Corporations, Universities, and Instrumental Communities

Commercializing Probe Microscopy, 1981–1996

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December 1984. Cancun, Mexico. A beach resort thronging with refugees from winter—except in one hotel room, where a dozen people sit listening, explaining, venting frustrations. They are Heini Rohrer, co-inventor of the scanning tunneling microscope (STM), and erstwhile STMers from various universities and corporate laboratories. Almost four years earlier, Rohrer, Gerd Binnig, and Christoph Gerber got their STM working at the IBM laboratory in Zurich, Switzerland. It took a long time to recruit new STM builders, and even longer to get the recruits' instruments running. Now, things are at a breaking point. Some new STMers have been working for two years, yet none can replicate the Zurich group's great achievement: images of single atoms on a silicon surface. One by one the attendees rise, describe their machine, show some blurry images, and ask Rohrer and the others what they're doing wrong.

This story ends happily. By March of 1985, several groups achieved atomic resolution of silicon and presented spectacular images to packed crowds at the American Physical Society meeting. Within five years, these physicists, chemists, electrical engineers, and surface scientists oversaw the rapid expansion of tunneling microscopy and its proliferation into related techniques such as atomic force microscopy (AFM), magnetic force microscopy (MFM), and near-field scanning optical microscopy (NSOM)—

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known collectively as "probe microscopy." Today, there are thousands of AFMs, MFMs, and STMs at universities, national laboratories, and industrial research and quality-control facilities. High school students make STMs from Legos, while chip manufacturers use million-dollar AFMs on the factory floor. One AFM has even made it to the surface of Mars.[1]

Stories about scientific instruments have long been a staple for historians of science and technology. This literature was crucial in elucidating the artifactual basis of scientific knowledge and the technological considerations underlying even the "purest" research.[2] These narratives, however, have largely focused on the "pre-Cancun" phase, from invention to replication. This can be a remarkably elastic phase, since some techniques (e.g., mass spectrometry or the laser) draw adherents simply through the opportunities afforded to newcomers to continually invent new variants.[3] A few exemplary works, such as Nicolas Rasmussen's history of biological elec-

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[1] All scanning probe microscopes bring a very small solid probe very close (usually to within a nanometer, which is one billionth of a meter) to a sample in order to measure the strength of different kinds of interactions between probe tip and sample to determine the height (and other characteristics) of the sample. The probe is then rastered much like the pixels on a television screen, and a matrix of values for the strength of the tip–sample interaction is converted into a visual "picture" of the surface. Different probe microscopes use different kinds of tip–sample interactions to generate their images. The first—the STM—works by putting a voltage difference between the tip and a metal or semiconductor sample; when the tip is brought close to the sample, some electrons will "tunnel" between them. Tunneling is a quantum mechanical process by which particles near-instantaneously displace from one point to another across a barrier. The strength of the current of tunneling electrons is exponentially dependent on the distance between the STM tip and the sample; also, the stream of tunneling electrons is very narrow. Thus, an STM has ultrahigh resolution both vertically and laterally: most STMs can actually detect individual atoms on many samples. Today, the STM's younger cousin, the atomic-force microscope (AFM), is more commonly used. An AFM employs a very small but flexible cantilever as a probe; as the tip of this cantilever (usually weighted with a small pyramid of extra atoms) is brought close to the surface, the cantilever bends due to the attraction or repulsion of interatomic forces between tip and sample. The degree of bending is then a proxy for the height of the surface. Originally, this bending was measured by putting an STM on the back of the cantilever; today, however, the deflection is detected by bouncing a laser off the cantilever and measuring the movement of the reflected spot. Another common and industrially relevant tool, the magnetic force microscope (MFM), works in a similar way, but uses a magnetic tip to map the strength of magnetic domains on a surface rather than the surface height. Both the AFM and MFM have slightly less resolution than the STM (that is, they cannot usually detect single atoms); but because they (unlike the STM) can be employed on insulators as well as conductors, and in air and fluids as well as vacuum, they have become much more popular.

[2] Some studies in this vein include Robert Kohler, *Lords of the Fly* (Chicago, 1994); Boelie Elzen, "Two Ultracentrifuges: A Comparative Study of the Social Construction of Artefacts," *Social Studies of Science* 16 (1986): 621–62; and Thomas P. Hughes, "Model Builders and Instrument Makers," *Science in Context* 2 (1988): 59–75.

[3] See Joan Lisa Bromberg, *The Laser in America, 1950–1970* (Cambridge, Mass., 1991), and Michael A. Grayson, ed., *Measuring Mass: From Positive Rays to Proteins* (Philadelphia, 2002). Indeed, since there are now more than forty *named* types of probe

tron microscopy or Timothy Lenoir and Christophe Lécuyer's study of Varian's popularization of nuclear magnetic resonance, have examined the "post-Cancun" phase of dispersion and commercialization.[4] Even here though, the emphasis has been on singular institutions, whether corporate (e.g., RCA or Varian) or nonprofit (e.g., Stanford University or the Rockefeller Foundation), rather than on the shaping of instruments by actors distributed across multiple corporate, academic, and national organizations and arrayed in shifting relationships of patron– client, consumer–producer, inventor–replicator, and builder–user.

This is unfortunate. The relationships between corporations and universities that are built around such research technologies form an important focus in public debates about academic capitalism and the future of higher education.[5] This old and wide-ranging debate gained momentum during the 1970s as changes in law, academic culture, corporate research, and national science funding have pushed universities to patent professors' research, incubate start-up companies, and form substantial (and sometimes controversial) corporate partnerships. Proponents of change desire that universities integrate fully with the market; naysayers decry the academy's loss of independence and critical voice.

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microscopes, one could easily present the history of the field as an unending series of invented variations. My focus here is less on these variants, most of which have few users, and more on the mainly standardized, usually commercially available instruments. For an analysis of the dichotomies between builders and buyers in probe microscopy, see Cyrus C. M. Mody, "How Probe Microscopists Became Nanotechnologists," in *Discovering the Nanoscale*, ed. Davis Baird, Alfred Nordmann, and Joachim Schummer (Amsterdam, 2004), 119–33.

[4] Nicolas Rasmussen, *Picture Control: The Electron Microscope and the Transformation of Biology in America, 1940–1960* (Stanford, Calif., 1997); Timothy Lenoir and Christophe Lécuyer, "Instrument Makers and Discipline Builders: The Case of Nuclear Magnetic Resonance," *Perspectives on Science* 3 (1995): 276–345. An excellent study of the transition from pre- to post-Cancun in several instrumental communities is Stuart Blume, *Insight and Industry: On the Dynamics of Technological Change in Medicine* (Cambridge, Mass., 1992). For analyses of the dispersion/dissemination of experimental tools, see Kathleen Jordan and Michael Lynch, "The Dissemination, Standardization, and Routinization of a Molecular Biological Technique," *Social Studies of Science* 28 (1998): 773–800. For a similar study of theoretical tools, see David Kaiser, *Drawing Things Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago, 2005).

[5] I adopt the phrase "research technologies" from Terry Shinn, "Crossing Boundaries: The Emergence of Research-Technology Communities," in *Universities and the Global Knowledge Economy: A Triple Helix of University–Industry–Government Relations*, ed. Henry Etkowitz and Loet Leydesdorff (London, 1997), 85–96. For a sampling of the academic capitalism debate, see Norman E. Bowie, ed., *University–Business Partnerships: An Assessment* (Lanham, Md., 1994); Derek Bok, *Universities in the Marketplace: The Commercialization of Higher Education* (Princeton, N.J., 2003); Roger L. Geiger, *Knowledge and Money: Research Universities and the Paradox of the Marketplace* (Stanford, Calif., 2004); and the essays in Donald G. Stein, ed., *Buying In or Selling Out: The Commercialization of the American Research University* (New Brunswick, N.J., 2004).

As Steven Shapin notes, both sides argue the issue abstractly, leading to ludicrous over-praising of new patent laws on the one hand, and overly dire warnings about corporate influence on the other.[6] What empirical work there is focuses exclusively on particularly entrepreneurial disciplines/industries (biotechnology, microelectronics), universities (Stanford, MIT), or regions (Silicon Valley, Route 128 near Boston).[7] Yet many commercialized research tools emerged from work done across disciplines, at multiple universities and corporations around the globe. To understand how technologies move among universities and corporations and become commercial products, we need a multi-institutional, multiregional, multidisciplinary unit of analysis—what I will call an "instrumental community."

By instrumental community I mean the porous group of people commonly oriented to building, developing, using, selling, and popularizing a particular technology of measurement. Such communities are "instrumental" primarily in focusing on new research tools, namely, scientific instruments. Because they include academic and commercial participants, such communities will seek ways to morph these tools into industrially relevant devices. Thus, such communities are also "instrumental" in focusing on new ways of doing or making things. Instrumental communities are ubiquitous: many tools' development has had moments like that in Cancun in 1984, when a community suddenly coalesces around a technology. Instrumental communities have been an enduring presence in scientific and technological development; indeed, the best recent work on the history of instrumentation

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[6] Steven Shapin, "Ivory Trade," *London Review of Books* 25 (2003): 15–19.

[7] For disciplines/industries, see Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High-Tech, 1930–1970* (Cambridge, Mass., 2006), and Martin Kenney, *Biotechnology: The University-Industrial Complex* (New Haven, Conn., 1986). For studies of MIT and Stanford University, see Bernard Carlson, "Academic Entrepreneurship and Engineering Education: Dugald C. Jackson and the Cooperative Engineering Course, 1907–1932," *Technology and Culture* 29 (1988): 536–69; David Noble, *America by Design: Science, Technology, and the Rise of Corporate Capitalism* (Oxford, 1977); Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York, 1993); John Servos, "The Industrial Relations of Science: Chemical Engineering at MIT, 1900–1939," *Isis* 81 (1980): 531–49; R. S. Lowen, "Transforming the University—Administrators, Physicists, and Industrial and Federal Patronage at Stanford, 1935–49," *History of Education Quarterly* 31, no. 3 (1991): 365–88; C. Lécuyer, "Academic Science and Technology in the Service of Industry: MIT Creates a 'Permeable' Engineering School," *American Economic Review* 88 (1998): 28–33; and Henry Etkowitz, *MIT and the Rise of Entrepreneurial Science* (London, 2002). For Silicon Valley, Route 128, and emulations thereof, see Anna-Lee Saxenian, *Regional Networks: Industrial Adaptation in Silicon Valley and Route 128* (Cambridge, Mass., 1993); Peter Hall and Ann Markusen, eds., *Silicon Landscapes* (Boston, 1985); Manuel Castells and Peter Hall, *Technopoles of the World: The Making of Twenty-First-Century Industrial Complexes* (London, 1994); Stuart W. Leslie, "Regional Disadvantage—Replicating Silicon Valley in New York's Capital Region," *Technology and Culture* 42 (2001): 236–64; and Martin Kenney, ed., *Understanding Silicon Valley: The Anatomy of an Entrepreneurial Region* (Stanford, Calif., 2000).

examines pre-twentieth–century artisanal instrument makers and their cultivation of communities of patrons and customers.[8] During the past century (and increasingly since the 1970s), examining the formation and organization of instrumental communities means better understanding the interplay of corporate and academic organizations—spanning multiple disciplines—that shapes the development and proliferation of high technologies.

Probe Microscopy

The cultivation of an instrumental community begins with the invention of the instrument itself; indeed, such promotional activities are integral to invention.[9] Community-building meets organizational or disciplinary goals and provides a safety net for inventors whose links to institutions are precarious.[10]

The STM, for example, originated in 1979 at IBM Zurich as a characterization tool in making thin films for a commercially important supercomputer.[11] When the supercomputer project died, Binnig and Rohrer lost the organizational justification for their work. They prolonged its life, however, first by hiding it within IBM's bureaucratic folds, and later by forming alliances with academic researchers. They assiduously cultivated academic STM replicators in Spain, Germany, Switzerland, California, and elsewhere, while also using the instrument to address basic research questions (particularly in the subfield of surface science) to attract the attention of both corporate and academic scientists. When these efforts succeeded, IBM pro-

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[8] Klaus Hentschel, *Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching* (Oxford, 2002); Myles W. Jackson, "Buying the Dark Lines of the Spectrum: Joseph von Fraunhofer's Standard for the Manufacture of Optical Glass," in *Scientific Credibility and Technical Standards in 19th and Early 20th Century Germany and Britain*, ed. Jed Z. Buchwald (Dordrecht, the Netherlands, 1996), 1–22; and David Pantalony, "Seeing a Voice: Rudolph Koenig's Instruments for Studying Vowel Sounds," *American Journal of Psychology* 117 (2004): 425–42.

[9] The STM, for instance, was preceded by a very similar instrument called the Topografiner, built by Russell Young at the U.S. Bureau of Standards in 1969–70. But because Young never convinced any wider group of people to attach themselves to the Topografiner, it is fair to state that probe microscopy was not "invented" until Binnig and Rohrer came along. See John Villarrubia, "The Topografiner: An Instrument for Measuring Surface Microtopography," in *A Century of Excellence in Measurements, Standards, and Technology—Selected Publications of NBS/NIST, 1901–2000*, ed. David R. Lide and Dean R. Stahl (Boca Raton, Fla., 2001), 214–18.

[10] Indeed, inventors of instruments (or those who take credit for having invented them) often seem to have troublesome positions within the firms that employ them. See, for instance, the description of Kary Mullis's antagonistic relationship with Cetus in Paul Rabinow, *Making PCR: A Story of Biotechnology* (Chicago, 1996).

[11] G. Binnig and H. Rohrer, "The Scanning Tunneling Microscope," *Scientific American* 253 (1985): 50–56, and G. Binnig and H. Rohrer, "Scanning Tunneling Microscopy—From Birth to Adolescence," *Reviews of Modern Physics* 59 (1987): 615–25.

moted STM at its labs in Zurich, Yorktown Heights, New York, and Almaden, California. IBM's research rival, Bell Labs, recruited STM groups in response. Binnig and Rohrer skillfully exploited the permeability of the corporate–academic boundary. By allying with academia, they created a corporate space for STM despite having lost an immediate commercial objective.

This permeability existed because corporate laboratories have long depended on academia to supply recent Ph.D.s for postdoctoral or junior staff positions. In subdisciplines such as surface science where researchers were needed, these labs fostered professional societies, journals, and other extramural institutions to maintain academic connections and participation.[12] Some researchers alternated between corporate and academic research, hence establishing networks between institutions; veterans of corporate labs became reliable feeders to, and consultants for, those same labs once they established their own academic groups. Most of the first academics to replicate the STM had direct ties of collaboration or employment to IBM, the Zurich laboratory, or personally to Binnig and Rohrer. A few schools (namely Cornell, Penn State, Caltech, University of California, Berkeley, and Stanford) supplied the postdoctoral associates and managers who developed STM at Bell Labs and at IBM's Yorktown Heights and Almaden research centers.[13]

Within such a small instrumental community, big corporate labs predominated. Early work centered on developing microscopes to meet minimal operational benchmarks, usually the atomic resolution of materials that the Zurich team had imaged. These materials—particularly silicon—were metals and semiconductors with long histories in research and manufacturing at IBM and Bell Labs. Corporate STMers could draw on in-house expertise in quickly making and understanding samples. After the Cancun meeting, these minimal benchmarks were turned into fields of active research in the race to achieve the atomic resolution of more and more metals and semiconductors.[14] Early academic STMers such as Paul Hansma at

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[12] For descriptions of the big corporate laboratories and their relations with universities, see George Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (New York, 1985); Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York, 1997); Lillian Hartmann Hoddeson, "The Roots of Solid-State Research at Bell Labs," *Physics Today* 30 (1977): 23–30; and Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge, Mass., 1985).

[13] Joe Demuth, interview with Cyrus Mody, Yorktown Heights, N.Y., 22 February 2001; Joe Stroscio, interview with Cyrus Mody, Gaithersburg, Md., 28 June 2000; John Villarrubia, interview with Cyrus Mody, Gaithersburg, Md., 28 June 2000; Randy Feenstra, interview with Cyrus Mody, Pittsburgh, 2 May 2001; John Foster, interview with Cyrus Mody, Santa Barbara, Calif., 19 October 2001; Jene Golovchenko, interview with Cyrus Mody, Cambridge, Mass., 20 February 2001.

[14] Such races appear to be a recurring feature of young instrumental communities. They are especially visible in Bromberg (n. 3 above).

the University of California at Santa Barbara, Calvin Quate at Stanford, and John Baldeschwieler at Caltech were players in these races, but soon realized they possessed neither the requisite expertise nor the resources to keep up with the corporate labs.

Thus Hansma, Quate, and Baldeschwieler began carving out niches in which they were not in direct competition with their corporate colleagues, but could still benefit from the corporate–academic interaction.[15] Their instrument designs followed corporate STM models, but were targeted for applications other than metals and semiconductors. For instance, almost all early corporate STMers built ultrahigh vacuum (UHV) microscopes, since metals and semiconductors grow oxide films or collect impurities in air. In response, Hansma, followed by most other academic STMers, shifted toward air operation. Air and UHV STMs have similar electronics and mechanics, but academics preferred air STM for its simplicity and price and because it appealed to disciplinarily diverse academic users rather than disciplinarily restricted corporate surface scientists. Hence, because they feared being left behind by their corporate colleagues, academic STMers sought out new research milestones and developed flexible designs that could yield new applications and attract new adherents. Clearly, here was commerce "influencing" academic research, yet it contradicts the dire scenario presented by some analysts. Corporations shaped academic work without "buying" professors or students, and their influence rendered the STM community more diverse and created spaces for unexpected innovation.[16]

Many other academic–industry linkages were part of early STM. From 1981 to 1986, all STMs (and, after 1985, AFMs) were custom-built rather than purchased off-the-shelf. Constructing an instrument encompasses a spectrum of practices, ranging from "building from scratch" to buying and assembling. The commercialization of research usually represents a gradual movement along this spectrum, rather than the sudden transformation of a home-built research tool into an off-the-shelf commercial product. STM builders spent much of their time locating commercial sources for microscope components and fixing faulty instruments by thumbing through manufacturers' catalogs for new op amps and probe materials.[17] The commercial availability of components shaped STM designs, but the builders

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[15] Paul Hansma, interview with Cyrus Mody, Santa Barbara, Calif., 19 March 2001.

[16] This is a more common phenomenon than has been recognized. For instance, some of today's academic nanotechnology centers can be traced back to efforts during the 1970s and '80s to build facilities in which electrical engineering and applied physics faculty could train students in the materials and methods used in the semiconductor industry. Since such facilities were never as well endowed as those in companies such as Intel and AMD, these faculty shifted focus by broadening their research for a multidisciplinary audience, hence giving current nanotechnology its interdisciplinary character. From Harold Craighead, interview with Cyrus Mody, Ithaca, N.Y., 26 May 2005.

[17] Golovchenko interview; Clayton Teague, interview with Cyrus Mody, Gaithersburg, Md., 6 June 2002.

were also active consumers: on the one hand, they took commercial products and adapted them for unforeseen uses; on the other, they negotiated with suppliers for equipment (vacuum chambers, piezoelectric crystals, video output devices, and so on) geared to their specific applications.[18] Some suppliers such as Burleigh (a piezoceramic maker in upstate New York) modified components and forged ongoing connections with STM builders to design products specifically for the STM market.[19] Creating the tools of university research, from buildings to microscopes to reagents, encompasses a wide variety of such corporate–academic linkages. Some activities (e.g., ordering materials from a catalog; contracting with a builder to remodel a laboratory) are relatively mundane; others (e.g., professors consulting with manufacturers; academic designs being transferred to corporate interests) attract both praise and protest.[20]

Once annual STM conferences commenced after Cancun, the labor intensiveness of microscope-building decreased as knowledge and experience were disseminated. In this way, STM-building became standardized through STMers' nearly ritualistic allegiance to certain manufacturers.[21] Experienced researchers recommended some brands over others because of their proven operation; consequently, newcomers, eager to gain time, rarely questioned such recommendations. For instance, IBM researchers used a trademarked rubber called Viton (from DuPont) to dampen vibration because it could survive ultrahigh vacuum.[22] Subsequently, academics adapted

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[18] Much recent history of technology has focused on the active role of users. For consumers' adaptations of artifacts for uses that manufacturers were ignorant of, or even opposed outright, see Ronald Kline and Trevor Pinch, "Users as Agents of Technological Change: The Social Construction of the Automobile in the Rural United States," *Technology and Culture* 37 (1996): 763–95. For users' pressure on companies (often—as in instrumental communities—through threats to form their own cooperatives or companies), see Claude S. Fischer, *America Calling: A Social History of the Telephone to 1940* (Berkeley, Calif., 1992). For an overview of different kinds of user activity, see the essays in Nelly Oudshoorn and Trevor Pinch, eds., *How Users Matter: The Co-Construction of Users and Technologies* (Cambridge, Mass., 2003).

[19] Dave Farrell, interview with Cyrus Mody, Rochester, N.Y., 29 May 2001; Golovchenko interview (n. 13 above). For an analysis of a similar phenomenon in particle physics during the 1930s, see Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, 1997), ch. 3.

[20] For similar instances of negotiations between academic users of laboratory products and the products' manufacturers, see Michael Lynch, "Protocols, Practices, and the Reproduction of Technique in Molecular Biology," *British Journal of Sociology* 53 (2002): 203–20.

[21] For treatments of the concept of tacit knowledge, especially as applied to instrument-building, see H. M. Collins, "The Seven Sexes: A Study in the Sociology of a Phenomenon, or the Replication of Experiments in Physics," *Sociology* 9 (1975): 205–24; Harry Collins, "Tacit Knowledge, Trust, and the Q of Sapphire," *Social Studies of Science* 31 (2001): 71–86; and Michael Polanyi, *Personal Knowledge: Towards a Post-Critical Philosophy* (New York, 1962).

[22] Christoph Gerber, interview with Cyrus Mody, Zurich, Switzerland, 12 Novem-

the IBM design and Viton became a hallmark of tunneling microscopy, even for those academic STMs that operated in air or fluid, not vacuum.[23]

Corporate and academic linkages also dictated what materials campus laboratory groups examined with their microscopes and, indeed, how microscope designs were geared to those materials. Sometimes this was the result of direct influence, although it is unclear just who influenced whom. Calvin Quate, for instance, framed his STM work within Stanford's long tradition of industrial connections and his own involvement during the 1970s in developing acoustic microscopy as a nondestructive characterization tool for manufacturing.[24] Nondestructive testing held tremendous promise for microelectronics, in which chips are inspected throughout manufacturing, but traditional tools (especially electron microscopy) require breaking and discarding expensive silicon wafers. Quate embraced STM, believing that it represented the next-generation nondestructive evaluation tool. He was quickly followed by his former students and postdoctoral associates at IBM.[25]

STM requires a conducting (metal or semiconductor) sample, however, whereas most microelectronic materials have an insulating oxide layer; indeed, the controlled growth of oxides is crucial to turning silicon wafers into integrated circuits. This requirement was not problematic for corporate surface scientists tasked with generating basic knowledge about materials like silicon and gallium arsenide. Yet STM's restriction to conducting materials prohibited its use in nondestructive testing and hindered its spreading into fields other than surface science. Those who wanted to carve out interdisciplinary niches for STM considered this restriction repressing; chief among these were Gerd Binnig (an IBM employee but not a surface scientist) and Quate (and his former students and postdoctoral associates at IBM). So when IBM allowed Binnig to take a sabbatical leave at Stanford University during 1985–86, he and Quate advanced beyond STM to invent AFM, which, because it uses interatomic forces rather than tunneling to sense height, can map insulating materials. Thus Quate positioned his research further in advance of IBM's manufacturing cycle than did most of

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ber 2001; Rudd Tromp, interview with Cyrus Mody, Yorktown Heights, N.Y., 23 February 2001; Virgil Elings, interview with Cyrus Mody, Santa Barbara, Calif., 20 March 2001.

[23] For similar instances of practices spreading throughout an experimental community by transmission of knowledge about particular brands, see Jordan and Lynch, "The Dissemination, Standardization, and Routinization of a Molecular Biological Technique" (n. 4 above).

[24] Mike Kirk, interview with Cyrus Mody, Sunnyvale, Calif., 12 October 2001; Dan Rugar, interview with Cyrus Mody, Almaden, Calif., 14 March 2001; Foster interview (n. 13 above). See C. F. Quate, "Acoustic Microscopy—Recollections," *IEEE Transactions on Sonics and Ultrasonics* 32 (1985): 132–35, for a brief description of scanning acoustic microscopy at Stanford.

[25] Quate's optimism for STM derived from its ultrahigh resolution and the fact that (ideally) the STM tip does not touch (and thereby mar) the sample surface.

the company's own STM researchers. Together, IBM and Stanford dramatically altered the world of academic and corporate probe microscopy.

As Daniel Lee Kleinman has shown, however, corporate influence over academic research usually flows through the indirect control over experimental materials rather than the overt guiding of objectives.[26] For instance, when academic STM researchers designed microscopes for use in water or air they needed new yardstick materials (given the unsuitability of metals and semiconductors). Gold, paraffin, and graphite vied for the job, but the latter won out partly because ultrapure samples could be obtained cheaply.[27] Union Carbide used graphite to make monochromators for neutrons, an application requiring extraordinarily pure samples. It rejected large amounts of slightly imperfect graphite that was still pure enough for STM use. Quate and colleagues heard about this and alerted other academic groups who then contacted Union Carbide's graphite man, Arthur Moore, to obtain cheap, standardized samples. Thus, these dispersed academic researchers built networks within their instrumental community by relying on corporate largesse. As dependence on this largesse spread, it formed the basis for a standardized research infrastructure.

The Road to Commercialization

Crucial to commercialization of academic work on STM and AFM was the early division of the community into two distinct, dynamically linked styles: surface-science STM researchers located predominantly in corporate laboratories; and early academics (Quate, Hansma, Baldeschwieler, and others), along with their collaborators and Quate's former students at IBM.[28] Corporate surface-science STMers, particularly at Bell Labs and IBM, worked in large, resource-rich institutions alongside many people who were qualified to judge their work, whether they were competitors assigned to similar projects or managers empowered to review and advance or hinder careers.[29] Postdoctoral associates and junior staff scientists building STMs were under tremendous schedule pressures and so stuck to institutionally approved projects. STM-building in corporate labs required a delicate balance: researchers not only had to design and use their micro-

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[26] Daniel Lee Kleinman, *Impure Cultures: University Biology and the World of Commerce* (Madison, Wisc., 2003).

[27] Andy Gewirth, interview with Cyrus Mody, Urbana-Champaign, Ill., 26 June 2001.

[28] The pedagogical roots of this split are analyzed in Cyrus C. M. Mody, "Instruments in Training: The Growth of American Probe Microscopy in the 1980s," in *Pedagogy and the Practice of Science: Producing Physical Scientists, 1800–2000*, ed. David Kaiser (Cambridge, Mass., 2005), 185–216.

[29] Jane Frommer, interview with Cyrus Mody, Almaden, Calif., 14 March 2001; Dawn Bonnell, interview with Cyrus Mody, Philadelphia, 26 February 2001.

scopes to demonstrate individual initiative, but also to integrate well with a disciplined and insular corporate style.

Academic STM researchers were more dispersed and looked to a more diffuse audience. Where the corporate labs built what Terry Shinn calls "narrow niche" instruments geared to limited applications, academic groups moved toward a "research technology" paradigm of generic tools relevant to a variety of disciplines.[30] Because they had yet to find suitable applications for these tools, Quate, Hansma, and other early academic STMers trained students primarily to *build* highly flexible microscopes, and only secondarily to *use* them. This led to a proliferation of microscope designs such as STM in water, air, oil, and gas, and the critical shift to AFM. It also led students to test microscopes on readily available materials rather than on scientifically disciplined specimens: leaves of houseplants, polaroids, bone from rib-eye steaks, ice, and the electrochemistry of Coke versus Pepsi, to name a few.[31] This whimsicality was accompanied by bricolage in instrument-building. The Baldeschwieler group made STM probes from pencil leads, for instance, while the Hansma group made AFM tips from hand-crushed, pawn-shop diamonds glued to tinfoil cantilevers with brushes made from their own eyebrow hairs.

It was difficult to make such images interesting or credible. Even where some disciplinary community had expertise about these materials—biochemists, for instance, know about bone and leaves—the specimens were prepared so haphazardly that images of them were unintelligible. These academic STM and AFM groups had little in-house expertise about what questions to ask concerning samples or how to interpret images of them. Therefore group leaders imported collaborators (postdoctoral associates or junior professors) for a few weeks or months to learn about probe microscopy and then leave to establish new STM and AFM groups and report on the microscopes to their specific disciplines.[32] These visitors fit into an on-

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[30] Shinn (n. 5 above). By manufacturing the relevance of STM and AFM to these disciplines, the academic groups turned those fields into "relevant social groups," parties to the eventual shape of the technology; see Wiebe E. Bijker and Trevor Pinch, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, Mass., 1987), 17–50.

[31] Craig Prater, interview with Cyrus Mody, Santa Barbara, Calif., 19 March 2001; Jun Nogami, interview with Cyrus Mody, East Lansing, Mich., 28 June 2001.

[32] This importation of credibility/knowledge through collaboration is apparent in many instrumental communities. It is best described in Rasmussen (n. 4 above). The coordination of different kinds of personnel and expertise around a common instrumental focus is nicely captured by the "trading zone" concept in Galison (n. 19 above), and the idea of circulating "boundary objects" described in Susan Leigh Star and James R. Griesemer, "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907–1939," *Social Studies of Science* 19 (1989): 387–420.

going tradition of teamwork at the California schools. Where corporate surface-science STMers worked in insulated, highly competitive, hierarchical groups (a manager overseeing postdoctoral associates and technicians), their academic counterparts thrived in a permissive atmosphere wherein students and their postdoctoral colleagues simultaneously worked on their "own" as well other microscopes, and personnel and materials moved from project to project as needed. When they left, some of these temporary collaborators founded similar microscope-building programs; others simply took a second-hand instrument with them to aid in their desire to carve out a distinctive place within their home disciplines and secure tenure.[33]

Eventually, this dynamic fostered commercial production of STMs and AFMs. Outright commercialization, however, was preceded by a gray market in which researchers produced surplus microscope parts that they traded with acquaintances in the expanding network of STMers and AFMers—sometimes for money, more often for other tokens such as prestige or experimental materials.[34] Once IBM research management discerned STM's discovery-making potential, for instance, it pushed for expansion of STM work at its facilities. New STM researchers were hired to build microscopes—a laborious task with few guarantees of success. Indeed, the first replication at the Yorktown Heights laboratory failed, and the next one took almost two years to catch up with Zurich.[35] Expansion proceeded more swiftly in Switzerland, where newcomers could interact personally with the inventors. Still, the labor investment was daunting, especially for those whose postdoctoral appointments meant operating on limited time horizons.

Consequently, IBM began making semi-standardized, batch-produced STM packages available to its researchers.[36] The first was the "Blue Box" designed by Othmar Marti, a Swiss graduate student undertaking doctoral work at IBM Zurich.[37] The Blue Box was primarily an electronics package. Researchers constructed the hardware themselves, often using the Zurich team's designs. STM electronics presented a significant challenge because

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[33] Jan Hoh, interview with Cyrus Mody, Baltimore, 10 June 2002; Barney Drake, interview with Cyrus Mody, Santa Barbara, Calif., 18 October 2001; Stuart Lindsay, interview with Cyrus Mody, Tempe, Ariz., 6 January 2003; Carlos Bustamante, interview with Cyrus Mody, Berkeley, Calif., 17 October 2001; Gewirth interview (n. 27 above); Nogami interview. The propagation of a technique through the "cascade" of postdoctoral associates and collaborators away from one of the centers of an instrumental community is described in Kaiser, *Drawing Things Apart* (n. 4 above).

[34] Pierre Bourdieu, "The Forms of Capital," in *Handbook of Theory and Research for the Sociology of Education*, ed. John Richardson (New York, 1986), 241–58.

[35] Joe Griffith, interview with Cyrus Mody, Murray Hill, N.J., 28 February 2001; Demuth interview (n. 13 above); Feenstra interview (n. 13 above).

[36] See Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865–1925* (Princeton, N.J., 1997), for an analysis of batch production.

[37] Othmar Marti, interview with Cyrus Mody, Ulm, Germany, 16 November 2001; Gimzewski interview (n. 17 above).

complicated feedback circuitry brings the probe to the surface, reads out and controls the tunnel current, and rasters the tip without crashing. The success of the Blue Box in allowing newcomers to work around these difficulties inspired a more ambitious effort at IBM Yorktown Heights. There, Joe Demuth, manager of an STM group, assigned his postdoctoral associates to work with the lab's Central Scientific Services (CSS) shop to develop and batch-produce complete STMs to "sell" to other researchers within the organization.[38]

By 1990, ten to twenty of these CSS STMs were in use at Yorktown Heights and the nearby Hawthorne facility. Some also traveled to academic groups when postdoctoral associates departed to assume professorships.[39] Yorktown Heights management encouraged the use of the CSS STM by making its purchase a zero-cost budget item. Still, groups had to invest labor—usually by a postdoctoral associate—to make the microscope productive. This created a dilemma for its postdoctoral users: on the one hand, they needed to creatively solve technical problems and display initiative to managers in order to advance to staff positions; but on the other, advancement also required navigating competitive institutional politics whereby groups worked in parallel on similar projects and were rewarded relative to one another. Postdoctoral associates using the CSS STM found that they were viewed as partisans of Demuth's style of microscopy. So as to avoid alienating other factions at the laboratory and also display their own prowess in experimentation, they redesigned and rebuilt large sections of the CSS instrument. The research organization at Yorktown Heights constrained the CSS microscope from becoming a widely commercialized black box.[40]

The CSS STM was a *kind* of commercialization of tunneling microscopy for the internal IBM market. Had the culture at Yorktown Heights promoted formation of start-ups or collaborations with instrument manufacturers, the CSS microscope could have become the first mass-marketed

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[38] Bob Hamers, interview with Cyrus Mody, Madison, Wisc., 9 May 2001; Demuth interview; Tromp interview (n. 22 above).

[39] Bonnell interview (n. 29 above).

[40] For the classic analysis of the instrument as "black box" (i.e., a technology that takes over epistemic responsibility from the experimenter by virtue of the inaccessibility of its workings), see Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton, N.J., 1986). My point here is that the "blackness" of the black box is continually reshaped in order to draw boundaries or form networks within an instrumental community. Commercialization can be a gradual process of making the black box less open to intervention; see Kathleen Jordan and Michael Lynch, "The Sociology of a Genetic Engineering Technique: Ritual and Rationality in the Performance of a 'Plasmid Prep,'" in *The Right Tools for the Job: At Work in the Twentieth-Century Life Sciences*, ed. Adele E. Clarke and Joan H. Fujimura (Princeton, N.J., 1992), 77–114. At the same time, the presentation of a commercial microscope architecture as "closed" (probe microscopists' term for a black box) or "open" (their term for translucent) is a political move designed to orient that microscope toward a particular market niche/subdisciplinary audience. See Mody, "How Probe Microscopists Became Nanotechnologists" (n. 3 above).

STM.[41] After the early 1990s' recession made IBM leaner and more outward-looking, it did market an AFM—Yorktown Heights' SXM—to the semiconductor industry. However, this exception proves the rule. The SXM was invented by a former postdoctoral employee of Quate's and owed much to his style of work, rather than to the surface-science tradition that produced the CSS STM. But its commercialization was hindered by its IBM origins: although capable of astonishing resolution of the sidewalls of integrated circuit features, it was too punctilious and unreliable (it needed a Ph.D. operator) to attract an industry devoted to tools that could be continuously operated by relatively unskilled workers.[42]

Researchers at Yorktown Heights clearly were not acquiring an unproblematic black box that commodified microscope-building knowledge. Groups that regarded it in this vein often couldn't get it to work.[43] Most researchers at the lab felt an institutionally driven need to prove they could obtain this knowledge on their own; therefore most users of the CSS STM were purchasing time, a chance to enter a dynamic instrumental community and quickly establish for themselves the instrument-building credentials of veterans. In return, its designers received prestige and influence rather than money. Similar motivations governed the first academic STM start-ups. Established STM and AFM groups—especially the ones of Quate, Hansma, and Baldeschwieler—had long given advice and blueprints to new builders. This often consisted of guidance in *buying* reliable components for a homemade instrument and *assembling* purchased components in accordance with available blueprints. Whatever could not be bought was made by hand or batch-produced. These custom components circulated widely as gifts.[44] Software in particular passed from group to group, and from student cohort to cohort within research groups. Both academic and corporate groups created software code that they proffered to collaborators, thereby strengthening the group's position within the instrumental community and ensuring access to collaborators' modifications to the code.[45]

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[41] For a similar analysis of how corporate culture at IBM sometimes kept innovations from percolating, see Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore, 2002).

[42] Likewise, attempts at spinning off small companies from Bell Labs' probe microscope research during the 1990s fell apart partly because of managers' inexperience in dealing with commercialization efforts by their subordinates. Moreover, the size and inward focus of both IBM and Bell Labs hindered these companies from cleanly patenting (and hence reaping profits from) their STM and AFM work. See Griffith interview (n. 35 above).

[43] Bonnell interview.

[44] Davis Baird, "Scientific Instrument Making, Epistemology, and the Conflict between Gift and Commodity Economies," *Ludus Vitalis Supplement* 2 (1997): 1–16. The "moral economy" of making gifts and exchanges in an instrumental community is described in Kohler (n. 2 above).

[45] Miguel Salmeron, interview with Cyrus Mody, Berkeley, Calif., 9 March 2001; Lindsay interview (n. 33 above).

Code was sometimes presented free of charge, other times at nominal cost; profit was not the motive for dissemination.

The most popular hardware innovation was the microfabricated AFM cantilever. One perceived defect of early AFMs was that probes were laboriously handmade from small strips of aluminum foil with a tiny sliver of diamond glued on one side and a tiny shard of glass on the other.[46] Although these cantilevers could yield exquisite AFM images, each required considerable time and training, and results were so particular to one cantilever and its maker that images taken with different cantilevers were difficult to compare. Handmade cantilevers sufficed early on, when every image was new and spectacular; but as the technique evolved, AFMers sought standardization. Quate's group delivered this by integrating itself with microlithography expertise at Stanford University and around Silicon Valley. Over several years, Quate shared his students with other electrical engineering professors at Stanford, thereby allowing them to understand AFM before going on to learn how to pattern and etch silicon into small, standardized batches of cantilevers. By 1990, Quate began sending surplus probes to friends and collaborators, occasionally so that he and his students could share authorship of collaborators' papers. Quate-type probes rapidly became essential to the AFM infrastructure.[47]

Generally, only *parts* of microscopes circulated in this way. Quate, Hansma, and Baldeschwieler occasionally gave complete microscopes to long-term collaborators, but not to casual acquaintances. Most newcomers desired the credentials and experimental control that came with building their own microscopes, but few wanted to take the time to build an STM from scratch. Thus, by 1986, demand grew for a commercial microscope to assist these researchers in their work. In this environment, Doug Smith, who was a student of Quate's, founded the Tunneling Microscope Company. Smith's company was an extension of, rather than a break from, the earlier probe-microscope gray market. Like the Blue Box and the CSS STM, Smith's instruments were more starter kits than black-boxed devices and sold to people with the skill, but not the time to build one themselves. In order to attain a completed instrument, customers needed to assemble much of it on their own.[48] All Smith's company sold was the microscope

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[46] Diamonds were used as tips because their sharp points were less likely than other materials to wear down from repeated use. The glass on the back of the cantilever acted as a small mirror, bouncing laser light into a photodiode; the position of the reflected beam in the photodiode indicated how much the cantilever was bending (i.e., a proxy for how much the surface was pulling or pushing on the diamond tip).

[47] Tom Albrecht, interview with Cyrus Mody, Almaden, Calif., 14 March 2001; Drake interview (n. 33 above); Kirk interview (n. 24 above).

[48] Nancy Burnham, interview with Cyrus Mody, Worcester, Mass., 20 February 2001; Rich Colton, interview with Cyrus Mody, Washington, D.C., 27 June 2002; Foster interview (n. 13 above).

"head": the piezoelectric scanner, tip, base, and vibration-isolating stacks of Viton. Customers built the electronics themselves, customizing the microscope for their own applications.

Smith had only one employee, a fellow student who helped put together scanners, and he solicited customers by word of mouth. He viewed the company less as an ongoing enterprise than as a way to sweeten the hardships of graduate school. An oft-told story is that he sold just enough microscopes to buy a BMW automobile before taking a postdoctoral position. Quate himself was ambivalent about commercialism creeping into his lab. He demanded that Smith separate scholarship and business more cleanly: "Dr. Quate said 'graduate students work, eat, and sleep, and most of the time they go hungry.' You can't have a company and be a graduate student at the same time, so Doug had to finish up and move out."[49]

Meanwhile, Virgil Elings, Hansma's colleague in the University of California, Santa Barbara physics department, heard about STM from Niko Garcia, a visiting Spanish academic with close ties to IBM Zurich. After talking with Garcia and Hansma and attending the 1986 STM conference in Spain, Elings discerned a market for off-the-shelf STMs and proposed co-founding a company with Hansma to manufacture them. Hansma was even more wary than Quate of letting commerce encroach upon his lab's activities, so he declined, but he did give Elings the same advice and schematics he made available to other STMers.[50] With these, Elings and his son built a prototype STM in their garage and entered it in the latter's junior high school science fair (where it took last place, since, as the judges pointed out, "everybody knows you can't see atoms").[51]

For Elings, building the prototype not only served the purpose of ensuring that the Hansma design was marketable, but also as a means of testing—and discarding—many axioms of STM-building that had accrued since 1981. Elings regarded STM builders' trade secrets as fostering instruments that were erratic and difficult to operate. He viewed the possession of these trade secrets as a limiting factor in the makeup of the STM community, because only those deemed "serious" enough to build their own microscopes could belong. Elings wanted to make STMs specifically for nonbuilders who demanded a simple-to-operate black box. Hence he delighted in debunking the STM-builders' secrets by creating a more streamlined, durable, and easy-to-use tool.

Elings co-founded Digital Instruments (DI), hoping to be the first to market a commercial STM microscope by the time of the annual STM conference in 1987. Although his plan was always to sell a computer-controlled

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[49] Kirk interview.

[50] Hansma interview (n. 15 above); Elings interview (n. 22 above).

[51] Matt Thompson, interview with Cyrus Mody, Chadds Ford, Pa., 26 February 2001; Elings interview.

microscope (hence *Digital* Instruments), his former student (and DI cofounder) Gus Gurley was brought in too late to complete all the coding in time. Instead, Elings marketed the analog Nanoscope I as DI's first product. Probe microscopists from this era—both builders and buyers—recall their first acquaintance with the Nanoscope as being a turning point in the field. Now, for the first time, researchers could join the STM community without having had to build any part of their own microscopes. Moreover, unlike the Tunneling Microscope Company's clients, DI's didn't need to have personal ties to the community. Researchers could (and did) simply contact Digital Instruments and order the instrument.

Still, although it marked an important shift, the Nanoscope I illustrated the gradual, emergent character of commercialization in the field. Digital Instruments retained much of the flavor of a laboratory like Quate's or Hansma's, for Elings only gradually came to sell a more finished, integrated product. Like the CSS STM and Smith's instrument, the Nanoscope I was more a kit than a full-fledged, black-boxed research tool. Indeed, both for the Nanoscope I's early imperfect design and its lack of "serious" applications, Elings now calls this era at DI the "toy business."[52] In following Hansma's lead, Elings designed an air STM rather than the expensive, narrow-niche, ultrahigh vacuum instruments used at IBM and Bell Labs. This made sense in establishing a broader market, since few disciplines were willing to work with or pay for ultrahigh vacuum (which, in any case, ruined samples relevant to everyone except surface scientists). But it was unclear during the 1980s just what air STM could be used for or what the images it produced meant. Only in 1991–92 did a consensus develop that air STM was, in fact, not relying on tunneling for its contrast mechanism, and that many well-publicized air STM images (particularly of DNA) were erroneous. As a result, most STM researchers using air abandoned the technique and followed Quate and Hansma to AFM, usually by acquiring one of DI's newly available "Multimodes" (which were capable of running both STM and AFM).

Therefore the Nanoscope I and other air STMs had little rigorous application, although until 1991–92 it seemed possible that such applications would materialize if researchers could acquire inexpensive commercial STMs and adapt them for unforeseen purposes. The Nanoscope I was a "toy" because it was meant to be superseded, and because its buyers were envisioned as instrument-savvy and willing to experiment playfully with their new device until promising applications were found (not unlike DI's engineers themselves).[53] This assumption of similarity between designers

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[52] Don Chernoff, interview with Cyrus Mody, Indianapolis, Ind., 5 September 2001; Elings interview.

[53] This analysis resonates with Barry Dornfeld's *Producing Public Television, Producing Public Life* (Princeton, N.J., 1998), and Trevor Pinch and Frank Trocco's *Analog Days: The Invention and Impact of the Moog Synthesizer* (Cambridge, Mass., 2002), which also describe producers' use of themselves as a template in imagining consumers. My

and users allowed new designs and applications to flow in from the market and inform production of the more black-boxed, all-digital Nanoscope II. Hence innovation came rapidly because participants in the probe-microscopy field comprised an experienced and critical body. In fact, researchers who had previously built their own STMs formed a small but elite group of DI's early customers. This demonstrates why analyses of academic commercialization (both pro and con) should focus less exclusively on production, and more on professors' strategic combination of consumption and production. Academic researchers are well positioned to be active consumers whose reinterpretations of products flow back to the manufacturers and reshape design and marketing. As recent work in the history and sociology of technology has shown, users of many technologies actively shape the design and use of artifacts. This phenomenon is especially pronounced in instrumental communities, where the boundary between producers and consumers is especially tenuous.[54]

The assumed similarities of DI's engineers and early customers also reinforced its self-image as a freewheeling start-up that could rely on its users to make up for its lack of marketing and customer service. Elings had no sales force—he simply advertised in *Physics Today* ("$25,000 for atomic resolution"), and orders subsequently arrived. Instruments were sent to purchasers who assembled them and got them up and running on their own. Despite this minimal marketing and customer service (and limited product utility), Elings's fledgling business succeeded. An advertisement from 1990 estimates that during its first three years, DI sold more than 300 Nanoscopes at $25,000 to $35,000 apiece.[55] The probe-microscopy community expanded quickly, and its center of gravity shifted as well. As more researchers purchased instruments, AFM and air STM started superseding ultrahigh vacuum STM, and consequently, the corporate laboratories became less dominant. High demand created a waiting list, which instigated the policy that researchers who wanted a microscope quickly could expedite matters by naming DI's founders or employees as co-authors of papers reporting on research generated with the company's products.

DI recognized that to create a market among scientists and engineers, it had to demonstrate its trustworthiness as a producer both of microscopes and expertise.[56] Through its existing customers, the company associated

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thanks to Christina Dunbar-Hester and Trevor Pinch for their discussion with me on this point.

[54] Similar markets are apparent among hobbyists and artists. See Kristen Haring, "Technical Identity in the Age of Electronics" (Ph.D. diss., Harvard University, 2002), for the former, and Pinch and Trocco's *Analog Days* for the latter.

[55] From *FASEB Journal* 4 (1990): 1.

[56] This analysis draws on Bruno Latour and Steve Woolgar's concept of the "cycle of credit," but from the perspective of the instrument seller rather than the buyer. See Latour and Woolgar (n. 40 above).

credible facts with its product and its employees, hoping thereby to entice potential consumers to join the probe-microscopy community.[57] Notably, because the community still operated largely in a gray market, DI had to rely heavily on tactics such as bartering waiting-list position for shared authorship. Such tactics gradually diminished as the community became more commercial. Indeed, in this context, "commercialization" often signifies the narrowing of the varieties of exchange as a technology stabilizes, rather than the encroachment of a peculiarly corporate ethic into academia.[58]

The Roots of Digital Instruments' Success

Because DI was the first serious STM manufacturer, its competitors and successors played according to its terms. Some competed head-on for the general, multidisciplinary market; in the end, these firms faltered. Others who concentrated on smaller subcommunities have fared better, but still have to cope with the prospect that someday DI might target their market niche. Unlike the majority of academic start-ups, DI has been immensely profitable and innovative, yet this unusual success highlights broader truths about the commercialization of academic knowledge.[59] In particular, the contingent character of the instrumental community surrounding STM and AFM—and DI's role in it—elucidates debates about how universities can promote entrepreneurial activities among their faculty and whether academic entrepreneurialism can be a driver in regional economies.

From a regional perspective, DI clearly benefited from the geography of probe-microscope research, but in unexpected ways. Hansma and Elings both molded their free-form experimental styles to their group members' notions of "California culture."[60] At the University of California, Santa Barbara, for instance (in contrast to STM groups at IBM and Bell Labs), Hansma's group integrated self-cultivating hobbies (photography, woodwork-

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[57] In fact, DI tirelessly promoted journal articles written by its favored customers, citing them in its advertising and even reprinting them as application notes.

[58] There is a complicated relationship between "commercialization" and "stabilization" of a technology; for analyses of stabilization, see Wiebe E. Bijker, *Of Bicycles, Bakelite, and Bulbs: Toward a Theory of Sociotechnical Change*, ed. Wiebe E. Bijker, Trevor Pinch, and Geoff Bowker (Cambridge, Mass., 1995), and Paul Rosen, "The Social Construction of Mountain Bikes: Technology and Postmodernity in the Cycle Industry," *Social Studies of Science* 23 (1993): 479–513.

[59] To give an idea of DI's success: when it was bought by Veeco Instruments in 1998, a dozen years after its founding, DI was estimated to be a $54 million company, with some 2,500 units sold since 1987 and a net income of $16 million in 1996 and $13.7 million in 1997. *1998 Annual Report: The Future Is About to Surface* (Plainview, N.Y., 1999), 4 and 27.

[60] This was also true at other centers of commercialization (Stanford, University of California, Berkeley, and Caltech), although what constituted being peculiarly "California" took on decidedly local flavors; Scot Gould, interview with Cyrus Mody, Claremont, Calif., 27 March 2001; Nogami interview (n. 31 above).

ing, meditation, travel) with gray-market activities in the laboratory: undisciplined exploration of the instrument's capabilities, trolling for new applications, and collaborations between instrument-builders and representatives of various disciplines. Eventually, this mélange of exploratory individualism and easy-going collaboration fed into DI and similarly offbeat start-ups at universities on the West Coast. None of the successful STM and AFM manufacturers were big, established companies like Hitachi, Philips, or IBM (although big companies did make forays), and except for small European firms, almost all manufacturers obtained their initial designs through collaborations with academic (or quasi-academic national laboratory) groups in the American West or Southwest.

Digital Instruments's greatest regional stimulus, however, was largely negative. DI emerged within, but was separate from, the enormous military-industrial manufacturing complex of Santa Barbara and the Los Angeles basin. Many early DI employees wanted to stay close to the area's picturesque and casual environment and viewed DI as the only alternative to local defense firms.[61] This offers a curious lesson for those hoping to stimulate regional innovation. Universities do participate in local culture, but they have little control over which aspects of local culture professors adopt as emblematic of their experimental styles. Nor can universities control how those professors integrate local culture with the values and social contours of widely distributed instrumental communities. When the STM community's division of labor encouraged academic groups to be more exploratory than corporate ones, Hansma and Elings were able to guide lab work via constructions of a "California" of casual lifestyle and self-actualization; but they also relied heavily on the military-industrial "California" of Lockheed Martin and Vandenberg Air Force Base in finding personnel and acquiring resources.

Likewise, DI's success had roots in institutional arrangements at the University of California, Santa Barbara, though not in the patent and technology-transfer offices favored by proponents of academic entrepreneurialism. Rather, DI and Elings thrived at the university's disreputable margins. When Elings arrived in the late 1960s as a brash, confrontational professor, it was hoped he would build the university's reputation in high-energy physics. His swagger, however, led to conflict with his department, which sidelined him into running its less prestigious Master's of Scientific Instrumentation program, a lucrative but unloved backwater.[62] Undaunted, Elings transformed the program into his personal empire and a fountainhead for patents and start-up companies.

Crucially, in Elings's master's program students from many educational

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[61] The same can be said for employees at the smaller start-up manufacturers in Los Angeles: Quanscan, Topometrix, Pacific Scanning, and Quesant.

[62] Jerome Wiedmann, interview with Cyrus Mody, Santa Barbara, Calif., 18 October 2001.

backgrounds (biologists, engineers, even psychology majors) learned how to build all kinds of measurement technologies, including not only research instruments but also industrially relevant meters and tools. Initially, Elings relied on orthodox classroom instruction; soon, however, he drifted toward an alternative method that prized tacit over formal knowledge and participation over instruction. Instead of using textbooks and lectures, he connected students with professors on campus who needed instruments built and then let them learn by actually doing. Because student projects were based on finding solutions to real problems faced by local researchers, they often yielded technologies that Elings could market to those researchers' subdisciplines. Students learned how to understand customers' needs and hence design technologies to address them. This approach made his former students the most important source of initial employees for all Elings's ventures, especially Digital Instruments.

So, in a way, the University of California, Santa Barbara encouraged the creation of DI, although no other school would replicate its method. By sidelining a brilliant but difficult professor to a poorly regarded master's program, it encouraged him to reject campus culture, denigrate academically instilled formal knowledge, and be receptive to the commercial possibilities of the knowledge his students accrued. Moreover, in warning that Elings's commercial ventures hindered his academic career, the university's physicists made it more likely that his next enterprise—Digital Instruments—would result in his leaving academia. Paradoxically, this tension between Elings and the university *smoothed* the technology transfer from Hansma to DI, because Elings's hostility toward academic researchers meant he rejected Hansma's designs until they had been engineered to look more like commercial products than most home-built instruments.

Nonetheless, the similarity of work in Hansma's group to the pedagogical style Elings derived for his master's program is striking. Both Elings and Hansma regarded tacit, rather than formal, knowledge as primary in instrument-building. This meant that both men sought out people with diverse and unusual educational backgrounds: junior high school students, river guides, undergraduates, yoga instructors, retirees, psychology majors, and historians.[63] This diversity would have been unthinkable at other centers of probe microscopy. The shared emphasis on tacit knowledge meant that both DI and Hansma's group thrived on self-cultivating activities that seemingly were unrelated to technical matters. Digital Instruments, for instance, held a weekly "inventing session" in which employees brainstormed for solutions

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[63] James Massie, interview with Cyrus Mody, Santa Barbara, Calif., 18 October 2001; Helen Hansma, interview with Cyrus Mody, Santa Barbara, Calif., 19 March 2001; Dan Bocek, interview with Cyrus Mody, Santa Barbara, Calif., 23 March 2001; Thompson interview (n. 51 above); Drake interview (n. 33 above); Paul Hansma interview (n. 15 above).

to esoteric (i.e., non-AFM-relevant) technical questions (e.g., "How do you make a self-balancing laundry machine?") to become better inventors and hone their skills at withstanding Elings's intense skepticism.[64]

As members of DI and Hansma's group recognized parallels between their organizational styles, they appropriated these similarities to accelerate the two-way flow of people, materials, designs, and knowledge. After the initial phase (when most DI employees were Elings's former graduate students), several of Hansma's graduates, postdoctoral appointees, and collaborators worked at DI.[65] Individuals in both organizations collaborated to translate Hansma's research into commercial products. For instance, the Hansma AFM (on which DI's fortunes eventually relied) was transformed into a product through negotiations between Barney Drake (Hansma's technician) and James Massie (Elings's former student) regarding which elements of the Hansma design were indispensable and which were too erratic for commercial use.[66] As DI's sales increased, Hansma's group remained in the vanguard of the AFM community through its steady supply of DI instruments and the capability of Hansma's students through proximity to visit DI to scavenge parts and advice.[67] Whatever his initial reservations about commercialization, Hansma came to regard the partnership with DI as a means to position himself—intellectually and socially—within the instrumental community. This kind of strategic use of commercialization for academic purposes is rarely commented on by either defenders or critics of academic capitalism.

Subsequently, once the "toy business" phase of DI ended in the early 1990s, Elings began to imitate Hansma's tactic of bringing in postdoctoral associates to guide his instrument-builders' efforts. Digital Instruments assembled its own group of researchers from biophysics, magnetics, and

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[64] Pete Maivald, interview with Cyrus Mody, Santa Barbara, Calif., 18 October 2001; Bocek interview.

[65] Jason Cleveland, interview with Cyrus Mody, Santa Barbara, Calif., 20 March 2001; Gould interview (n. 60 above); Prater interview (n. 31 above). Personnel ties between the Hansma group(s) and DI were complex. Of Paul Hansma's graduate students, Scot Gould worked at DI for a summer, Craig Prater eventually became a senior executive in the company, and Jason Cleveland was there for a few years before starting another company, Asylum Research (double entendre intended), with other DI rebels; another, Mario Viani, went straight to Asylum. One of Paul Hansma's postdoctoral associates, Roger Proksch, was at DI before going on to Asylum; one of Helen Hansma's postdoctoral associates, Irene Revenko, moved to and stayed at DI. Paul Hansma's most important technician, Barney Drake, started a company, Imaging Services, that was housed within DI and acted as a clearinghouse for potential DI customers. Stuart Lindsay, an early collaborator of Paul Hansma's, started up a company, Molecular Imaging, that, early on, primarily made complementary hardware for DI's products (which DI marketed). Many more Hansma group personnel also had less formal consultative relationships with DI.

[66] Drake interview; Massie interview.

[67] Hoh interview (n. 33 above).

polymer chemistry who (as did Hansma's postdoctoral associates) worked with instrument-builders, developed and published articles on new STM and AFM applications, and traveled to lecture and attend conferences to publicize the company's efforts.[68] Although DI was a profit-making venture, its success came partly from the nonprofit practices of the Hansma group that it emulated: undertaking research, publishing articles, and training employees in the skills needed to "graduate" and found their own probe-microscopy companies. These practices were then widely emulated by other start-ups, such as Park Scientific Instruments (founded by Sung-Il Park and Sang-Il Park, who were [unrelated] Stanford postdoctoral associates), Molecular Imaging (founded by Stuart Lindsay and Tianwei Jing, one of Lindsay's former postdoctoral associates), and Quanscan (later reorganized as Topometrix, founded with John Baldeschwieler's help by Paul West, one of his former postdoctoral associates). All of these companies brought aspects of academic research to their operations.[69]

This movement of cultural values, experimental practices, and organizational structure from university to start-up is well documented in other fields of commercialization, especially biotechnology, where it was used to entice professors out of the ivory tower. This led to trouble when professors-turned-entrepreneurs were reluctant to guide their companies from research to profit-making. In contrast, with STM and AFM the corporate–academic isomorphism was successful less as a deliberate strategy than as a contingent and emergent harmonization of practices. It was largely an accidental outcome of the organization of the instrumental community that Quate, Hansma, and other academics promoted a gray market of circulating personnel, practices, and technologies that ultimately fostered successful commercialization. The pedagogy associated with this gray market was disinterested in commercialism, yet when players in these groups commercialized their instruments, they used that very pedagogy as a paradigm for companies and markets.

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[68] Instrument manufacturers' use of researchers to produce articles and application notes is a prominent feature of both Rasmussen (n. 4 above) and Lenoir and Lécuyer (n. 4 above); Sergei Magonov, interview with Cyrus Mody, Santa Barbara, Calif., 21 March 2001; Mike Allen, interview with Cyrus Mody, Alameda, Calif., 12 October 2001.

[69] The copying of experimental/organizational style first from university to start-up, and then among a field of start-ups, is a classic example of "institutional isomorphism"—the spread of innovations across organizations due to competition for personnel whose professional affiliations demand particular organizational forms or practices. See Paul J. DiMaggio and Walter W. Powell, "The Iron Cage Revisited: Institutional Isomorphism and Collective Rationality in Organizational Fields," *American Sociological Review* 48 (1983): 148–60, and Paul J. DiMaggio, "Constructing an Organizational Field as a Professional Project: U.S. Art Museums, 1920–1940," in *The New Institutionalism in Organizational Analysis*, ed. Walter W. Powell and Paul J. DiMaggio (Chicago, 1991), 267–92.

Conclusions

So what does probe microscopy tell us about the commercialization of academic knowledge and the value of corporate–academic linkages? First, the development of probe microscopy illustrates how completely—though intricately and indirectly—the corporate and academic worlds are interconnected. The locus of "academic research" is much wider than the university campus, just as the locus of "commerce" is wider than the for-profit business. Instrumental communities and other informal organizations are distributed across academic and corporate institutions. Commercialization—the transformation of academic research into commerce—is not a simple pipeline from university to firm. Commercialization can play many roles within an instrumental community, and academic research can be traded for many things other than money. Attempts, therefore, to directly stimulate and accelerate the transformation of academic research into cash may well backfire. As we have seen, it was the looser, *indirect* ties between corporate and academic groups that fostered the growth of STM and AFM and encouraged start-ups to emerge from universities, rather than direct pressure from corporations or overt incentives from governments and universities.

Proponents of academic entrepreneurialism should be wary of focusing too narrowly on increased profits as the outcome of commercialized universities. As indicated above, exchange is continuous in instrumental communities and usually is a mix of knowledge, prestige, personnel, time, materials, money, and opportunity. The popularity of various forms of barter changes as the community itself changes; for example, commercialization can restrict some exchanges and promote others, such as money-based trades. Few instrumental communities reach this point, however. Even within the probe-microscopy community, only the atomic-force microscope and magnetic-force microscope have been commercial successes. The STM, which provided the first product for microscope manufacturers, was effective in training engineers to build microscopes, but it never found an industrial application. The presence of gray markets in instrumentation may enhance national economic growth over time, but university administrators who hope that a particular gray market can be converted into a profit-making start-up to enhance local, short-term economic growth will almost always be disappointed.

Moreover, development of an entrepreneurial instrumental community may require that its members be recruited from less-profitable fields in which commercialization did not occur. The STM and AFM community, for instance, initially drew on its members' expertise in low-energy electron diffraction, sandwich tunnel-junction spectroscopy, and field ion microscopy—all instrumental communities with poor records of commercialization. Later, STM and AFM attracted participants from many fields (such as surface science, biophysics, mineralogy, electrochemistry, and polymer science, some of which were more commercialized than others) who aided groups such as Quate's and Hansma's in their gray-market activities. Instrumental communities in which the cultural map is not conducive to profit-making nonetheless provide the infrastructure and knowledge/labor pool for communities in which the profit motive may be enormous. Policy-makers cannot predict which communities will generate profits, and will hinder all if they try to encourage only profitable ones at the expense of the rest. Therefore policy-makers may be best advised to encourage professors to foster gray markets within their instrumental communities, whether as consumers, producers, or both. Gray-market activities such as exchanging research materials, personnel, and components of technologies enlarge the perspective of academic research. By focusing on the wider instrumental community that surrounds a technology, it is seen that the university may actually be more influential in maintaining a pool of skeptical, independent consumers who can threaten startups by the prospect of making their own tools or even founding their own firms.

Finally, both opponents and supporters of corporate involvement in academia have seized on grains of truth. Supporters have it right that corporate–academic linkages are desirable, even necessary, for research and innovation. There was no golden age in which faculty operated independently of commerce, pursuing disinterested research. Knowledge-production in physics, engineering, and chemistry was always aided by academic consulting and the exchanging of personnel and ideas. The oft-criticized commercialism of the "biotech revolution" merely extended long-standing entrepreneurial practices into molecular biology. The STM and AFM case study does, however, provide reason for opposing the notion that universities should be operated as businesses, seeking profit where they might and run along the "rational" lines of modern management. The probe-microscopy community developed rapidly because participants could point to different institutional poles: corporations, universities, and national laboratories. Sometimes innovation occurred because these poles were opposed, as when Hansma and Quate shifted from surface science and UHV STM to new designs and applications; at other times, innovation occurred because participants created hybrid forms between these poles: the gray market of software trading, the CSS STM, and the so-called toy business. Instrumental communities rely on a variety of actors who are part of different kinds of institutions. If all these institutions are operated on the same highly managed, profit-driven model, then the exchange of people and ideas and the production of new technologies will likely be hindered.