and biomedicine.⁵³ The intertwining of the

51. Management and Cost Analysis Staff, GCO, “Materials Research Laboratories Study, January 1974,” Office of the Historian: Agency Organizational History and Selected Backgrounds, Records of the NSF, Record Group 307, National Archives and Records Administration II, College Park, MD, Box 20, Folder Materials Research Lab. (73-74).

52. For multiple examples of administrators, faculty members, and student protestors at Stanford equating interdisciplinarity and relevance in the early 1970s, see Cyrus C. M. Mody, “Conversions: Sound and Sight, Military and Civilian,” in Trevor Pinch and Karin Bijsterveld, eds., *Oxford Handbook of Sound Studies* (New York: Oxford University Press, 2012), 224–48 and Cyrus C. M. Mody and Andrew J. Nelson, “‘A Towering Virtue of Necessity’: Computer Music at Vietnam-Era Stanford,” *Osiris* 28 (forthcoming).

53. Works that survey the turn toward civilian “relevance” include: Eric J. Vettel, *Biotech: The Countercultural Origins of an Industry* (Philadelphia: University of Pennsylvania Press, 2006); Juan C. Lucena, *Defending the Nation: Policymaking to Create Scientists and Engineers from Sputnik to the ‘War Against Terrorism’* (Lanham, MD: University Press of America, 2005); Jennifer S. Light, *From Warfare to Welfare: Defense Intellectuals and Urban Problems in Cold War America* (Baltimore: Johns Hopkins University Press, 2003); Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993).

center model and the desire for applied (or engineering) research with civilian relevance was forcefully accelerated in 1970 when the Nixon administration made a deal with the NSF to grow its total budget by \$100 million (the NSF had only asked for a \$13 million increase).⁵⁴ About half of that budgetary expansion was due to the MRLs and other programs shifted to the NSF because of the Mansfield Amendment. Most of the rest was targeted to new programs in civilian, applied research.

The NSF's budgetary inflation and new emphasis on applied research in turn reinforced the growing influence within the Foundation of academic engineering scientists. By 1970, slightly more *doctorates* were being awarded in the United States each year in engineering than in the physical sciences (and, of course, many more master's degrees), despite a downturn in engineering employment. Indeed, these academic engineering scientists were precisely the type fostered by the ARPA-IDLs in the 1960s. Leaders of the NSF's Engineering Division were eager to capitalize on that growing constituency. Thus, in 1974, the sixteen engineering program officers were each told to propose a marquee project⁵⁵ that would place the Engineering Division in the same rank as the Materials Research Division (with its new stable of MRLs) and other units (such as the Office of Polar Programs) that controlled one or more large centers or facilities.

But what sort of facility would be most likely to succeed in the NSF of the mid-1970s? Declining overall research budgets, Congressional pressure to spread the wealth over a larger geographical area, and a widespread belief that research equipment was becoming prohibitively expensive combined to create incentives to fund a facility that (unlike the original MRLs) would serve external users at least as much as local researchers.⁵⁶ Within the NSF, this national or regional "user facility" model spread in the 1970s from magnetics research to astronomy to synchrotron-based materials science and biology to biology more generally and to chemistry.⁵⁷

54. Dian Belanger, *Enabling American Innovation: Engineering and the National Science Foundation* (West Lafayette, IN: Purdue University Press, 1998).

55. Jay Harris, "It's a Small World," text of talk delivered at the twenty-fifth anniversary of the Cornell Nanofabrication Facility/NRRFSS in 2003, copy given to Cyrus Mody by Jay Harris; also, Jay H. Harris et al., "The Government Role in VLSI," in Norman G. Einspruch, ed., *VLSI Electronics: Microstructure Science*, vol. 1 (New York: Academic Press, 1981), 265–99.

56. *An Assessment of the Needs for Equipment, Instrumentation, and Facilities for University Research in Science and Engineering* (Washington, DC: National Academy of Sciences, 1971).

57. The Francis Bitter National Magnet Laboratory at MIT (FBNML) was founded in 1961 on an Air Force Office of Scientific Research grant, but was transferred to the NSF in 1971 along

Thus, the marquee project that Engineering Division leaders sought in 1974 would stretch thin budgets to serve a large, nonlocalized user base, rather than one that would coordinate a local stable of research projects (as had been the model with the original IDLs). As Charles Polk, head of the Engineering Division in 1976–1977, put it:

We have talked about a national center or several regional laboratories *where that major, expensive equipment would be available* [T]he large initial investment and the continuing support which are required could be justified only in terms of benefits to many research workers and to many different institutions. As a consequence, a national or regional laboratory, supported by NSF, would have to make very good provisions for guest workers and would have to engage permanent personnel which would help visitors with physical implementation of their ideas.⁵⁸

The center model circa 1974 differed from the IDLs circa 1960 in other ways as well. For instance, where much of the ARPA-IDL grant had paid for Cornell's physicists to build Clark Hall, federal funding agencies of the '70s were less inclined to pay for bricks and mortar:⁵⁹ money for a new building to house the

with the MRLs. See Arthur Fisher, "The Magnetism of a Shared Facility," *Mosaic* 11, no. 2 (1980): 38–45. Jay Harris claims that he had the FBNML in mind when he conceived the idea for a national microfabrication facility. Jay Harris, interview with author (Mody), San Diego, CA, 5 May 2006. W. Patrick McCray, *Giant Telescopes: Astronomical Ambition and the Promise of Technology* (Cambridge, MA: Harvard University Press, 2004) describes the fights over construction of publicly funded "national" telescopes in the '70s and '80s. Olof Hallonsten, "Small Science on Big Machines: Politics and Practices of Synchrotron Radiation Laboratories" (PhD dissertation, Lund University, 2009) offers background on the NSF's 1973 decision to fund the Stanford Synchrotron Radiation Laboratory as a "national user facility." That facility was an outgrowth of Stanford's Center for Materials Research (one of the MRLs) attached to the AEC-funded Stanford Linear Accelerator. In 1977, Berkeley's Museum of Vertebrate Zoology requested funding from the Biological Research Resources Program of NSF's Division of Environmental Biology in order to make the "Collections [available] as a National Resource." Proposal "Operational support of the regular collection of mammals in the Museum of Vertebrate Zoology," W. Z. Lidicker and J. L. Patton, 23 Nov 1977, Museum of Vertebrate Zoology archives, Berkeley, CA (courtesy of Mary Sunderland). For the adoption of the user facility concept in chemistry, see William J. Cromie, "Regional Instrumentation Centers," *Mosaic* 11, no. 2 (1980): 12–18.

58. Charles Polk, "Address to the NSF Workshop," in *Report of the NSF Workshop on Needs for a National Research and Resource Center in Submicron Structures (East Coast)*, submitted by J. N. Zemel and M. S. Chang (Philadelphia: Moore School of Electrical Engineering, University of Pennsylvania, 10 May 1976), 25–35.

59. Defense Science Board Task Force study on "Defense Requirements and University Preparedness," 19 Oct 1981, Office of the Director Subject Files, 1964–1983, Records of the NSF,

NSF Engineering Division's marquee project would have to come from other (mostly private) sources.

But what area of engineering should be served by such a facility? As with the IDLs, a perceived external threat to the United States helped boost a particular research agenda promoted by a small number of institutional entrepreneurs. This time, that threat was the rapid increase in Japanese firms' share of the microelectronics market and the Japanese government's announcement of a crash program in very large-scale integrated circuits (VLSI) in 1975.⁶⁰ The VLSI program decisively marked a new era at the NSF, and in American science policy more generally. Where the paramount goal for federally funded research in the 1950s and early 1960s had been to contribute to national defense, and the stated goal in the late 1960s and early 1970s had been to serve "national needs" for the environment, energy, and urban areas, the goals of American science policy since 1975 have largely been framed by a rhetoric of "national economic competitiveness."⁶¹

When a program officer for electrical engineering, Jay Harris, proposed that the NSF's Engineering Division sponsor a user facility in an area related to microelectronics manufacturing, therefore, his supervisors were enthusiastic. Harris's concept was a center that would make equipment available for academic researchers to fabricate microelectronic devices. His own experience at the University of Washington had taught him that academic researchers could benefit from using the expensive tools found in industry, but that

Record Group 307, National Archives and Records Administration II, College Park, MD, Box USDA to DoE, Folder Department of Defense.

60. For an overview of the VLSI program and its aftermath in Japan, see Scott Callon, *Divided Sun: MITI and the Breakdown of Japanese High-Tech Industrial Policy, 1975–1993* (Stanford, CA: Stanford University Press, 1995). We have observed elsewhere that the crises spawned by Sputnik and the Japanese VLSI program had very similar effects on research fields located at the intersection of the physical and engineering sciences. Both crises opened spaces for institutional entrepreneurs to grab resources by supplying shaken bureaucracies with visions of revolutionary research that would fend off the United States' competitors. The difference, however, is that the most urgent field of national competition had shifted from defense to commerce between 1957 and 1975. See Hyungsub Choi and Cyrus C. M. Mody, "The Long History of Molecular Electronics: Microelectronics Origins of Nanotechnology," *Social Studies of Science* 39 (2009): 11–50.

61. See Lucena, *Defending the Nation* (ref. 53) and Sheila Slaughter and Larry L. Leslie, *Academic Capitalism: Politics, Policies, and the Entrepreneurial University* (Baltimore: Johns Hopkins University Press, 1999). We are talking about shifts in emphasis and political attractiveness here. National security frames never disappeared, of course; indeed, national security research funding dwarfed non–National Institutes of Health civilian research funding throughout the period we are discussing. Moreover, national security framing for science policy has seen periodic resurgences, particularly in the mid-'80s and after 2001.

industrial colleagues, however helpful, were not able to make that equipment reliably available: “In the late ’60s and early ’70s, I used to visit various industrial laboratories to try to get some help in making small optical structures. I got my best reception at the Hughes research labs in Malibu, from a guy named Ed Wolf, who was working with electron beams, but Ed didn’t really have time to devote to supporting academics trying to work over their heads.”⁶²

Professors had to rely on industry in this way because microfabrication techniques were rapidly evolving in the early 1970s. As Wolf put it, “a very noticeable gap opened between university research on the one hand and the accomplishments of industrial laboratories on the other—a gap due mainly to the expensive equipment and the interdisciplinary nature of microstructure science and engineering that universities found difficult, if not impossible, to support.”⁶³

Changes in the technology of microfabrication were largely responsible for that gap. The dominant technique for making commercial microcircuits since about 1960 has been optical lithography: shining visible light through a “mask” (a specialized stencil or template) onto a “photoresist” (a varnish-like film that changes chemical composition when exposed to light) coated on a silicon or silicon dioxide substrate, then “etching” the resist and substrate with acid, thereby transferring the pattern on the mask into the substrate surface. Crude photolithography can be done cheaply, but by the early ’70s, various improvements were making state-of-the-art optical lithography prohibitively expensive for academic researchers. At the same time, even more expensive competitors to optical photolithography, such as X-ray photolithography and electron and ion beam lithography, were emerging. The availability of these techniques, and the professionalization of a microfabrication research community in the early ’70s, “ignited the ‘lithography wars’—a titanic struggle for supremacy among a dozen or so competing lithographic technologies, the winner [of] which was assumed would inherit the mantle of optical lithography in the manufacturing of integrated circuits.”⁶⁴

62. Harris, “Small World” (ref. 55).

63. E. D. Wolf and J. M. Ballantyne, “Research and Resource at the National Submicron Facility,” in Einspruch, ed., *VLSI Electronics* (ref. 55), 129–83.

64. Mark L. Schattenburg, “History of the ‘Three Beams’ Conference, the Birth of the Information Age, and the Era of Lithography Wars,” 2007, http://eipbn.org/2010/wp-content/uploads/2010/01/EIPBN_history.pdf (accessed 15 Dec 2011).

THREE WORKSHOPS AND A COMPETITION

Our point is that the proposal for a microfabrication facility was buoyed by trends within the NSF and American science policy circles, by the perceived external threat to the United States from Japanese microelectronics competition, and by professionalization and technological advances in microfabrication. The convergence of these trends was enough to win over the NSF administrators directly above Harris—Gene Chenette, head of the electrical engineering program; Tom Meloy, head of the Engineering Division; and Ed Creutz, head of the Math, Physics, and Engineering Directorate. Yet some members of the National Science Board (NSF’s governing body) worried that Harris’s plan for a large block grant to the university hosting the facility would attenuate the NSF’s oversight of how its money would be spent and undermine the Foundation’s traditional commitment to meritocratic, peer-reviewed awards.⁶⁵

Some members of the NSB were apparently also concerned that important external constituencies were unenthusiastic about the proposal. Department of Defense grant officers, for instance, advised that an academic microfabrication facility was unnecessary because industry drove innovation in miniaturization of electronics. Researchers at East Coast corporate powerhouses in microfabrication—especially Bell Labs—expressed similar views.⁶⁶ Robert Noyce from Intel maintained that an academic microfabrication facility would only be worthwhile as long as it “st[u]ck to the idea of working on the general concept of making small structures” while leaving *silicon* microelectronics research to firms in Silicon Valley. Harris seems to have been responsive to that argument, since “the relationship of submicron techniques to engineering and science concerns outside of VLSI [i.e., for making things other than silicon ICs] was emphasized in every presentation to the [NSB].”⁶⁷

To assuage its concerns, the NSB asked Harris to provide evidence of academic and industrial support for his proposal. Thus, Harris organized three workshops in May, 1975, at the University of Pennsylvania, University of Utah, and Washington University. Attendees were generally enthusiastic, and emphasized repeatedly the industrial relevance and economic importance of

65. Harris, “Small World” (ref. 55).

66. Harris, “Government Role” (ref. 55); also, interview with Fabian Pease, conducted by author (Mody), Palo Alto, CA, 16 Nov 2005; and comment by William Brinkman of Bell Labs in “Discussion of the Objectives, Program and Organization of the Proposed Center,” in Zemel and Chang, *Report of the NSF Workshop* (ref. 58), 36–40.

67. Harris, “Government Role” (ref. 55).

silicon microelectronics as justification for such a center. The Washington University workshop report, for instance, noted that “adding to the urgency of the need for research in the submicron domain is the effort made by our international competitors to leap-frog the U.S. technology in this field. The most noteworthy program is the Japanese decision to spend \$233 million in the next four years to develop submicron device research and fabrication capabilities with their industry-university teams.”⁶⁸

In October of 1976, the NSB gave final approval to fund a submicron facility, and by February 1, 1977 eighteen proposals had been submitted, with Cornell, Berkeley, and Lincoln Lab/MIT dominating the competition.⁶⁹ Hank Smith, a researcher at Lincoln Lab, led the proposal for a facility “under M.I.T. management in Lexington, Massachusetts, adjacent to M.I.T. Lincoln Laboratory.”⁷⁰ Tom Everhart, a professor in Berkeley’s Electrical Engineering department, led his school’s proposal, with significant input from Ed Wolf at Hughes. Joe Ballantyne, a professor in the School of Electrical Engineering, led Cornell’s proposal, with the help of fellow members of the MSC such as Art Ruoff and Boris Batterman.

The NSF review panel’s reasoning in winnowing down to these three can only be indirectly inferred. One likely consideration is that these three proposals were probably the strongest in the X-ray and e-beam lithographies deemed most likely to overthrow mainstream optical lithography. Certainly, the Cornell team believed that they and Berkeley’s Everhart were the leaders in academic e-beam lithography.⁷¹ Smith was the acknowledged pioneer of X-ray lithography, as

68. William S. C. Chang, Marcel W. Muller, Fred J. Rosenbaum, and Charles M. Wolfe, *Opportunities and Requirements for a National Center for Research on Submicron Structures* (St. Louis: Laboratory for Applied Electronic Sciences, Washington University, May 3, 1976), 5.

69. Henry Smith indicates that a joint proposal by the University of Colorado and the National Bureau of Standards also made the short list. See Henry Smith oral history, conducted by author (Mody), Cambridge, MA, 25 Oct 2005, available from the Chemical Heritage Foundation, Philadelphia, PA. It is not clear how seriously the NSF review panel took the Colorado proposal. Certainly, it seems to have largely disappeared from the memories of leading microfabrication specialists of the era—though that may be mostly due to later events. However, the Cornell team reported to their Dean of Engineering prior to submitting their proposal the scuttlebutt that “if only 1 center, will be on a coast.” “Some reasons why Cornell has a strong chance to attract such a center,” undated but probably summer, 1976, probably from Joe Ballantyne and/or Charles Lee, in CCMR, Box 29, Folder 37.

70. Henry Smith (PI), “Proposal Submitted to National Science Foundation for National Research and Resource Facility for Submicron Structures,” 1 Jul 1977; copy given to Cyrus Mody by Henry Smith.

71. CCMR, “Some reasons why” (ref. 69).

evidenced by participant histories and by the fact that he was asked to give reviews of the topic at Harris's Penn workshop and many other microfabrication conferences.⁷² The Cornell team, though, felt their X-ray expertise was in the same league as Smith's, and a Berkeley faculty member, Andrew Neureuther, gave the X-ray lithography review at Harris's Utah workshop.⁷³

Another consideration that likely played into the NSF's decision was the level of integration between the proposed facilities and other local centers, particularly the MRLs. As the Cornell team put it, "We have the strongest MRL with excellent supporting facilities (thought to be important at [the Penn] Workshop)" and "We are one of two universities in the country where significant research on E-beam lithography has been done. (The other is Berkeley and they have no MRL)."⁷⁴ MIT did have an MRL, but Smith included little interaction with the Center for Materials Science and Engineering in his proposal, other than to note that facility users could travel the thirteen miles from Lincoln Lab to the main campus to use the center's electron microscopes.

The Cornell team especially played on the MSC's tradition of interdisciplinary collaboration as a model for the microfabrication facility, claiming in their NRRFSS proposal that "A very significant feature of this MRL is that it has provided an atmosphere of cooperation among faculty members in different departments [including] electrical engineering, materials science, applied physics, physics and chemistry."⁷⁵ Even Tom Everhart later told Cornell's dean of engineering that "he perceives a constructive attitude toward interdisciplinary work at Cornell, while at Berkeley such interaction is more difficult to achieve."⁷⁶

72. H. Smith, "X-Ray Lithography," in Zemel and Chang, *Report of the NSF Workshop* (ref. 58), 7–9; Schattenburg, "History of the 'Three Beams (ref. 64);'" Henry I. Smith and R. Fabian Pease, "Reaching for the Bottom: The Evolution of EIPBN," *Journal of Vacuum Science and Technology B* 22, no. 6 (2004): 2882–84.

73. CCMR, "Some reasons why" (ref. 69); Andrew R. Neureuther, "X-Ray Lithography and Photoresist Technology," in *Needs for a National Research and Resource Center in Submicron Structures: Report on National Science Foundation Workshop Held in Salt Lake City, Utah May 21, 1976*, submitted by Richard W. Grow, Robert J. Huber, and Roland W. Ure, Jr. (Salt Lake City, UT: Microwave Device and Physical Electronics Laboratory, University of Utah, 15 Sep 1976), 30–39.

74. CCMR, "Some reasons why" (ref. 69).

75. Joseph Ballantyne et al., proposal for National Sub-Micron Facility, undated (must be Jan 1977), DOR, Box 39, Folder 14.

76. E.T. Cranch, Dean of the College of Engineering, memorandum for the record, re: "Telephone discussion with Professor T. Everhart, November 15, 1977," 16 Nov 1977, in DOR, Box 37, Folder 33. Also, interview with Tom Everhart conducted by David Brock and author (Mody), Santa Barbara, CA, 3 May 2011.

Hank Smith's proposal projected quite a few interdisciplinary applications of microfabrication, particularly in astronomy, alternative energy (fusion and solar) research, and biology; but these were only *projections*, rather than examples taken from a long institutional history.

The MSC's track record of collaboration not just among disciplines but between the Colleges of Engineering and Arts and Sciences must have been extraordinarily appealing to the NSF review panel since, as one contemporary proponent of academic microfabrication research put it, "Microstructure fabrication involves an extreme spectrum of disciplines."⁷⁷ The Cornell team also gestured to the MSC in orienting to the economic rationale for a national microfabrication facility: "We have a history of successful collaboration with industry in our semiconductor work. ([Harris' Penn] Workshop felt industrial participation was important.)"⁷⁸

Finally, the Cornell team emphasized that the MSC would serve as a seed organization for a network of campus centers, including the microfabrication facility, that would share resources and personnel. Especially prominent in the Cornell proposal were plans to establish a synchrotron user facility that could supply very bright X-rays as a lithographic beam in microfabrication. At the time, "user-dedicated synchrotron radiation facilities" were extremely rare: Stanford, Cornell, and Wisconsin were the only U.S. universities with major efforts in this area.⁷⁹ The leader of synchrotron research at Cornell (and, from 1978, director of the NSF-funded Cornell High Energy Synchrotron Source, CHESS) was Boris Batterman—a long-time member of the MSC and prominently listed in Cornell's NRRFSS proposal. The Cornell proposal may have highlighted Batterman's role to blunt Smith's advantage in the area of X-ray

77. Robert W. Keyes, proposal for Gordon Research Conference on Chemistry and Physics of Microstructure Fabrication, 3 Mar 1975, in Gordon Research Conference archives, Chemical Heritage Foundation, Philadelphia, PA, Series III – Director's Files, Box 51 (AM Cruickshank Ma-Mi), Folder Microstructure Fabrication.

78. CCMR, "Some reasons why" (ref. 69).

79. "Background paper on microelectronics and related microfabrication, microscience, and engineering," probably compiled by the Office of the Assistant Director for Mathematical and Physical Sciences, and Engineering (NSF), sent by Assistant Director James Krumhansl to Frank Press, Director of the Office of Science and Technology Policy, 30 Oct 1978, found in the in-office archives of the Stanford Center for Integrated Systems. The background paper makes clear that NSF officials saw their main contribution to VLSI and the domestic microelectronics industry's competitiveness as a function of the NSF-funded centers and user facilities: those listed include the MRLs, the three synchrotron facilities, the National Magnet Lab, the Chemistry Departmental Instrumentation Program and Regional Instrumentation Facilities, and the NRRFSS.

lithography, in that the Cornell team could claim access to much brighter X-rays than Smith could. Cornell's proposal certainly pointed to Batterman and others to indicate that the MSC was successful and well-run enough to spin off centers such as CHESS and NRRFSS that would use the MSC's equipment, personnel, and organizational model.

CREATING AN ORGANIZATIONAL FIELD

Whatever the reasons, Cornell slipped past Berkeley and (perhaps more narrowly) MIT to win the NSF competition, thereby setting off dramatic changes in the upper echelons of the microfabrication community. Initially, the decision elicited an incensed reaction from the MIT and Berkeley teams. Everhart apparently attempted to recruit Smith to Berkeley with the offer that "You come out here as a faculty member. I'll raise the money, you do the work. We'll set up our own nanofabrication facility and we'll beat the pants off of Cornell."⁸⁰ As a counteroffer, the director of Smith's division at Lincoln Lab "asked what I was going to do. So I told him that I would like to demonstrate that the NSF had made a big mistake. He says, 'Great! Let's do it.' Just like that, they gave me a million dollars."⁸¹ Lincoln Lab's "Submicron Technology Program . . . was operational by late 1977."⁸² Meanwhile, MIT offered Smith an adjunct position in order to oversee construction of a Submicron Structures Laboratory on the main campus. The SSL opened in 1978, even before Cornell's NRRFSS did. By 1980, Smith had moved into a full-time faculty position at MIT.

At Cornell, Joe Ballantyne became interim director of the facility while he recruited a permanent director. The top candidates were: Fabian Pease from Bell Labs; Ed Wolf from Hughes Research; Tom Everhart, Cornell's erstwhile rival at Berkeley; and Truman Blocker from Texas Instruments.⁸³ Wolf was hired, perhaps because (as Jay Harris's experience showed) he was used to dealing with outside users while at Hughes. Everhart, however, made enough

80. Smith oral history (ref. 69).

81. Ibid.

82. See "Materials Research: Meeting the Challenge of Microelectronics Technology," and "Faculty Profile: Henry I. Smith," *RLE Currents* 2, no. 1 (1988): 1–8 and 9–14; also Smith oral history (ref. 69).

83. EE Faculty Meeting minutes, 3 Oct 1977, forwarded to Dean E. Cranch, in DOR, Box 37, Folder 33.

of an impression that he was offered the position of Dean of Cornell's College of Engineering instead! Since the NRRFSS director reported to the Dean of Engineering, Everhart ended up advising, supervising, and aiding Wolf considerably.

Stanford, which already had an Integrated Circuits Laboratory (ICL) that exceeded anything at Cornell, Berkeley, or MIT, had not submitted a proposal for Harris's facility, largely because the ICL's director, James Meindl, did not see NSF funding as sufficiently substantial or stable.⁸⁴ The Cornell award, however, stimulated Meindl's plans to build a "Center for Integrated Systems" (CIS) incorporating a much-expanded ICL designed to outshine the NRRFSS. The rivalry between Stanford and Cornell was mitigated, however, by Meindl's presence on the NRRFSS advisory board. Other Silicon Valley luminaries, such as Gordon Moore, also served on the NRRFSS board at various times, perhaps with the aim of balancing the influence of East Coast firms such as IBM and Bell Labs.

Over the medium term, the competition for a national submicron facility led to organizational innovations at MIT, Stanford, and Cornell that were then replicated independently and (at first) rather haphazardly across many sites. What sociologists would call an "organizational field" of microfabrication began to emerge, in much the same way that the MRLs had fostered an organizational field for materials science.⁸⁵

The University of Minnesota, Rensselaer Polytechnic, Arizona State, Caltech, the University of Arkansas, Auburn, and university consortia in North Carolina and Texas all founded or dramatically expanded their microfabrication facilities between 1978 and 1984.⁸⁶

84. Interview with James Meindl conducted by Cyrus Mody, Atlanta, GA, 30 Mar 2010.

85. Paul DiMaggio and Walter W. Powell, "The Iron Cage Revisited: Institutional Isomorphism and Collective Rationality in Organizational Fields," *American Sociological Review* 48 (1983): 147–60.

86. Gregory T. Cibazar, "Microelectronics at the University of Minnesota," *Proceedings of the Tenth Annual University/Government/Industry Microelectronics Symposium* (IEEE: 1993), 170–73. Jerry R. Yeagan, "Developing a Program in Analog Electronics," *Proceedings of the Sixth Annual University/Government/Industry Microelectronics Symposium* (IEEE: 1993), 9–11. R. C. Jaeger et al., "The Alabama Microelectronics Science and Technology Center and the Microelectronics Program at Auburn University," *Proceedings of the Sixth Annual University/Government/Industry Microelectronics Symposium* (IEEE: 1993), 42–45. Other papers in the IEEE University/Government/Industry proceedings for the early '80s give a sense of the growth of the microfabrication organizational field. See also John F. Mason, "VLSI Goes to School," *IEEE Spectrum* 17, no. 11 (1980): 48–52. Dale Whittington, *High Hopes for High Tech: Microelectronics Policy in North Carolina* (Chapel Hill: University of North Carolina Press, 1985).

As this organizational field grew, each site continually looked to the others for models of how to work with industry, set charges for equipment use, foster interdisciplinary collaboration, and so on. The proposal for Texas's Microelectronics Research Center in 1983, for instance, offered comparison data for the Cornell, Stanford, MIT, North Carolina, Arizona State, and Minnesota facilities (listed in that order).⁸⁷ The Cornell, MIT, and Stanford facilities, in particular, provided not just access to tools, but also access to knowledge of how to establish and operate an organization like NRRFSS. That knowledge then fostered the propagation of the microfabrication organizational field through industry and academia, and helped maintain ties among the organizations in that field. As Joe Ballantyne reported in 1986, "NRRFSS is continually called on to help/advise other companies and universities in setting up similar laboratories Over the last several years we have advised more than forty organizations."⁸⁸

The growth of an academic microfabrication organizational field may or may not have been one of the NSF's goals when it held the NRRFSS competition. Unlike ARPA in 1960–1961, the NSF in 1975–1976 could afford to support just one facility rather than a dozen. But when the opportunity presented itself, the NSF was quick to stimulate diffusion of the microfabrication user facility form. For instance, in 1978 the Assistant Director for Mathematical and Physical Sciences and Engineering, James Krumhansl, established a Microstructures Science, Engineering, and Technology (or μ SET) program that widely touted the Cornell (and, to a lesser extent, MIT and Stanford) facilities and provided small grants to schools starting their own microfabrication facilities.⁸⁹ The NSF also encouraged Cornell to aid other schools with nascent facilities. According to the NRRFSS policy board, "A strong recommendation came out of the site review team that the facility host a meeting of microelectronics-related center directors to encourage collaborations and technology transfer. The NSF . . . has endorsed this concept

87. Ben Streetman et al., "Proposal for a Texas Microelectronics Center in the College of Engineering, The University of Texas at Austin," Mar 1983, in University of Texas Executive Vice President and Provost's Office records (collection 96-273), The Center for American History, University of Texas at Austin, Box 24, Folder Microelectronics Research Center, 1983–1984.

88. Joe Ballantyne, memo to Greg Galvin, re: Information for Frank Rhodes [president of Cornell], 11 Aug 1986, FRP, Box 160, Folder 59.

89. See, for example, the special issue of *Physics Today* on "microscience" that Krumhansl instigated, including Edward D. Wolf, "The National Submicron Facility," *Physics Today* 32, no. 11 (1979).

and will both request the facility to do so and will provide funding for such a meeting.”⁹⁰

Of course, sometimes facilities had to obtain information about their peer organizations through backchannels: for example, by phoning industry leaders to ask how their companies had been approached by rival academic facilities, or by surreptitiously obtaining prospectuses for competitors’ industrial programs and policy memos describing competing schools’ intellectual property policies.⁹¹ The leading microfabrication facilities also broadcast information about their organizational model through public channels. For instance, by 1982 the NRRFSS had appeared in some “22 magazines and 43 newspapers,” as well as televised segments on the BBC and CBS.⁹² Congress, too, took an interest. In 1979 Ed Wolf testified before a House Subcommittee on Science, Research, and Technology hearing on “Government and Innovation: University-Industry Relations.” Five years later, Cornell’s president, Frank Rhodes, was also called before the House, where he used both the MSC and the National Submicron Facility (as the NRRFSS came to be known) as examples of how to overcome the problem of access to increasingly expensive instrumentation.⁹³

Yet the Submicron Facility’s actual relations with industry and provision of access to non-Cornell users were halting at first. As Everhart noted in 1981, there was at that point “considerable difference between the expectations of the scientific community of the Submicron Facility and what was proposed to the National Science Foundation by Cornell.”⁹⁴ In large part, the first five years of the facility were taken up with hiring faculty and staff, forming committees, and experimenting with administrative procedures (such as deciding what

90. NRRFSS Policy Board, “Background Material for Topics to Be Discussed,” 17 Nov 1986, DOR, Box 39, Folder 13.

91. For instance, one of us (Mody) found several such items in the in-house archive of the Stanford Center for Integrated Systems, including: an MIT patent policy draft from May 1982, with handwritten note indicating it came “from SRC [Semiconductor Research Corporation] file” of John Linvill, director of CIS, and attached to a memo from Jim Gibbons to CIS Executive Committee, 29 Oct 1982; and a May 1989 prospectus for Hank Smith’s MIT Microsystems Technology Laboratories’ Microsystems Industrial Group program.

92. NRRFSS, “Report on the National User Research Program ’82–’85,” in DOR, Box 38, Folder 5; also E.D. Wolf, “Recent National Press Coverage of NRRFSS,” handout for NSF discussions, 7 Jan 1982, DOR, Box 37, Folder 32.

93. “Improving the Research Infrastructure at U.S. Universities and Colleges,” Hearing before the Committee on Science and Technology, US House of Representatives, 98th Congress, Second Session, 8 May 1984.

94. T.E. Everhart, memo to NRRFSS Policy Board, 25 Feb 1981, DOR, Box 39, Folder 12.

equipment to buy, what to charge Cornell and non-Cornell users for time on that equipment, and how to make decisions about what to buy and charge).

The facility's first five years were also spent raising the \$3.4 million for a state-of-the-art building. This was necessary because microfabrication had become so sophisticated that cutting-edge techniques could only achieve their full capabilities if housed in a new building with special shielding from vibration and electromagnetic interference.⁹⁵ Yet the NSF, unlike ARPA in the early '60s, was unwilling to put money into bricks and mortar. Funds for the building came from private philanthropies, especially the Pew Charitable Trust, and from an alumnus, Lester Knight, for whom the building was named. By 1985 Wolf and his team could report that the Knight Laboratory "has been used as a model by many educational institutions, government labs, and companies in the construction of research facilities for high-resolution fabrication."⁹⁶

The preoccupations of building administrative and concrete structures meant that at the end of its first five-year grant the National Submicron Facility was not yet a "national" resource. Indeed, the National Science Board made its authorization for renewal of the facility's grant dependent on submission of more detailed reports on (and greater commitment to) the Submicron Facility's user program.⁹⁷ Accordingly, the facility hired more full-time staff to help users and named a younger faculty member, Robert Buhrman, Associate Director for the User Program.⁹⁸ Under Buhrman's leadership, the user program quickly took off, until by 1986 "over 60% of the normal 40 hour work week at the facility was utilized by non-Cornell user research projects."⁹⁹

95. "A New Home for the Facility," *PROSUS* (Program on Submicrometer Structures) newsletter, Spring 1980, DOR, Box 32, Folder 19.

96. [Author unknown], "The Role of NRRFSS" ["a report prepared for Cornell University President Frank H.T. Rhodes describing the past accomplishments of NRRFSS"], DOR, Box 39, Folder 16.

97. Ronald Gutman [NSF Program Director for Solid State and Microstructures Engineering] to Ed Wolf, Jul 1982, DOR, Box 39, Folder 15.

98. NRRFSS, "Report on User Program" (ref. 92).

99. E. D. Wolf et al., "Proposal for National Nanofabrication Facility at Cornell University," Aug 1986, DOR, Box 39, Folder 15. It should be noted, however, that the next sentence of the proposal states that "the resources of the NRRFSS are available 24 hours a day, 365 days a year to trained users." It's likely, therefore, that the 60% figure overstates the proportion of non-Cornell users. Non-Cornell visitors would depend on assistance from facility personnel—present during normal working hours—for a much greater proportion of their time in Ithaca than Cornell users. Thus, Cornell graduate students would probably have found it much easier to use the facility's equipment during off-hours, and therefore likely took up much more than 40% of total user time.

FIG. 3. Cornell's Engineering Quad, circa 1984. The Knight Laboratory, specially constructed for the National Submicron Facility, is the building with the Greek mu (for μm or micrometer) painted on its roof. The Knight Laboratory was attached to Phillips Hall, home of the School of Electrical Engineering; Phillips Hall is seen toward the bottom of the map in Figure 2. *Source:* Gladys McConkey and Hillary Retzig, eds., *Submicron Research: Investigations at Cornell University in the National Submicron Facility* (Ithaca, NY: College of Engineering, Cornell University, 1984).

Most of those nonlocal users were from other universities, but by 1985 12% of users came from industry and 7% from government labs.¹⁰⁰ By 1986, the facility had enrolled some thirty-seven companies in its industrial affiliates program. These companies paid, at least at the beginning of the program, a mere \$8500 per year— compared to the Stanford CIS's industrial sponsors, each of which put in \$250,000 per year for three years, followed by \$120,000 annually after that.¹⁰¹ That difference is presumably an indication of Ithaca's geographic and social distance from the center of the American

100. NRRFSS, "Report on User Program" (ref. 92).

101. Cornell University News Bureau news release, "Background: Visiting Scientists, Industrial Affiliates Participate in National Research and Resource Facility for Submicron Structures," Oct 1981, DOR, Box 37, Folder 32; Stanford Center for Integrated Systems Industrial Sponsors Advisory Committee draft report, 16 Sep 1988, CIS in-house archive. Note, though, that there were less than half as many CIS sponsors, and that only a fraction of CIS sponsorship funds went to the Integrated Circuits Laboratory.

microelectronics industry. Yet despite that distance, the facility built up a thick web of industrial ties. In 1986, Joe Ballantyne could report that “No one has yet told me that another school does a better job of industrial interactions than Cornell. We have active collaborative research with industry directly in the facility (e.g. AT&T Bell Laboratories, McDonnell Douglas and General Electric) and the largest source of support for the projects utilizing NRRFSS is industrial grants/contracts.”¹⁰²

CENTERS ASCENDANT

Whether or not the MSC and NRRFSS paid their hoped-for dividends to the nation, by 1985 they were clearly benefiting Cornell’s ability to acquire further interdisciplinary centers. As Roger Segelken, a Cornell public relations officer, put it that year in describing how the school won NSF funding for its Theory Center (a supercomputing facility):

We prepared a background piece saying that “Cornell University is a promising location for a national, advanced scientific computing center because of its experience in operating highly successful interdisciplinary centers for the benefit of the scientific research community.” And we took the opportunity to brag about the Cornell Manufacturing Engineering and Productivity Program (COMEPP) and the Cornell High Energy Synchrotron Source (CHESS) and the Materials Science Center and the National Research and Resource Facility for Submicron Structures (which spells NRRFSS) and the Cornell Biotechnology Institute and the Semiconductor Research Corporation Center of Excellence in Microscience and Technology.¹⁰³

Indeed, in the mid-80s, the proliferation of Cornell centers led to “growing concern at NSF, which may underlie [NSF Director] Erich Bloch’s longstanding complaint about the Submicron Facility, that too much NSF money is going to New York State and particularly to Cornell.”¹⁰⁴

102. Ballantyne memo to Galvin (ref. 88).

103. Roger Segelken, “A Case History of a Computer Media Event—Introducing a Super-computer Center,” *Proceedings of the Fourth International Conference on Systems Documentation* (New York: ACM, 1985), 146–60.

104. John F. Burness, Vice President for University Relations, to Frank Rhodes, President of Cornell, 10 Sep 1986, FRP, Box 160, Folder 59.

Yet if Cornell's success in securing funding for a growing, interconnected roster of interdisciplinary centers was one reason for Bloch's opposition to the Submicron Facility, those centers were also widely recognized as critical to Bloch's own achievements as NSF director. Bloch was installed at the NSF largely to carry out the Reagan administration's agenda of gearing American academic research more closely to the needs of high-tech industry. The vehicle for that vision that Bloch pushed through in 1984 was the Engineering Research Centers program—originally a suite of six academic facilities (currently thirteen, plus twenty-nine “graduated” ERCs) that, as Dian Belanger puts it, “addressed immediate concerns in both engineering research and engineering education—concerns articulated by both academe and industry.”¹⁰⁵

In Belanger's view, the ERCs “represented a fundamental rethinking of traditional NSF engineering activity.” Over time, they came to be viewed as such a successful program that they spawned cascades of new center programs at the NSF: e.g., the Science and Technology Centers and the Centers for Research Excellence in Science and Technology programs in 1987, the Materials Research Science and Engineering Centers (a revamped version of the MRLs) in 1994, and several smaller current center programs (e.g., Centers for Analysis and Synthesis; Centers for Chemical Innovation; Science of Learning Centers)—not to mention other interdisciplinary centers that were not part of any larger center program. Interdisciplinary centers—and especially programs spawning peer groups of centers—have become an almost instinctive mode of funding at the NSF, and of doing business on American campuses.

Bloch and the NSF owed much to the MSC and NRRFSS in establishing that orthodoxy. As the industrial members of the NRRFSS's Policy Board put it in 1986, “The National Science Foundation's investment in the Submicron Facility has enabled it to serve as a model for scientific and engineering centers nationally.”¹⁰⁶ Later that year, the head of the NSF's Engineering Directorate acknowledged that “The model of NRRFSS as a user facility role has been utilized in the planning and establishment of NSF's Regional Instrumental Laboratory program. More recently, the interdisciplinary operation of NRRFSS has provided the feasibility model for the innovative ERC

105. Belanger, *Enabling American Innovation* (ref. 54), 219.

106. Letter from the corporate members of the NRRFSS Policy Board (from Intel, IBM, Motorola, Bell Labs, and GE) to Nam Suh, NSF Assistant Director for Engineering, 16 Oct 1986, FRP, Box 160, Folder 59.

program.”¹⁰⁷ As Joe Ballantyne put it, looking back from 1999, these national programs showed that “the old MSC philosophy came to pervade Cornell and the nation.”¹⁰⁸

Cornell and the NRRFSS were, in turn, deeply affected by the entrenchment of the “‘centers’ mode of support” in ways that facilitated the emergence of nanotechnology as a national science policy priority. In the mid-1980s, the NRRFSS’s leaders desperately sought a new mission for their facility, since NSF awards last, at maximum, ten years. In 1984, they submitted a proposal to turn the facility into one of the first ERCs, but were bluntly turned down. Pressured by the facility’s industrial partners, however, the NSF the next year agreed to fund Cornell’s proposal for what it now called the “National Nanofabrication Facility” (NNF).

By the early 1990s, the NNF was again approaching the end of its award, with Stanford and MIT’s peer facilities vying to take away Cornell’s “national” status. This time, the head of NSF’s Directorate for Engineering, Joe Bordogna, decided that the time had come for greater coordination within the organizational field that had spawned around the MIT, Stanford, and Cornell facilities.¹⁰⁹ Thus, the NSF announced a competition not for a single facility, but for a “National Nanofabrication Users Network” (NNUN). Initially, Cornell and MIT joined forces for the competition; but then, probably after some signaling from the NSF, Cornell and Stanford agreed to co-lead a five-member consortium. A decade later the NNUN again hit the ten-year limit and therefore revamped and expanded as the fourteen-member National Nanotechnology Infrastructure Network, with Cornell again the lead facility and Stanford the co-leader.

In adopting the “nano” prefix, the NNF and NNUN lent weight to the arguments of federal grant officers promoting the creation of a National Nanotechnology Initiative. Conversely, by making available the tools of nanoscale research, the NNUN sites boosted their universities’ faculty members’ chances of securing NSECs and other interdisciplinary nano centers once the NNI was founded. Twelve of the fourteen NNIN campuses also have a MRSEC and/or

107. Nam Suh, NSF Assistant Director for Engineering, to National Science Board Committee on Programs and Plans, about 16 Oct 1986, re: Report on User Research at the National Research and Resource Facility for Submicron Structures, FRP, Box 160, Folder 59.

108. Ballantyne, “Centers: Collaboration, Coordination, Competition, Collegiality, Cost, and Continuity,” draft for talk at symposium in honor of Dale Corson, given to Hyungsub Choi by Ballantyne.

109. Joe Bordogna, interview with author (Mody), Philadelphia, PA, 1 May 2007.

at least one other nano center (as categorized by the NNI). Five schools (including Cornell and Stanford) have an NNIN site, a MRSEC, plus *two* other NNI-defined nano centers.

CONCLUSION: GENERALIZABILITY IN HISTORY AND SCIENCE POLICY

Our story has taken us across a half-century in time, during which successive cascades of federal centers programs have spread peer groups of interdisciplinary academic centers into every corner of the United States.¹¹⁰ Over that half-century, the interdisciplinary academic research center concept has been both durable and continually evolving. It took many years for universities and funding agencies to learn how to build and operate such centers. Those growing pains are evident in the MSC's struggles to become "relevant" to ARPA and NSF's priorities and in satisfying those agencies' definitions of interdisciplinarity, and in the NRRFSS's steep learning curve in developing an external user community.

Moreover, the problems that this organizational form has been used to solve have changed, sometimes rapidly and dramatically, since the IDL program was created after Sputnik. Successive perceived national crises have jolted academic centers and their federal funders from one goal to another: defeating communism, solving "human problems," maintaining national economic competitiveness, providing a peace dividend, defending the homeland, increasing diversity in the technical workforce, and so on. Through it all, though, the center form has maintained some continuity. The MSC still exists (though now as the Cornell Center for Materials Research), as does Clark Hall. The Knight Laboratory is gone, but only because it created the need for a much larger nanofabrication building, Duffield Hall, on the same spot. Similarly, the

110. The MRSECs and NNI-defined nano centers are located in thirty states and the District of Columbia. While our story is primarily about U.S. universities and federal agencies, the communities of researchers interacting with those institutions were transnational in scope. For a similar survey of the spread of an organizational field for materials science in France, see Pierre Teissier, "Solid-State Chemistry in France: Structures and Dynamics of a Scientific Community since World War II," *HSNS* 40, no. 2 (2010): 225–58. Similarly, the Korea Science and Engineering Foundation (KOSEF) also began its Science and Engineering Research Centers (SRC/ERC) program in 1989. KOSEF ed., *Han'gukkwahakchaedanüi palchach'wiwa saeroun toyak: Han'gukkwahakchaedan 20yönsa* [*Trajectory and New Leap Forward of KOSEF: A 20-year History of KOSEF*] (Daejeon, Korea: KOSEF, 1997) (in Korean).

NRRFSS has disappeared, but its direct descendant, the Cornell NanoScale Science & Technology Facility, now leads the NNIN.

So the stability and decentralization of the “centers’ mode of support” allow organizations such as the MSC and NRRFSS to nimbly adapt to new circumstances. No wonder, then, that the center form is so popular with both universities and their federal funders. No wonder, too, that the center form was so instrumental in a few leading universities’ adaptation to the early Cold War science policy regime. As we acknowledged in our introduction, one-off interdisciplinary academic research centers have existed for a long time. There is a deep literature on the role of such one-off centers in the emergence of a postwar military-industrial-academic complex, particularly at MIT and Stanford. From this literature, historians have learned a great deal about what other universities strove to look like as they adapted (more slowly) to postwar circumstances.

Yet much more has been written about the export of MIT and Stanford’s organizational innovations into industry and to America’s current and potential allies than about the spread of MIT and Stanford’s interdisciplinary centers to other U.S. universities.¹¹¹ For the post-Sputnik period, this article has described an important mechanism (federally funded interdisciplinary research centers programs) that stimulated multi-site adoption of centers in fields (materials science, microfabrication, and nanotechnology) where MIT and Stanford have indeed been important players. However, we have demonstrated that the “centers’ mode of support” also allowed other schools, such as Cornell, to act as the *primus inter pares* within their centers’ peer groups.

Cornell’s role in the propagation of the center concept has taken many forms. It has competed for (and usually won) awards in many successive federal centers programs. Locally, its established centers have repeatedly spun off new centers, while nationally its centers have been important models for federal agencies starting (and other universities joining) new center programs.

III. Stuart W. Leslie and Robert H. Kargon, “Selling Silicon Valley: Frederick Terman’s Model for Regional Advantage,” *Business History Review* 70 (1996): 435–72; Dong-Won Kim and Stuart W. Leslie, “Winning Markets or Winning Nobel Prizes? KAIST and the Challenges of Late Industrialization,” *Osiris*, 2nd series, 13 (1998): 154–85; Stuart W. Leslie, “Regional Disadvantage: Replicating Silicon Valley in New York’s Capital Region,” *Technology and Culture* 42, no. 2 (2001): 236–64; Stuart W. Leslie and Robert Kargon, “Exporting MIT: Science, Technology, and Nation-Building in India and Iran,” *Osiris* 21 (2006): 110–30; Ross Bassett, “Aligning India in the Cold War Era: Indian Technical Elites, the Indian Institute of Technology at Kanpur, and Computing in India and the United,” *Technology and Culture* 50, no. 4 (2009): 783–810; Margaret Pugh O’Mara, *Cities of Knowledge: Cold War Science and the Search for the Next Silicon Valley* (Princeton, NJ: Princeton University Press, 2005).

Graduates of its centers have founded or joined similar centers at many other schools. Leaders of its centers (such as Robert Sproull, James Krumhansl, and Ed Wolf) have joined federal agencies or national committees where they have overseen their centers' peer groups or guided the formation of new center programs.

Cornell is hardly unique in cultivating all of these inter- and intra-university ties among centers. We believe, however, that the web of ties from Cornell's federally supported centers to other centers is thick enough that the Cornell case can provide general insights into the changing role of U.S. universities since Sputnik. Our examination of Cornell's centers has particularly highlighted two significant transitions in the academic sector of national science policy. The first entailed the sudden civilianization of large portions of federally funded university research around 1970, and enhanced status for civilian agencies such as NSF and NIH going forward. The second, which accelerated in earnest in 1975, increasingly shifted universities' focus toward the market and fostered a wide variety of new forms of university-industry partnership. As we have tried to show, both these transitions were viewed as significant departures at the time, and both occasioned much anxiety and hasty improvisation at Cornell and elsewhere.

Yet neither of these transitions should be seen as an "epochal break" in which past practices were disowned.¹¹² In both cases, the high Cold War provided explicit precedents that made the transition easier. Both ARPA and NSF, for instance, used the language of "relevance" in pushing the MSC to pursue a more problem-oriented form of interdisciplinarity. Similarly, Cornell's NRRFSS proposal touted the MSC's high Cold War, ARPA-guided coupling with industry in making the case that Cornell could aid American semiconductor firms in the post-VLSI era. If the Cornell case is at all generalizable, it may indeed be true that today's academic research is "postmodern" in its orientation to technological and commercial applications; but if so, it is only because American universities have been postmodern for a very long time.

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112. Alfred Nordmann, Hans Radder, and Gregor Schiemann, eds., *Science Transformed? Debating Claims of an Epochal Break* (Pittsburgh, PA: Pittsburgh University Press, 2011).

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