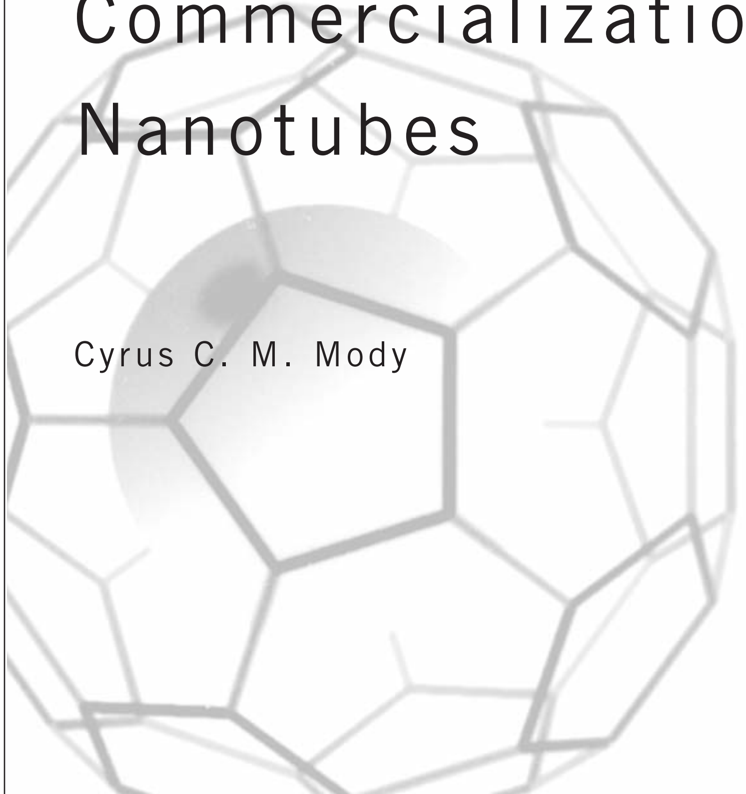
Studies in Materials Innovation

Center for
Contemporary
History and Policy

Institutions as Stepping-Stones:
Rick Smalley and the Commercialization of Nanotubes



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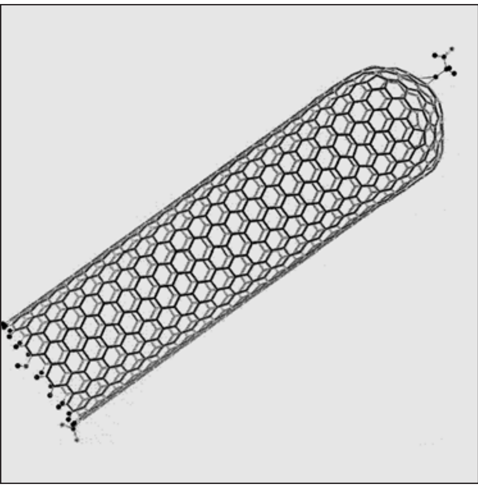

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For information about the Chemical Heritage Foundation, its Center for Contemporary History and Policy, and its publications, write

Chemical Heritage Foundation
315 Chestnut Street
Philadelphia, PA 19106-2702, USA
Fax: (215) 925-1954
www.chemheritage.org

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STUDIES IN MATERIALS INNOVATION SERIES

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I. INTRODUCTION: WHY DO STAR SCIENTISTS MATTER?

The creation of the biotechnology industry in the 1970s brought a new feature to materials-based innovation: small, high-tech firms started by (or linked closely to) prominent academic scientists. Though there is a very long history of professors starting or consulting with science-based firms, the patenting of recombinant-DNA research by Herbert Boyer of University of California, San Francisco, and Stanley Cohen of Stanford University in 1980 marked a new, self-conscious era of professorial start-ups.[1] With Boyer and Cohen's patent the venture-capital industry expanded out of its most successful niche—funding spin-off firms from established semiconductor companies—and into financing professorial start-ups. Academic researchers, many initially ambivalent about commercial ventures, eagerly founded companies once they saw the fortune Boyer reaped in the initial public offering of Genentech. Legislation (most notably the Bayh-Dole Act) quickly passed to facilitate further academic start-ups.[2] And regional economic-development offices in the United States and the world began cultivating clusters of professorial start-ups in the hopes of eventually rivaling Boston and the San Francisco Bay Area.[3]

Economists, sociologists, policy makers, and scientists themselves have struggled to understand what precisely made the biotech industry possible and whether lessons from that industry can be applied to new waves of materials innovation. Studies of biotechnology have focused on the role of social networks,[4] the likelihood of new regional clusters forming,[5] the effect of patenting on academic research,[6] and the relative importance of tacit and formal knowledge in commercialization.[7]

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[1] Sally Smith-Hughes, "Making Dollars out of DNA: The First Major Patent in Biotechnology and the Commercialization of Molecular Biology, 1974–1980," *Isis* 92 (2001), 541–575.

[2] But see David C. Mowery et al., "The Growth of Patenting and Licensing by U.S. Universities: An Assessment of the Effects of the Bayh-Dole Act of 1980," *Research Policy* 30 (2001), 99–119. This article shows that Bayh-Dole had little effect on either the rate or quality of patents from U.S. academic institutions despite a great deal of fanfare to the contrary.

[3] But see Joseph Cortright and Heike Mayer, *Signs of Life: The Growth of Biotechnology in the U.S.* (Washington, DC: Brooking Institution, 2002). Cortright and Mayer show that virtually all attempts to start a new biotech cluster will end in failure, and even those few regions that succeed will derive very little economic benefit from hosting such a cluster.

[4] Walter W. Powell, "Neither Markets nor Hierarchies: Network Forms of Organization," *Research in Organizational Behavior* 12 (1990), 295–336.

[5] Jason Owen-Smith and Walter W. Powell, "Accounting for Emergence and Novelty in Boston and Bay Area Biotechnology," in *Cluster Genesis: The Emergence of Technology Clusters and Their Implications for Government Policy,* ed. P. Braunerhjelm and M. Feldman, 61–85 (Cambridge: Cambridge University Press, 2005).

[6] Fiona Murray and S. Stern, "Do Formal Intellectual Property Rights Hinder the Free Flow of Scientific Knowledge?" *Journal of Economic Behavior and Organization* 63:4 (2007), 648–687.

[7] Kathleen Jordan and Michael Lynch, "The Sociology of a Genetic Engineering Technique: Ritual and Rationality in the Performance of the 'Plasmid Prep,' " in *The Right Tools for the Job: At Work in Twentieth-Century Life Sciences,* ed. Adele E. Clarke and Joan H. Fujimura, 77–114 (Princeton, NJ: Princeton University Press, 1992).

The latest science-based materials industry to emerge, nanotechnology, has been strongly influenced by the biotech example. Federal and state policies for nanotech aim to foster the same levels of patenting and academic commercialization seen in the life sciences. Universities and regional development offices see nanotech as a chance to make up for missed opportunities in biotech. As one official at Northwestern University put it, "Chicago and the Midwest missed the information technology boom and largely missed biotechnology, but we are not going to miss nanotechnology."[8]

Moreover, the same social scientists who developed tools for analyzing biotechnology are now applying those tools to understand nanotechnology. One result from studies of biotechnology has particularly shaped approaches to nanotechnology: Lynne Zucker and Michael Darby's finding that biotech firms that collaborated with academic "star scientists" outperformed firms with no links to a star (and, conversely, that academics who partnered with start-up companies were more likely to become "star scientists").[9] Zucker and Darby were among the first social scientists to switch from biotechnology to nano technology; the National Nanotechnology Initiative sought their advice in planning research on the "ethical, legal, and social implications" of nano; and other social scientists have taken the "star scientists" thesis as a starting point in analyzing nanotech.[10]

Zucker and Darby's findings appear to be robust with respect to the early days of the biotech industry. There is no reason to assume, however, that star scientists will play the same outsized role for nanotech. Nor is it clear that star scientists can even be *defined* in the same way for nanotech as for biotech. Most critically, Zucker and Darby's study (and most other studies that apply their findings) relies on quantitative data. Statistical analysis can demonstrate the generality of star scientists' importance, but it is a crude tool for understanding why star scientists matter.

This white paper offers a qualitative study of one nanotech star scientist, Rick Smalley, and the commercialization of his work through a start-up company, Carbon Nanotechnologies, Inc., or CNI (now part of Unidym). Tracking Smalley's career from his arrival at Rice University as an assistant professor in 1976 to his death in 2005 allows an understanding of how he gained and then used his star status. It becomes clear that some of the superficial explanations for why star scientists matter were of minimal importance in the commercialization of Smalley's research. For instance,

- except for the founders of CNI, Rice faculty and alumni had almost no affiliation with the company;

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[8] Megan Fellman, "Small Is Big," *Northwestern Winter* (2002); available at www.northwestern.edu/magazine/northwestern/winter2002/features/coverstory/index.htm (accessed 13 August 2009).

[9] Lynne G. Zucker and Michael R. Darby, "Star Scientists and Institutional Transformation: Patterns of Invention and Innovation in the Formation of the Biotechnology Industry," *Proceedings of the National Academy of Sciences* 93 (1996), 709–712; Lynne G. Zucker, Michael R. Darby, and Jeff S. Armstrong, "Commercializing Knowledge: University Science, Knowledge Capture, and Firm Performance in Biotechnology," *Management Science* 48 (2002), 139–153.

[10] Michael R. Darby and Lynne G. Zucker, "Growing by Leaps and Inches: Creative Destruction, Real Cost Reduction, and Inching Up," *Economic Inquiry* 41 (2003), 1–19; Frank T. Rothaermel and Marie Thursby, "The Nanotech versus Biotech Revolution: Sources of Productivity in Incumbent Firm Research," *Research Policy* 36 (2007), 832–849.

- Smalley had almost no say in the day-to-day operations of the company;
- once CNI was founded, Smalley's research at Rice was largely unconnected to CNI; and
- though his star power opened doors for negotiations between CNI and larger firms, practically all the resulting deals fell through.

Smalley's star status was, however, important to CNI in less obvious ways:

- Smalley convinced Rice to build on-campus institutions that gave him and CNI cofounders executive experience similar to running a start-up;
- Rice made exceptions to its traditional policies on patenting and on-campus manufacturing to prevent Smalley from leaving the university;
- Rice put Smalley in contact with a local network of donors and executives who were drawn to Smalley's star quality and supplied the early money and management for CNI;
- as a Nobel laureate for his work on a new class of materials (fullerenes), Smalley was the obvious choice to lead an influential workshop on fullerenes at the U.S. Patent Office (USPTO)—allowing CNI's framing of patent issues to become the USPTO's starting point;
- Smalley's Rice lab was a clearinghouse for the global fullerene research community; fullerene researchers routinely contacted him with results or questions, allowing him to alert CNI to promising partners or applications; and
- Smalley's academic prominence allowed him to recruit rising stars to Rice, some of whom built their own on-campus institutions, such as the Center for Biological and Environmental Nanotechnology, that partnered with CNI.

Some of these findings complement recent work in the star-scientist literature. Sociologists and management scholars are coming to realize that a scientist's "star" quality cannot be measured by article output alone. What makes stars helpful to start-up companies is also the social capital—in terms of links to wider networks that can bring in resources—that they loan to the firm. This white paper will articulate the ways a star scientist like Smalley accrued and deployed social capital and network connections to aid the start-up with which he was affiliated.

Social capital is not the whole story of Smalley's star power, however. An equally important aspect of his career in aiding CNI was that the start-up was merely the last in a series of institutions that Smalley founded or molded. Through this series of institutions Smalley and his closest aides gradually built up the administrative experience and technical know-how needed to commercialize his research. That is, this sequence of institution building allowed Smalley to ameliorate the so-called valley of death between laboratory discovery and commercialization.[11] Economists and policy makers have long noticed and worried about the challenges in taking a new, high-tech material from a stage where small academic labs and start-up firms can make small quantities for R&D purposes to a

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[11] Stephen K. Markham, "Moving Technologies from Lab to Market," *Research Technology Management* 45 (2002), 31–42.

stage where more established firms can make large quantities for commercial purposes. Small Business Innovation Research Program grants and a handful of angel investors finance early-stage start-ups, while venture capitalists prefer to wait until a firm is established enough that they have a reasonable expectation of making a profit. The handoff from angels to venture capitalists is rarely smooth, and many firms die trying to make the transition from R&D to commercial production.

This valley of death can be thought of as a dual problem of scale-up. On the one hand, production (and demand for applications) of the new material must be scaled up. Scaling up production is usually thought of as a straightforward chemical-engineering problem. Scaling up of production of the material, however, must be accompanied by proper scaling up of the organizations around it. Smalley's star power gave him leverage that forced his employer, Rice University, to give him the resources to do that dual scaling up of production and organization long before he cofounded CNI. Smalley's star power allowed him to cross some of the valley of death while still in the supportive environment of Rice. CNI was the last step in a four-phase program of institution building rather than the first leap in a perilous process of commercialization.

II. PHASE I: RICE QUANTUM INSTITUTE

Before examining Rick Smalley's career, however, we should ascertain that he really was a star scientist in the sense meant by Zucker and Darby. Qualitatively, compelling evidence of his star status would include the 1996 Nobel Prize in Chemistry (for discovery of the buckyball) as well as dozens of other awards, along with the fact that he was the only academic scientist invited to the Oval Office for the signing of the 21st Century Nanotechnology Research and Development Act. But Smalley shared the Nobel Prize with two scientists—Harold Kroto and Robert Curl, Jr.—who would not count as star scientists in Zucker and Darby's sense.[12]

Zucker and Darby define "stars" as scientists whose publication rate far outpaces the rest of their field: their original sample of biotechnologists looked at just the top 0.8 percent of genetic researchers who had produced 17.3 percent of published articles in the field. Similar metrics show that Smalley was a—if not *the*—star scientist of nanotechnology. Data on the most cited articles in nanotechnology as of 1998 show Rice University at number 6 on the list, on the strength of both Smalley's work and that of the people he recruited there.[13] By 2002 Rice had slipped to number 16—still a remarkable feat given Rice's small size (Rice is the second smallest research university in the United States). Smalley himself, however, topped the list of individual authors of the 401 most-cited articles in the nanotechnology literature.

Expectations for Smalley were high from the moment he arrived at Rice in 1976, as reflected in his meteoric rise: from assistant to associate professor in 1980, to full professor in 1981, and in 1982 to an endowed chair named after the then-president of Rice, Norman Hackerman, and his wife. Smalley was brought to Rice on the strength of his work in laser spectroscopy, an area that several Rice faculty members already specialized in. In 1979 several of these senior faculty members, primarily from the chemistry, electrical engineering, and physics departments, founded the Rice Quantum Institute (RQI) to foster interdisciplinary research in the laser-spectroscopy field. Smalley was not part of the formation of the RQI, though he was drawn in as a founding member and his work with other Rice professors was seen as a model of the kind of collaborations the RQI would foster.

For its first few years the RQI was a very low-key affair. Although individuals and small teams of RQI members were successful in gaining funding, none of the external funding proposals for the RQI as a whole were awarded. Then in 1985 a series of events changed

[12] Interestingly, Jim Heath, one of the two graduate students closely involved in the discovery of the buckyball, probably would count as a star scientist by Zucker and Darby's definition.

[13] Ronald N. Kostoff, Raymond G. Koytcheff, and Clifford G. Y. Lau, "Technical Structure of the Global Nanoscience and Nanotechnology Literature," *Journal of Nanoparticle Research* 9 (2007), 701–724.

both Smalley and the RQI dramatically. That summer Smalley, Curl (one of the founders of the RQI), and Kroto (from the University of Sussex) discovered C_{60}, the first of a class of molecules known as buckminsterfullerenes that formed the third allotrope of pure carbon (after diamond and graphite).[14]

Although full acceptance of their claims about C_{60} would only come five years later, the initial Rice-Sussex discovery was greeted with wide acclaim. Smalley's work on small clusters of other materials, especially silicon, had already established him as a rising star. Buckminsterfullerene, however, made him the kind of scientist other universities wanted to lure away from Rice. It quickly became obvious that Rice would have to build a significant program around Smalley to keep him in Houston. Action could not be taken immediately, though, because at just this point Rice's provost retired. Perhaps as a preemptive bid to keep him happy, Smalley was named the chair of the committee to find a replacement. That is, Smalley was essentially given first pick of the administrator who would directly oversee his research ambitions.

In the end this committee chose a Rice physicist, Neal Lane. Lane went on to become the director of the National Science Foundation (NSF) and then presidential science adviser in the 1990s; he was as responsible as any other government official for the founding of the National Nanotechnology Initiative. In dealing with Smalley from 1986 to 1993 Lane clearly internalized Smalley's vision for science and took it with him to Washington. When other civil servants presented him with a blueprint for American research that resembled Smalley's, Lane was able to argue passionately for it to the Clinton Administration.

By coincidence Rice also installed a new president, George Rupp, in the fall of 1985. By early 1986 the new administration of Rupp and Lane were looking for initiatives to put their personal stamp on the university. At the same time, a minor but pressing item on their agenda was the problem of keeping Smalley from going to a competing university. In the end they offered a combined solution to both issues. Rupp introduced a new initiative to create multidisciplinary research centers to "identify niches in which [Rice's] relatively small scale offers us a comparative advantage because collaboration is required from a number of departments—departments that in larger, more differentiated universities are much less likely to interact with each other."[15]

The centerpiece of this effort was to be the Rice Quantum Institute, newly transformed into a formal research center. The director of the RQI, Michael Berry, resigned, and Smalley was installed in his place. For the first time Rice appointed an executive director, a physicist named Ken Smith, to run RQI's day-to-day operations. Smith was given a budget of $70,000 (to cover half his salary and a full-time secretary) and "a permanent RQI office complex (two offices and conference room)."[16] Most important, the adminis-

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[14] For the fullerene story see Hugh Aldersey-Williams, *The Most Beautiful Molecule* (London: Aurum Press, 1995); Jim Baggott, *Perfect Symmetry: The Accidental Discovery of Buckminsterfullerene* (Oxford: Oxford University Press, 1994); and descriptions of the discovery in the Nobel lectures of Smalley, Kroto, and Curl.

[15] Michael Berryhill and Greg Kahn, "Timing a Change," *Sallyport* Dec./Jan (1992–1993), 22–26.

[16] Memo from King Walters to George Rupp and Neal Lane, 30 July 1986, "RQI Enhancement Proposal—Preface and Executive Summary," in Rice University Assistant to the President papers: Carl MacDowell, 1963–2001, Woodson Research Center, Fondren Library, Rice University, Box 24, Folder 4.

tration agreed to add five new faculty lines in the next five years (one each in physics, astronomy, mechanical engineering, chemistry, and electrical engineering) in coordination with the RQI. This addition meant that Smalley could suddenly influence hiring across a wide swath of science and engineering departments at Rice.

By 1991 Rice had hired twelve new professors into the RQI through various departments. The RQI and Smalley appear to have had real veto power over these hires. Hiring through the RQI would, it was hoped, "maximiz[e] the potential for collaborative research and creat[e] a 'critical mass' of researchers working in an interdisciplinary area."[17] But Smalley's attempts to get external funding for that critical mass, especially a 1988 proposal to the NSF's Science and Technology Centers program, were all turned down. With centerwide research funding elusive Smith and Smalley turned instead to funding RQI's educational initiatives. In 1990 they won approval to administer a Ph.D.-granting program in applied physics through RQI; and in 1992 they were awarded a million-dollar grant from the NSF to support this program.

At the same time, Smalley was drifting away from fullerene research. By 1990 he was satisfied that he had overcome all possible objections to the C_{60} model he, Kroto, and Curl had proposed. Unfortunately, it was still impossible to make more than minute quantities of C_{60}—not nearly enough to analyze using bulk characterization tools. The amount that could be learned about C_{60} seemed to be disappointingly constrained. As Bob Curl notes, so long as production of C_{60} could not be scaled up, there could be no thought of a Nobel Prize for discovering it.[18] Nor was there any chance of commercial application, even though Smalley routinely spoke of the molecule's potential as, among other things, a drug-delivery system.

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[17] Memo from Ken Smith to Neal Lane, 27 August 1991, "RQI after Five Years in Its 'Enhanced Form,'" Rice Quantum Institute information file, Woodson Research Center, Fondren Library, Rice University.
[18] Robert Curl, Jr., oral history interview conducted by the author, Houston, Texas, 29 May 2008.

III. PHASE II: CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY

So Smalley began to wind down his fullerene work and returned to the research he had been working on before C_{60}. Then in the early 1990s three discoveries convinced him to return to fullerenes and to begin scaling up institutions at Rice in order to scale up production of these materials. First, in 1990 Donald Huffman and Wolfgang Krätschmer discovered an astonishingly simple process for making larger quantities of buckyballs. Simply by running an electric arc across two graphite rods in a helium atmosphere at reduced pressure, they could make enough C_{60} to analyze with an infrared spectrometer. Suddenly, a lot more became known about buckyballs very quickly. Smalley referred to this as "C_{60}, Chapter 2" in a talk the next year.

Chapter 2, as it turned out, moved quickly away from buckyballs and toward carbon nanotubes. Both were closed cages of pure carbon, but Smalley could foresee much more interesting electrical and mechanical properties for the elongated nanotubes than for their spherical cousins. The year 1991 saw the first production of macroscopic quantities of multiwalled carbon nanotubes. Then in 1993 came the discovery of single-walled nano tubes (or SWNTs) by groups at NEC and IBM. Smalley dubbed these "the world's most perfect material" and dedicated the rest of his career to making, understanding, and applying them.

With the RQI evolving into primarily a pedagogical institution, Smalley saw a need for a new center to aid his nanotube research. Once again, as in 1985, changes in the Rice administration aided his institution-building plans. In the fall of 1992 George Rupp abruptly resigned as president of Rice. At almost the same time, Bill Clinton took office and asked Neal Lane to become director of the NSF. So, as in 1985, Rice would be starting over with new people in its top two positions. This time Smalley was put on the search committee for the new president rather than the provost. Everyone agrees that Smalley had an extremely forceful, and usually charming, personality, which he used to bend the ears of the presidential candidates to sway them to his vision for scientific research.

Not that they probably needed much persuading. As in 1986 a new administration would want to start some new initiatives to make its mark. If those initiatives were suggested by a faculty member whom the school was desperate to keep from going to another university, then all the better. When the new president, Malcolm Gillis, arrived in 1993, he was able to articulate Smalley's vision as his own within weeks. After just four months in office Gillis laid out the three areas in which he believed Rice faculty excelled, one of which was the "50 faculty members related to research in nanotechnology—science on the nanometer scale. And of course we have people like [chemistry Professor Richard] Smalley who are known all over the world."[18] After a year in office Gillis described his top four achievements; number three was "the emergence of a rapidly emerging program in nanotechnology."[20]

Not coincidentally, number four was that "last year we lost no faculty member we wished to keep. Many other universities came calling, the likes of Princeton and Berkeley, for example, and Stanford and Ohio State and others. But they walked away empty-handed." Princeton and Berkeley were two of the schools that had made significant offers to Smalley in that year. As Bob Curl notes, by the early 1990s Smalley was receiving as much in salary and research funding as Rice—or almost any other university—would pay. So when other universities tried to lure him away, he had to use that leverage with Rice to accrue other kinds of resources. In particular, he convinced Rice to expand the institutions over which he had influence in order to let him direct a coordinated research program encompassing, by one estimate, a quarter of Rice's faculty in science and engineering.

As the quotes above indicate, the focus of that research program would be in nanotechnology. Over the course of the early 1990s, just as the term *nanotube* was becoming current, Smalley was repeatedly exposed to arguments that "nanotechnology," or science at the nanometer scale, would be the next big research wave. By September 1992 he had internalized those arguments enough to refer to his own work as "fullerene nanotechnology." By mid-1993 Smalley was testifying to Congress about "how [he planned] to build on [his] success with 'buckyballs' to work toward practical, useful nanotechnology."[21]

"Nanotechnology" gave Smalley a way not only to frame institution building at Rice to aid his own research but also to appeal to a larger constituency than just fullerene researchers. At this point Smalley still did not have the clout to build an institution that would solely specialize in carbon nanotubes, but "nanotechnology" gave him an organizing principle by which he could portray nanotube research as one strand of a new cutting-edge field. Smalley therefore proposed that Rice build a new Center for Nanoscale Science and Technology (CNST), which he would direct. Ken Smith, executive director of RQI, would now also be executive director of the CNST. Just as in 1986 there would be a new round of faculty hiring—a dozen tenure-track positions—over which Smalley would have considerable influence.[22] Smalley also demanded a new building to house the CNST. Malcolm Gillis, then moving Rice into a capital campaign, agreed largely because he estimated that Smalley could be used to elicit as much as $50 million in donations. A headline from the *Houston Chronicle* from November 1993 put it concisely: "New Building to Keep Rice Up with Science and Prof on Campus."[23]

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[19] Melissa Williams, "President in Full Swing after 1st Months in Office," *Rice Thresher*, 17 Sept. 1993. Words in brackets in original.

[20] Michael Cinelli, "Issues and Answers/Looking Back on an Inaugural Year," *Rice News*, 30 June 1994, 8.

[21] Letter from Radford Byerly, Jr. (chief of staff, U.S. House of Representatives, Committee on Science, Space, and Technology) to Rick Smalley, 1 Mar. 1993, Richard Smalley Papers, 1990–1998, MS#490, Woodson Research Center, Fondren Library, Rice University, Box 2, Folder 49.

[22] Michael Cinelli and Lia Unrau, "Rice's Interdisciplinary Science Centers: A Reporter's Resource," 5 Nov. 1996, Lia Unrau science news research files, 1992–2001, MS #072, Woodson Research Center, Fondren Library, Rice University, Box 1, Folder 17.

[23] Todd Ackerman, "New Building to Keep Rice Up with Science and Prof on Campus," *Houston Chronicle*, 11 Nov. 1993, 38A.

Once the CNST was formed and its home built, Smalley began using its resources to develop new ways to scale up production of carbon nanotubes. He had two objectives in mind: to make more single-walled tubes available to researchers, and to inch toward founding a company to commercialize his research. These objectives would be intermingled: Smalley hoped that once researchers did not have to worry about making their own nanotubes, they would be free to develop applications that Smalley's company could commercialize. In 1998 he and Ken Smith formed an entity called Tubes@Rice to manufacture SWNTs to sell to researchers worldwide. This enterprise was run out of the CNST and sold tubes for two thousand dollars per gram—relatively cheap at the time and only enough to break even or post a slight loss.

Tubes@Rice appeared on Rice's books as a service center—the equivalent of a copy center or a machine shop. Yet its service was only indirectly to Rice: the tubes were almost all going off-campus. In part, this explains why Tubes@Rice sold its product at a loss: legally, it could not be a profit-making entity.[24] Yet even had the legal bar not existed, profit was not the point. Tubes@Rice was designed primarily to increase the number of nanotube researchers. It was also meant to carry commercially useful information about applications back to Smalley's ears, since buyers had to give some indication of what they planned to use the tubes for.

While Tubes@Rice was not an unheard-of venture for Rice, it certainly constituted a bending of the rules. For one thing selling a chemical with unknown properties, even at a loss, put the university at a liability risk. More important, the formation of Tubes@Rice was accompanied by levels of patenting that were new to the university. Smalley and Smith designed Tubes@Rice as a stepping-stone to the formation of a start-up company, but they knew that when they formed that company, it would need a strong intellectual-property portfolio. Rice, however, had no technology-transfer office and traditionally very low levels of patenting. In 1994, for instance, the university had estimated that its intellectual-property needs would be met with an annual target of two to three new patents.[25]

To overcome this obstacle Smalley used his star status—now greatly enhanced by the 1996 Nobel Prize—to pressure Rice into building an infrastructure for faculty patenting. In 1998 Rice brought in consultants to help it make the "transition from a 'behind the hedges' ivory-tower institution to one that is outward looking and research oriented" by advising on how to set up a technology transfer office.[26] The consultants also suggested that Rice organize a seven-member Patents Committee—to which Rice promptly

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[24] Memo from Jordan Konisky to Malcolm Gillis, "Tubes@Rice," 3 Mar. 1998, Rice University President's Office Records: President Malcolm Gillis, 1993–2004, Rice University Archives, Woodson Research Center, Fondren Library, Rice University, Box 155, Folder 4. Also, Ken Smith, interview with the author, Houston, Texas, 6 June 2008.

[25] Memo from Arun Jain to Malcolm Gillis et al., "Discussion on Technology Transfer on 2/1/94," 14 Feb. 1994, Rice University Assistant to the President papers: Carl MacDowell, 1963–2001, Woodson Research Center, Fondren Library, Rice University, Box 135, Folder 2.

[26] Edward E. David and Frank Press, "Report to Malcolm Gillis by WAG Concerning Technology Transfer at Rice University," 6 Jan. 1998, Rice University Assistant to the President papers: Carl MacDowell, 1963–2001, Woodson Research Center, Fondren Library, Rice University, Box 135, Folder 2.

appointed Daniel Colbert, a Smalley postdoc who was already planning to cofound Carbon Nanotechnologies, Inc. (CNI), with Smalley and Smith.[27]

Having a Smalley representative on the committee made sense, given the outsized contribution of Smalley's group. A 2000 review of the Rice Office of Technology Transfer's activities, for instance, broke patent applications into three categories: "U.S.," "Foreign," and "Smalley Research." The review found that Smalley's group accounted for seven of the forty-seven patent applications filed by Rice that year.[28] To help him achieve that pace, Smalley used his leverage to get Rice to provide help not available to his colleagues. Rice engaged Baker and Botts, a law firm long tied to the university, to shepherd the patents CNI would need to license through the long patenting process.

Baker and Botts is a high-end firm, and Rice worried about the cost of its services. By the end of 1997 Rice was estimating that the legal fees for inventions Smalley had made up to that point would cost $70,000.[29] This amount seems to have been an unavoidable consequence of Smalley's demands that Baker and Botts assign his patent portfolio to Rodger Tate, a lawyer based in Washington, D.C., *and* that it send someone to meet with Smalley every two weeks *and* have someone in the Houston office familiar with nanotube research who could meet with Smalley on less than a day's notice.[30]

Smalley's case sheds new light on an urgent policy question: why (and when) do faculty members patent their research? One widely held view has been that the removal of legal barriers (e.g., through the Bayh-Dole Act) would stimulate widespread patenting. As noted above, though, Bayh-Dole seems to have had a very small effect on academic patenting; certainly Smalley only began patenting in the early 1990s, some ten years after Bayh-Dole and five years after the (clearly patentable) discovery of buckminsterfullerene. More sophisticated analyses have pointed out that scientists can be stimulated to patent by rapid movement in their research field.[31] This theory holds well for Smalley's dramatically increased rate of patenting in the wake of the discovery of single-walled nanotubes. However, Smalley had been involved in rapidly moving and potentially commercializable fields before, without being moved to patent.

A possible explanation for why Smalley began patenting in the early 1990s but not before comes from work by Jason Owen-Smith and Walter Powell.[32] They show that rates of academic patenting are strongly influenced by the character of a professor's home university's technology-transfer apparatus. If the local technology-transfer office is perceived as

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27 E-mail from Daryl Boudreaux to Malcolm Gillis et al., "Brief Update to IP Advisory Board," 17 Sept. 1999, Rice University President's Office Records: President Malcolm Gillis, 1993–2004, Rice University, Box 144, Folder 5.

28 Office of Technology Transfer, "Activity and Financial Summary," 12 Oct. 2000, Rice University President's Office Records: President Malcolm Gillis, 1993–2004, Rice University, Box 144, Folder 5.

29 Memo from Shirley Redwine to Rick Smalley, "Work Schedule and Budget for Legal Fees," 14 Nov. 1997, Rice University Assistant to the President papers: Carl MacDowell, 1963–2001, Woodson Research Center, Fondren Library, Rice University, Box 21, Folder 4.

30 Memo from Shirley Redwine to Rodger Tate and Charles Szalkowski, "Meeting Regarding Patent Representation," 8 Sept. 1997, Rice University Assistant to the President papers: Carl MacDowell, 1963–2001, Woodson Research Center, Fondren Library, Rice University, Box 21, Folder 4.

31 Pierre Azoulay, Waverly Ding, and Toby Stuart, "The Determinants of Faculty Patenting Behavior: Demographics or Opportunities?" *Journal of Economic Behavior and Organization* 63 (2007), 599–623.

32 Jason Owen-Smith and Walter W. Powell, "To Patent or Not: Faculty Decisions and Institutional Success at Technology Transfer," *Journal of Technology Transfer* 26 (2001), 99–114.

competent and unobtrusive and the university administration seen as encouraging to entrepreneurship, then faculty members will patent at a higher rate. Conversely, if faculty members see patenting as a thankless and time-intensive process, they will avoid it. What should be added to Powell and Owen-Smith's analysis, though, is the observation that academic star scientists have the ability to shape this patenting environment. Rice had virtually no patenting capacity before Smalley and a few other stars demanded that a technology-transfer office be set up; when they did, they created an environment where all Rice faculty members saw patenting as an easier, more rewarded activity.

IV. PHASE III: THE CENTER FOR CARBON NANOTECHNOLOGY LABORATORY AND THE CENTER FOR BIOLOGICAL AND ENVIRONMENTAL NANOTECHNOLOGY

Why would Rice go to such lengths to help Smalley patent his research and prepare to form a start-up company? As Timothy Lenoir has written, successful universities see little profit in licensing their patents to their professors' start-ups.[33] Instead, they see start-ups as a way to raise the stature and morale of star scientists who also bring in large amounts of federal funding, from which the university can skim healthy percentages in overhead costs. Smalley was no exception. Even as Tubes@Rice was growing, he was working to get CNST what the RQI had lacked—centerwide federal research funding.

Smalley's first tack was to use his star power to get increased funding for nanotechnology (and specifically fullerene) research at all American universities, on the theory that Rice, as a leader in the field, would benefit disproportionately. Thus, when he was invited to the White House along with the other American Nobel laureates for 1996, Smalley launched a coordinated campaign of letters and visits to the U.S. Navy, NSF, the Department of Energy, the Department of Commerce, the White House, and the Texas congressional delegation, calling for a "strategic program" for "development of fullerene fibers and cable."[34] Because of this campaign Smalley was called to testify before both houses of Congress on behalf of a potential National Nanotechnology Initiative, and he also joined the President's Committee of Advisers on Science and Technology panel on nanotechnology that molded the initiative.

Smalley also began using his star power to recruit other star scientists to join him in forming multi-university collaborations. This recruitment initially succeeded because Smalley had a major new discovery that would allow him and his collaborators to scale up their fullerene research. The laser-oven process, invented in 1995, took the research community from (as one of Smalley's Rice colleagues puts it) " 'no' availability of high-quality" single-walled nanotubes to "very low availability."[35] Then, three years later

[33] Timothy Lenoir, "Inventing the Entrepreneurial University: Stanford and the Co-Evolution of Silicon Valley," in *Building Technology Transfer within Research Universities*, ed. Thomas J. Allen and Rory O'Shea (Cambridge: Cambridge University Press, forthcoming).

[34] Letter from Rick Smalley to Fred E. Saalfeld (Office of Naval Research—copied to other Office of Naval Research officers) referencing similar letter to Neal Lane (NSF—copied to other NSF officers), 18 Nov. 1996, Richard E. Smalley Papers, Chemical Heritage Foundation Collections, Chemical Heritage Foundation, Box 57, Folder 5.

[35] Micah Green, lecture to Nanotechnology: Content and Context class, 30 Sept. 2008, Rice University, Houston, Texas.

Smalley's group followed up with the high-pressure carbon monoxide (HiPco) process, which produced "high quality [single-walled nanotubes at] high yield, high rate."

With the invention of the laser-oven process Smalley began inviting other star scientists to form a Center for Carbon Nanotechnology (or CCN), to be funded through the NSF's Science and Technology Centers program. Initially, this center would have encompassed just Rice and Harvard universities, through Charles Lieber and George Whitesides (number 2 and number 6 in the list of authors of the most-cited nanotechnology papers).[36] With the cheaper, higher-volume HiPco process, Smalley felt confident enough to extend the collaboration to include nine universities, two government labs, and four corporate research labs.[37] Notably, Ken Smith and Dan Colbert would have been the codirectors of the CCN. Since Smalley, Smith, and Colbert were already planning to start a company to commercialize the HiPco process and applications of single-walled tubes, it is not surprising that the program of the proposed center consisted of four research areas that would complement their company's work: one area in new growth technologies for single-walled tubes (led by Smalley), and three in new applications of tubes ("nano-materials," "nano-electronics," and "nano-probes and sensors").

By early 1999 Smalley had secured a million-dollar-a-year grant from the National Aeronautics and Space Administration to support Rice's portion of the CCN. He had also won a site visit for the NSF to review the CCN proposal. By the time of the site visit, however, Smalley had been diagnosed with leukemia and was unable to attend. According to Ken Smith this was the *sub rosa* reason given by the NSF for denying Rice's center—the NSF being reluctant to fund a proposal centered so strongly on a scientist in such ill health. It is probably impossible to ascertain whether this was actually the NSF's reasoning. It is clear, however, that the NSF review committee was reluctant to see Smalley take on the major administrative challenge of running a center. As the reviewers put it, "If funded, the organizational and managerial responsibilities imposed on the extremely creative principal investigator could actually inhibit his fruitful scientific contributions."[38]

Whatever the reason, the message—as perceived at Rice—was that the NSF was willing to give the university a center only if Smalley's contribution did not unduly take him away from his science and if other scientists were more deeply involved. Thus, over the next two years Smalley began championing a new proposal for a Center for Biological and Environmental Nanotechnology (CBEN). This concept had begun with two of the faculty he had helped hire, Vicki Colvin and Mark Wiesner, and was Rice's entry for the NSF's new Nanoscale Science and Engineering Centers competition, a program fashioned partly on the model of the CNST and started partly as a result of Smalley's lobbying for a National Nanotechnology Initiative.

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[36] Letter from Rick Smalley to Charles Lieber and George Whitesides, 4 Dec. 1996, Richard E. Smalley Papers, Chemical Heritage Foundation Collections, Chemical Heritage Foundation, Box 57, Folder 5.

[37] Rick Smalley et al., "Center for Carbon Nanotechnology: An NSF Science and Technology Center," before 30 Nov. 1998, Rice University Assistant to the President papers: Carl MacDowell, 1963–2001, Woodson Research Center, Fondren Library, Rice University, Box 22, Folder 2.

[38] Report from the NSF to Rick Smalley, "Panel Summary," before 30 Nov. 1998, Rice University President's Office Records: President Malcolm Gillis, 1993–2004, Rice University Archives, Woodson Research Center, Fondren Library, , Rice University, Box 102, Folder 5.

V. PHASE IV: CARBON NANOTECHNOLOGIES, INC.

The CBEN proposal succeeded in bringing in an initial $10.5 million in NSF funding, starting in 2001. Smalley spent the next few years, until his death in 2005, concentrating on the new center. However, in the wake of the failure of the CCN, Smalley had already set in motion the formation of a start-up company, Carbon Nanotechnologies, Inc (CNI). Smalley shaped CBEN to aid CNI: CBEN research would focus on getting nanoparticles "from testing to commercialization." It would "broaden the applications of a field" while "address[ing] non-technical roadblocks to growth." It would ally with various industrial affiliates and try to push its research down an "entrepreneurship 'pipeline.' "[39] Thus, Smalley's institution building within Rice fully complemented his commercialization activities outside the university.

This picture of the links between Smalley's intramural and extramural networks complements and extends recent work on star scientists by management scholars. Fiona Murray, for instance, has shown that star scientists aid firms by proffering not just human capital (primarily technical know-how) but also social capital (a network of associates that acts as a conduit for resources). She further subdivides the contribution of social capital into stars' connections to a "laboratory network" (current and former students, postdocs, technicians, and advisers) and a "cosmopolitan network" (collaborators, competitors, and peers).[40] Smalley's case shows that there is perhaps a third kind of social capital that he brought to CNI—his "institutional network" of people associated with Rice who owed him various debts, were persuaded by his charisma, or wished to prevent his leaving the university.

By 1999 Smalley had the science and the intellectual property he needed to start a company. The two major things he lacked were money and personnel. His star power—and the leverage over Rice that it gave him—were critical to acquiring both. Two key personnel—cofounders Colbert and Smith—had both acquired extensive knowledge useful in a start-up while working for Smalley at Rice. Colbert had been a member of the Rice Patents Committee and was intimately involved in the patenting of Smalley's nanotube research. Smith had for thirteen years been executive director of the RQI and CNST—a job not dissimilar to that of a chief science officer or chief operating officer at a high-tech start-up. Next, Smalley found financing and a CEO for CNI through a lunch organized

[39] Slides for presentation on Center for Biological and Environmental Nanotechnology, no date, Richard E. Smalley Papers, Chemical Heritage Foundation Collections, Chemical Heritage Foundation, Box 36, Folder 22. Also Elise McCarthy and Christopher Kelty, "Responsibility in Nanotechnology," unpublished draft.

[40] Fiona Murray, "The Role of Academic Inventors in Entrepreneurial Firms: Sharing the Laboratory Life," *Research Policy* 33 (2004), 643–659.

by Paul Howell, the donor who endowed Smalley's chair in 1982. There, Smalley met Robert (Bob) Gower, a former CEO of Lyondell Chemical, who agreed to become CNI's CEO and largest initial investor.[41] Over the next couple of years Gower was the conduit for more money from so-called Friends of Bob.

Initially, the CNI team believed two related things about nanotube supply and demand: 1) that scale-up of their manufacturing process would be easy and they would soon be producing tons of tubes a day at very low cost; and 2) the richest markets for their product would be those requiring extremely large numbers of nanotubes. Smalley spoke of using SWNTs to replace and expand transmission lines in the world's power grids and of eventually using SWNTs to build a space elevator from the earth to geosynchronous orbit. Gower foresaw a market in using SWNT additives to make plastics electrically conducting. This application would not require many SWNTs per pound of plastic, but since it would allow plastics to replace metals in an even wider array of settings than they already do, total production of SWNTs would be very large.[42]

Over the next few years, though, these two beliefs co-evolved in a more minimalist direction. Each manufacturing process that CNI tried either would not scale up or would scale up, but without any economies of scale. The price per pound stubbornly refused to drop in the way the principals had hoped. At the same time, the applications dependent on such mass production never materialized. Instead, CNI found potential markets in very low-volume applications. For most applications, such as conductive plastics or field emitters for flat-screen televisions, it slowly became clear that for the moment SWNTs offered only marginal, and costly, improvement over other materials, such as carbon black and liquid crystals. Thus, CNI's only partnerships that went to market were in industries where marginal improvement is important even at high cost. For instance, the company's most successful product thus far has been an electrically conductive plastic wafer tray produced by Entegris for the semiconductor industry—an industry willing to pay almost any price to inch a little bit farther down Moore's curve.[43]

As Smalley's health declined, he had fewer interactions with the company. Still, CNI found ways to leverage his star status. For instance, the National Nanotechnology Initiative asked him to teach two day-long, well-attended courses for the USPTO on nano tube chemistry to clue patent examiners into the basics of single-walled nanotubes, thereby smoothing CNI's relations with that office. CNI also occasionally brought Smalley in for meetings with potential partners, though almost all those partnerships foundered. Further, Smalley visited CNI regularly (the start-up's offices were just a twenty-minute drive from Rice) to help CNI work through problems while also acting as a clearinghouse for information from all over the nanotube community. Indeed, CNI's partnership with Entegris came about when an Entegris researcher contacted Smalley for scientific advice.[44]

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[41] Bob Gower, interview with the author, Houston, Texas, 9 June 2008.

[42] Ibid.; Ken Smith, interview with the author, Houston, Texas, 6 June 2008.

[43] David Karohl, lecture to Nanotechnology: Content and Context class, 18 Sept. 2008, Rice University.

[44] Ken McElrath, interview with the author, Houston, Texas, 19 June 2008.

Curiously, the star-scientist advantage for CNI did not reside in some things that might have seemed obvious. For instance, few Rice people came to CNI, and almost none from Smalley's lab; the company's greatest need was for chemical engineers to help scale up, most of whom came from various chemical companies. Even the nanotube researchers CNI hired came from places like Georgia Tech rather than Rice. Smalley also did not play much of a role in management of the company or even in its strategic or research direction. This lack of involvement was planned from the beginning so that Gower would have a free hand, but Smalley's involvement became even more tenuous as his health declined. Finally, the ongoing research in Smalley's lab was not closely tied to CNI's research: the tech transfer was mostly at the founding.

The star-scientist advantage did reside in some less intuitive relationships between CNI and Rice. First, before CNI's founding Smalley's star status pushed Rice to create two new organizations that gave both Smalley and Smith executive experience not dissimilar to running a small company. This experience was arguably more important in Smith's case because he left Rice to become an executive at CNI. Rice also felt compelled to make exceptions for Smalley in terms of patenting and allowing a quasi-commercial entity (Tubes@Rice) to operate on campus at some risk to the university. Rice also put Smalley in touch with a network of donors who were willing to invest in his company or introduce him to people like Gower who had money and executive experience. After CNI's founding Smalley's star status gave the company a way to cultivate a good relationship with the USPTO and potential partners and offered a bird's-eye view of the research community dedicated to their product.

CNI also managed to draw, somewhat indirectly, on the nano institutions Smalley left behind at Rice. The Center for Biological and Environment Nanotechnology pursued research on nanotechnology's ability both to help and harm organisms—primarily biomedical applications and toxicological consequences of a suite of nanoparticles, including single-walled nanotubes. On the "help" side, therefore, CBEN has fulfilled much of what Smalley had hoped for the proposed CCN in that it develops possible uses of carbon nanotubes that CNI can potentially take advantage of.

The "harm" side of CBEN has also benefited CNI. Rice and CNI have been major suppliers of carbon nanotubes to other universities researching the toxicological effects of nanomaterials. CBEN also attempts to influence policy through its International Council on Nanotechnology, which brings together representatives from industry, government, academia, and nongovernmental organizations. Most of the industry representatives are from big companies, but because of its local ties CNI has been the representative for smaller firms. Through that connection CNI has been better apprised of research on risks from nanomaterials than any of its competitors. It has also been better placed to spin public perception of those risks by, for instance, pushing the argument that toxicological effects of nanotubes have only been demonstrated for multiwalled tubes, not the single-walled tubes that CNI exclusively produces.

VI. FINDINGS

Rick Smalley was not a typical scientist or even a typical star scientist. The lessons we learn from looking at Smalley's career may not be transferable. Examination of Smalley and CNI can, however, offer some things to look for when economists and sociologists do try to generalize. We have seen that some of the intuitive reasons why star scientists are important do not always hold and that nonintuitive reasons sometimes do. It pays to take a closer look.

Three primary themes emerge from this story that may help explain why star scientists are key to commercialization of academic research.

1. STAR SCIENTISTS HAVE LEVERAGE OVER THEIR UNIVERSITIES THAT LESS HIGH-PROFILE SCIENTISTS DO NOT.

Universities, particularly smaller or less well-established schools, will do almost anything to keep a faculty member with the highest international reputation. Some scientists use that leverage; others do not. At Rice, Rick Smalley repeatedly used the possibility of going to Berkeley, Princeton, or Harvard to force the administration to meet his demands.

2. STAR SCIENTISTS ARE ABLE TO SHAPE THEIR INSTITUTIONAL ENVIRONMENT TO A MUCH GREATER EXTENT THAN NONSTARS.

At key junctures Rice put Rick Smalley in charge of picking the people who would ostensibly oversee his work. This act allowed him to put his vision for research at the top of their agenda. In turn, he was given considerable influence over personnel, through the RQI's and CNST's involvement in faculty hiring. He could shape the research environment at Rice, and his own collaborations, through those hires. At a national and international level Smalley was able to shape the institutional environment for nanotechnology research through membership on various committees and testimony to Congress.

3. STAR SCIENTISTS HAVE ACCESS TO MUCH MORE INFORMATION THAN NONSTARS.

Smalley's group was a clearinghouse for information about fullerenes and nanotechnology research more generally. For many years Smalley maintained and distributed a compendium of fullerene abstracts for the global fullerene community. He was also routinely invited to almost every conference or workshop dealing with fullerenes and invited to sit on almost every advisory panel dealing with nanotechnology research proposals. As the Clinton Administration formed the National Nanotechnology Initiative, Smalley was perhaps their most oft-used representative of academic science to various government panels. This web of contacts and information proved invaluable to CNI.

Two additional themes are more debatable but seem to have played a role in the commercialization of Smalley's research.

1. UNIVERSITIES ARE MORE WILLING TO BEND OR BREAK THEIR OWN RULES FOR THEIR STAR SCIENTISTS.

In this case Rice was willing to accommodate Tubes@Rice and to start a technology-transfer program largely to appease Smalley. In general, university policies are probably applied in a more preferential, less systematic way to star scientists. This treatment may have good or bad consequences. One good consequence in the Rice case is that the university's traditional stance toward intellectual property was disrupted by its accommodation of Smalley. Star scientists can break up institutional inertia and set new precedents that are more in line with the current climate.

2. STAR SCIENTISTS NEVER WORK ALONE: THEY MAY HAVE LONG-STANDING ALLIES WHO CAN AID IN THE COMMERCIALIZATION PROCESS.

Certainly Ken Smith and to a lesser extent Dan Colbert were part of Smalley's retinue long before they moved to CNI. As star scientists build institutional fiefdoms, they may rely on the same people to fill key positions over long periods. Those people accrue important skills and knowledge that may be useful to commercialization. Any future studies of star scientists should attempt to identify such retainers and explore their roles.

VII. APPENDIX

ABOUT THE ROBERT W. GORE MATERIALS INNOVATION PROJECT

Begun in 2006, the Robert W. Gore Materials Innovation Project, conducted by the Chemical Heritage Foundation's Center for Contemporary History and Policy, aims to illuminate the diverse contributions of materials innovation within the broader process of technological development in the contemporary age. Conceived as a three-year project, it documents, analyzes, and makes known the immense benefits of materials innovation through its white-paper series, Studies in Materials Innovation, and public symposia.

The Gore Innovation Project is made possible by the generous financial contribution of Robert W. Gore, chairman of W. L. Gore & Associates.

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HYUNGSUB CHOI
MANAGER OF INNOVATION AND EMERGING TECHNOLOGIES
CENTER FOR CONTEMPORARY HISTORY AND POLICY
CHEMICAL HERITAGE FOUNDATION