CHAPTER 9

CONVERSIONS: SOUND AND SIGHT, MILITARY AND CIVILIAN

CYRUS C. M. MODY

Introduction

Scholars in science and technology studies (STS) have long noted scientists' predilection for converting data into visual representations. Indeed, examining visual representations yielded many early STS keywords. Laboratory ethnographers, for instance, famously reinterpreted scientists as producers of "inscriptions" (Latour 1987). The conversion of Geiger counter "clicks" into "splodges" on a graph offered insights on inferential chains and interactions among subfields (Pinch 1985). Conversion to the visual provided a hook to mutually implicate vision and science as hallmarks of modernity (Crary 1990). Visual representations became raw materials for art historical analyses of science (Jones and Galison 1998) and histories of objectivity (Daston and Galison 2007).

Visual representations, however, are neither inexorable nor ubiquitous in science. Scientists still work with their ears, fingertips, and taste buds. Some scientists

---

Research for this chapter was supported by the National Science Foundation under Grant no. SES 0531184. Any opinions, findings, and conclusions are my own and do not necessarily reflect the views of the National Science Foundation.

prefer certain data in audible rather than visual form (Helmreich 2007). Alexandra Supper (this volume) has described the nascent "sonification" community's struggles for acceptance of this practice. Despite these struggles, sonification has found favor even among scientists whose work is primarily visual. I first ran across sonification, for instance, among scanning probe microscopists (Mody 2005), a group generally committed to visualization (hence micro*scopy*). Yet probe microscopy technology lends itself equally well to visual and auditory outputs. The "microscope" is a small solid probe that scans and interacts with a surface; it assembles measurements of the probe-surface interaction into a data array that is usually rendered visually but sometimes in auditory or other forms.

Sonification has been part of probe microscopy since its invention in the 1980s. The technique's ability to image individual atoms, for instance, was discovered when its inventors heard—rather than saw—an unusual repetition in how a chart recorder printed data (Mody 2004, 107). Yet only a small minority of microscopists audibilize their data. Those who do offer justifications in phenomenological terms: Some consider sound better for perceiving change over time, while some combine visualization and sonification for a richer data environment. These reasons, however, are inseparable from sociological motivations. Sonification is usually practiced by high-end probe microscopists who build rather than buy their instruments. Sonification helps them present their work as distinctively fine-tuned and artisanal compared to the mass of probe microscopists. Prominent builders such as Jim Gimzewski use sonification to forge collaborations with artists (Roosth 2009), and other builders play their microscopes' auditory output as background music during public talks. Those who buy their microscopes are much less likely to use sonification this way.

Two Senses of "Conversion"

Let us group visualization and sonification under a wider category of "synesthetic conversion" from one sense to another. In probe microscopy, the same people who practice sonification often venture into other senses as well. For instance, when the inventors of the technique heard their chart recorder and realized they could image individual atoms, they turned the chart recorder strips into a three-dimensional, tactile sculpture of the atoms rather than a (more ordinary) two-dimensional micrograph. Other prominent microscope builders who audibilize data also sometimes use haptic feedback, where the microscope physically pushes against its operator (e.g., when the microscope nudges carbon nanotubes or pries proteins apart). As with sonification, tactile or haptic representations are associated much more with microscope builders and tinkerers than with those who buy a microscope for use with few modifications.

That is, those probe microscopists who view synesthetic conversion as an embodied strategy for perceiving data in nuanced ways also deploy synesthetic conversion in the politics of their research community. Sonification and haptic feedback distinguish developers of new microscope technology from the mass of microscope users. Synesthetic conversion provides unusual interdisciplinary bridges to fields such as art, computer science, and robotics, and it locates skill and authority in probe microscopy by showing whose data or technology is so subtle and sophisticated that multiple senses (rather than vision alone) are needed to understand or operate them.

In today's probe microscopy, synesthetic conversion is generally limited to the small-p politics of jockeying within a field. But synesthesia can be embroiled in big-p politics. To demonstrate how, this chapter traces the prehistory of probe microscopy back to Vietnam-era protest at Stanford University. At that time, Calvin Quate (the coinventor of the atomic force microscope [AFM], the most common kind of probe microscope) invented a closely related instrument, the scanning acoustic microscope. Acoustic microscopy and other synesthetic conversion technologies were at the forefront of Stanford researchers' response to calls for more socially responsible science. Synesthetic conversions—from sound to sight, sight to touch, sight to sound, touch to sound, and so on—were embroiled in the "reconversion" of American academic research from military funding and applications to civilian funding and an orientation to "human problems."

As today's probe microscopy shows, synesthetic conversion in science does not have to be freighted with ambitions for societal reform. Moreover, "reconversion" at Stanford and elsewhere was never limited to new synesthetic conversion technologies. However, the acoustic microscopy case shows that, at times, projects for reforming knowledge making are coproduced with scientists' conversions of phenomena into visual, tactile, haptic, or auditory form.

Boiling Campus, Anxious Engineers

In the late 1960s, "reconversion" was the widely used term for the turbulent, occasionally violent, debate about whether American academic scientists needed to forego defense research and take up civilian social problems. Often historians' stories about this period end with reconversion as the dissolution of the early Cold War "military-industrial-academic" arrangement. The last chapter of Bill Leslie's (1993) *The Cold War and American Science*, for instance, is "The Days of Reckoning: March 4 and April 3," the dates in 1969 when the reconversion debate erupted at, respectively, MIT and Stanford.

One need only visit the Stanford University Archives—the primary data source both for this chapter and for the Stanford portion of Leslie's book—to see how deeply reconversion affected that campus in the late 1960s and early 1970s. University administrators' memos, campus newspapers, and faculty members' private correspondence (including Quate's) all speak to the frantic need to make up for declining defense research funding and to either quash or appease campus protestors' demands for more civilian research. Yet Leslie demonstrates that most of the reconversion movement's long-term effects were cosmetic. Both MIT and Stanford ended classified research and divested themselves of some defense-oriented institutes, but most of the proposed reforms were abandoned. Postdivestment, centers such as the Stanford Research Institute and Draper Laboratory prospered and maintained closer ties to Stanford and MIT than reconversion proponents hoped.

Reconversion's consequences were not all short-lived, though. Matthew Wisnioski (2005) sees reconversion as part of a wider movement in which American scientists and engineers questioned their motivations and practices, founded STS programs, read works by the Frankfurt School, and collaborated with artists. Eric Vettel (2006) sees reconversion as triggering the emergence of the biotech industry. Both Leslie (2010) and Wisnioski show that, at MIT, some researchers did successfully move away from military funding and applications—though those who succeeded were skeptical their actions could be widely replicated.

Nevertheless, reconversion proponents heralded such success stories. As Holt Ashley, a Stanford aeronautical engineering professor in the Stanford School of Engineering, put it in a short-lived student-faculty publication dedicated to debate about reconversion, "Against the unregenerateness and glacial metamorphosis of some, I don't hesitate to place the valuable progress on socially significant projects led by Lusignan, Meindl, Anliker, Homsy, Pantell, McCarty, and DeVoto."[1] Of these, James Meindl offers the clearest instance of the entanglement of reconversion and synesthetic conversion and an explicit model for Quate's foray into acoustic microscopy.

An electrical engineer working for the Army Signal Corps, Meindl moved to Stanford in 1967 and began working with John Linvill, chair of the electrical engineering department (Lécuyer 2005). Since 1962, Linvill had been developing the Optacon, a device for scanning printed pages and converting text into mechanical vibrations that could be felt by a blind reader. Linvill's original work predated the lean budgets and political turmoil of the late '60s and was based partly on personal motivations (his daughter was blind). Meindl's arrival, though, coincided with the first reconversion murmurs at Stanford and triggered an acceleration of Optacon research and its extension into other civilian and socially conscious applications.

As a 1973 brochure put it, Meindl's lab's "central objective . . . is to prepare the student to use integrated circuit technology in an innovative manner in solving the problems of our society . . . particularly in the field of medical electronics."[2] "Problems of our society" was typical reconversion rhetoric. Synesthetic conversion was a recurring motif of the approach Meindl's lab took to solving those "problems of our society": conversion from sight-to-touch (the Optacon, or "OPtical to TActile CONverter"), sound-to-sight (ultrasonic soft-tissue imaging), and later sight-to-sound (an adaptation of the Optacon to read scanned letters aloud via synthesized voice) and touch-to-sound (an artificial ear project).

That synesthetic conversion was upheld by Stanford administrators as a model for reconversion can be seen in the annual reviews of Stanford's electronics research. These reviews summarized the results of funding from the military services and NASA. Thus, through 1968, defense applications headlined, with civilian applications tucked at the back. In the 1968 review, for instance, the Optacon was described briefly (in purely technical terms) on page 27. The 1969 review, however, came just four months after a student takeover of Stanford's Applied Electronics Lab and the university administration's decision to ban classified work on campus. Suddenly, the Optacon was promoted to page 1, where the report pointed out the following:

> Two nontechnical aspects of the [Optacon] reading-aid project are noteworthy. (1) Integrated circuits, principally developed to the present stage for space and military applications, are powerful tools for the solution of human problems, as this research project illustrates. (2) Such projects . . . [are suited to] channeling [the] interest of the imaginative graduate student to important social problems.[3]

The rhetoric here contains clear gestures to reconversion: "Space and military applications" are specifically contrasted with "human problems," and graduate students are imagined as above all interested in solving "social problems."

From Acoustic Wave Devices to Acoustic Microscopy

Linvill and Meindl's Optacon and other synesthetic conversion technologies were a bright light in a dark year for the Stanford administration. The Optacon offered a riposte to reconversion proponents and a guide to other faculty members, especially those needing new funding after Stanford lost $2 million when it canceled its classified research contracts. It is perhaps unsurprising that Calvin Quate was one of those who followed their example. His research was heavily funded by the military and therefore jeopardized both by the new Stanford policy and by cuts in federal defense research funding. Moreover, Quate was an ardent admirer of Meindl, and Linvill was his department chair.

Quate received his doctorate from Stanford in 1950, working on microwave traveling tubes. He continued that research for almost a decade at Bell Laboratories before taking a joint appointment in electrical engineering and applied physics at Stanford in 1961. In the '60s, he studied ultrasonic-electromagnetic interactions in crystals, particularly for signals processing. He became well known for research on acoustic wave devices, by which an electrical signal is converted into an ultrasonic wave, processed via interaction with a crystalline matrix or tiny interdigitated structures, and then reconverted into an electrical signal. The U.S. Air Force and U.S. Navy funded Quate to develop acoustic wave devices to pick radar signals out of background noise and recognize radar patterns corresponding to specific aircraft.

The idea that Quate's electroacoustic research could be adapted to microscopy was suggested by Rudolf Kompfner—another Bell Labs veteran—while they "were sitting around the swimming pool one day" in 1966 (National Science Foundation 1978, 36; Pierce 1983). Kompfner proposed that a thin film transducer could create an ultrasonic wave that could be focused with a lens onto a sample (figure 9.1). After interacting with the sample, the transmitted ultrasonic radiation would then hit another transducer (or reflected ultrasonic radiation would hit the original transducer) and be converted into an image.

The way Quate and Kompfner spoke of their turn to acoustic microscopy gestured toward an intertwining of synesthetic conversion and reconversion. For a few years after their poolside chat, they did little work in the area. As reconversion boiled over in 1969, though, both men put aside other commitments and focused on acoustic microscopy in a way that, consciously or not, aligned with the aspirations of reconversion proponents. In their justifications for this work, Quate and Kompfner made the case that acoustic microscopy would have enormous civilian benefits. They did so partly by investing the visual apprehension of invisible phenomena with nearly magical importance in world history:

> If one makes the crude assumption that the acquisition of new knowledge is in some way proportional to the extension of the scale of magnitude of the

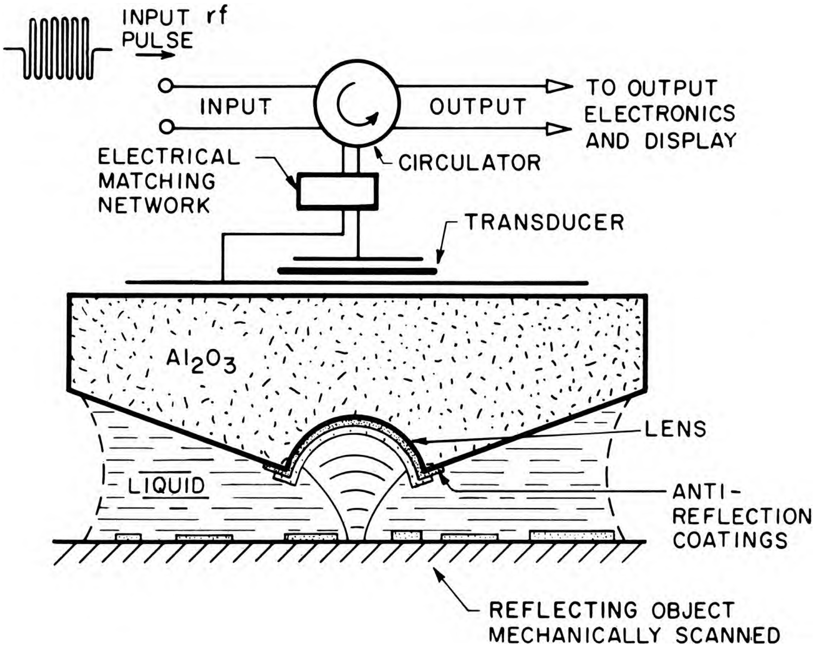

Figure 9.1 Schematic of (reflection mode) scanning acoustic microscope. Reproduced with permission of University of California Press, from Edwin S. Boatman, Michael W. Berns, Robert J. Walter, and John S. Foster, "Today's Microscopy: Recent Developments in Light and Acoustic Microscopy for Biologists," ***Bioscience*** **37 (June 1987): 384–94. Permission conveyed through Copyright Clearance Center.**

> perceived objects . . . one might even be tempted to compare the total amount of information about nature at any time with the . . . useful magnification of the best microscopes. (Kompfner 1975, 619)
>
> It is hard to conceive of a modern laboratory involved with technology or the advancement of science that is without a microscope of some kind. It has been suggested that the number of instruments in a given country used to extend our "vision" beyond the limits of the unaided eye can be used as an indicator of the progress and advancement of that region.[4]

That is, for Quate and Kompfner, a society capable of making progress was necessarily one where human "vision" was extended "beyond the limits of the unaided eye" both in scale and in the types of radiation that could be perceived. Synesthetic conversion was therefore inseparable from societal "advancement."

For the first few years, the Office of Naval Research funded Quate's acoustic microscope work as part of an umbrella package to Stanford rather than an individual grant.[5] Before long, though, Quate disentangled acoustic microscopy from defense funding. I have no direct evidence that this was in response to reconversion pressure. There is no reason to think Quate ever had any personal qualms about defense funding for his research. Indeed, he was not cooperative with reconversion-minded students' investigations of defense-funded research at Stanford (SWOPSI, 1971, 215). It is probable that, like Meindl, Quate enthusiastically embraced "human problems" research while also viewing defense-funded research as both good science and good citizenship.

However, Quate's turn to acoustic microscopy eerily matched specific Stanford administration recommendations in the wake of the first protests against on-campus classified research in 1966. In particular, a memo from Linvill in 1967 detailed the electrical engineering department's steps toward reform:

> Stanford University can and should become more effective in studying and attacking the problems of today's society. Electrical Engineering, with its aim to bring technological tools to the solution of man's problems, is interested to join with other departments in working on these contemporary problems. . . . The usefulness of university engineering and science to our defense efforts since the beginning of World War II is clear and well documented. It is also clear that attention should be directed in a university to other problems. . . . [E]nvironmental studies, urban problems, problems of developing countries, etc.—are timely problems to which the university in many of its parts should be directed. These problems cannot be attacked within a single discipline. . . . Financial support for the research must be found outside the university, however, as has been the case in our DOD and space research. . . . Representative areas providing opportunities are: (a) education by teaching machines, (b) automation and cybernetics, (c) applications of solid-state electronics to the life sciences, and (d) application of computers in life and economic systems.[6]

Note that "defense efforts" are specifically contrasted with work on "the problems of today's society" and that the memo clearly encourages Stanford engineers to include more of the latter in their research portfolios.

LINVILL'S MEMO

The acoustic microscope aligned with Linvill's memo in a variety of ways. Most important, it answered Linvill's call for "applications of solid-state electronics to the life sciences." At the time, Quate and Kompfner spoke of their microscope as having application only in biomedicine and not in areas of interest to the military. "[T]he original intention behind the Stanford work was to make an instrument which would achieve a resolution on the order of 0.1 μm for the purpose of studying biological objects, particularly the nuclei of cells" (Kompfner 1975, 627).

This initial exclusive emphasis on biological specimens is curious. The first suggestion for an acoustic microscope in the West was a translation (Devey 1953) of a Soviet article by a program manager at the Office of Naval Research (ONR). That article mentioned only metal and glass samples, not biological ones. Yet when Quate and Kompfner approached the problem, they were initially oblivious to nonbiological samples. They were acutely aware that the initial funder for the acoustic microscope, the military's Joint Services Electronics Program, might object and ask whether Quate was "going to come up with an instrument for studying materials or an instrument for studying biological structures? And why is any of this related to a research program for electronics?"[7] Yet despite that potential objection (and their awareness of the 1953 ONR article), Quate and Kompfner initially downplayed acoustic microscopy's application to military-relevant materials, while highlighting its relevance to medicine.

Acoustic microscopy also aligned with Linvill's reconversion memo in that it enabled Quate to search for new "financial support . . . outside the university." Unlike his earlier defense-funded microwave work, Quate's acoustic microscopy research was funded by the John A. Hartford Foundation, National Science Foundation, National Institutes of Health, National Bureau of Standards, and IBM. Quate also licensed acoustic microscope patents to companies selling to the civilian market—something he had not attempted before. Those licenses were negotiated through Stanford's new Office of Technology Licensing (OTL—one of the first of its kind; see Smith-Hughes 2001; Colyvas 2007; Yi 2008, 182–3). The rhetoric of reconversion suffused justifications for the OTL. As a Stanford vice president put it, "I am pleased by the high societal value of inventions we have licensed [such as] a potential cure for viral infections and a potential ecologically safe insect control" (quoted in Colyvas 2007, 69–70).

As the quote indicates, the OTL concentrated on fields favored by reconversion proponents, especially biomedical and environmental applications. The OTL's initial contacts with Stanford engineers, therefore, emphasized inventions with humanistic and civilian application, especially ones that used synesthetic conversion to forge interdisciplinary links. John Chowning's patents for electronic sound synthesis and proprioceptive perception of sound, for instance, linked engineering to music (Nelson 2005). Similarly, Meindl's patents for ultrasonic blood imaging tied engineering to biomedicine. Meindl and Linvill's Optacon was also commercialized in the early '70s (Lécuyer 2005, 60).

The OTL viewed acoustic microscopy as yet another bridge between engineering and life science. In 1974, the office licensed American Optical to use Quate's patents to manufacture commercial microscopes. By that point, Quate had realized acoustic microscopy had applications in microelectronics manufacturing in addition to biomedicine. However, for the OTL, microelectronics had neither the "high societal value" nor the interdisciplinary cachet of life science. For that reason, OTL saw microelectronics as secondary to (indeed, a subset of) biomedical applications:

> A license agreement for commercial development of a microscope that uses ultrahigh-frequency sound waves to see into living cells and other materials has been signed. . . . By comparing [acoustic and optical microscopy], diagnosticians should be able to tell more about cell functions and disorders. Since ultrasonic waves can penetrate materials, they also can be used to show defects in microscopic integrated circuits. The new integrated circuit technology already has provided the world with life-saving heart-pacers, hearing aids, minicomputers, and many other benefits.[8]

For the OTL, electrical engineering was worth mentioning not for itself but for its contribution to biomedicine.

The OTL's attitude was common at Stanford at the time. As Linvill's 1967 memo and *The Grindstone*'s praise for Meindl's biomedical collaborations show, engineers working on biomedical topics were seen as "attacking the problems of today's society" in a way that those working on radar-signals processing were not. Linvill's declaration that biomedical, environmental, urban, and other civilian "problems cannot be attacked within a single discipline" was intended to make engineering expertise relevant to such problems and to stimulate Stanford's engineering faculty to pursue interdisciplinary collaborations that would bring diversified funding and a positive reception from reconversion proponents.

As Bill Leslie (1993) notes, the military had promoted interdisciplinarity among electrical engineers, physicists, and applied physicists at Stanford since the 1950s. Reconversion, however, brought calls for much wider-ranging collaborations between engineering and music, philosophy, economics, biology, and so on. Reconversion proponents believed narrowly discipline-based questions distracted engineers from solving "human problems" and shielded them from the moral consequences of their work. Working with other disciplines would allow engineers to become aware of a wider range of society's problems to which they could apply their knowledge.

Along those lines, Linvill's 1967 memo proposed to:

> introduce a Senior or Master's level program involving both engineers and students from the Humanities and Sciences for the purpose of discussion and formulation of problems of significance which society needs to have solved and to which technology can contribute as a partner with the humanities.[9]

The STS programs formed in this period—including Stanford's—also reflected this view of the healing power of interdisciplinarity. More generally, the number of degree-granting interdisciplinary programs at Stanford *doubled* from 1968 to 1969 (the largest relative or absolute increase in the school's history) and grew seven times more rapidly in the '70s than in the '60s (Nelson 2005).

Nor was Stanford alone in connecting interdisciplinarity to civilian reconversion. For instance, when the National Science Foundation was commanded in 1971 to fund research "to solve major problems such as pollution, transportation, energy and other urban, social and environmental problems and to initiate and expand applied research essential to technological advancement and economic productivity,"[10] it did so not through its traditional disciplinary units but through a program called Interdisciplinary Research Relevant to Problems of Our Society (renamed RANN—Research Applied to National Needs). In a time of declining federal research funding in general and defense research funding in particular, such interdisciplinary funding streams provided a lifeline. Quate, for one, sought funding from RANN for acoustic microscopy, as well as for power transmission line research.

From the Life Sciences to Microelectronics

So acoustic microscopy aligned Quate with reconversion aspirations by facilitating connections to life science, to new funders, and to the market (and hence to wider society). Those connections consisted in the microscope's ability to combine sound and vision and allow life scientists to see "the density, the elasticity and the viscosity [of cells]—properties which are far more vital to the functions of living tissue than the optical refractive index."[11] Getting nonengineers to "see" acoustically, though, was harder than Quate anticipated.

In the first place, he had difficulty weaning himself from defense funding partly because civilian agencies needed visual proof of synesthetic conversion before they would fund him. " 'We had a concept, [but] we had no lens, we had no photographic film, we had no way of displaying the image,' Quate recalls. He applied for funding from the federal government, but was unsuccessful 'because there were no images, there were no results, there was just a theory' " (Jacobson 1984, 132).

Luckily for Quate, a Stanford Medical School colleague told him about the Hartford Foundation, a philanthropy that funded biomedical research. Hartford gave Quate $170,000 for two years starting in 1969, after which he had a prototype. From that first grant, Quate learned that the microscope would need to scan the lens relative to the sample (figure 9.1). Without scanning, the acoustic image would have to be received by an array of detectors, each kept in phase with the rest—a nearly insurmountable task at the time. With scanning, a single detector could capture a tiny picture of the sample at any moment; by moving over the sample, in time a complete two-dimensional image could be generated on an oscilloscope.

Quate then secured $300,000 from Hartford for the next three years by promising to collaborate with biomedical researchers. Thus, he began soliciting colleagues for biological samples to be imaged with the acoustic microscope. Eventually he could point to samples received from the Stanford departments of surgery, pathology, psychology, radiation oncology, hematology, anatomy, medical microbiology, and biology, as well as from the Mayo Clinic, University of California at Irvine, Albert Einstein School of Medicine, University of North Dakota, National Cancer Institute, U.S. Department of Agriculture, and the Faculty of Medicine in Montpellier, France.

Quate's pitch to collaborators and to funding agencies pivoted on comparing the resolving power of acoustic microscopy with more familiar optical and electron microscopes. The basic milestone Quate set himself was a comparative one:

> One of the earliest goals that we set for ourselves in the acoustic microscope program was to record an image using an acoustic wavelength smaller than that used in the optical microscopes. . . . Now it has happened—we have an instrument operating with an acoustic wavelength in water equal to 5450 Å!![12]

Later Quate described the event with even more excitement: "Never again will we have to state that the resolution is within 'a factor of two of the optical resolution.' Never again will we have to answer the query 'what is it good for?' "[13]

As I've written elsewhere (Mody 2000), proponents of a new technology use comparisons to other artifacts at their peril. Comparisons can create a logic that makes it difficult to exploit the new technology's unique abilities. In the case of acoustic microscopy, the technique's resolution matched the optical microscope's only after a decade of work, during which biomedical researchers provided Quate with samples but saw few reasons to adopt the new instrument.

Even after Quate achieved parity with optical microscopy, life scientists complained that (on the one hand) acoustic microscopy still had poorer resolution than electron microscopy, while (on the other hand) it was still less user friendly than optical microscopy. American Optical, in declining to manufacture commercial microscopes for life scientists, noted that "the key problem in encouraging broader use of the acoustic microscope was that it took on the order of one day from receipt of a specimen until a useable picture was obtained."[14] That is, one reason life scientists avoided the technique was that the synesthesia of acoustic microscopy was not effortless enough. Biomedical researchers could simply walk up to an optical microscope and peer through it to get the answers they wanted, whereas acoustic microscopy required patience. As Quate (1985, 134) put it, "We can compete in resolution, but we cannot compete with the immediacy of the optical images. When you look, the optical image is there. For an acoustic image of similar quality you must wait."

Biomedical researchers preferred the immediacy of vision to acoustic microscopy's mediation of sight and sound. To overcome the invidious comparison, Quate pointed out that acoustic microscopy could "see" things optical microscopes couldn't:

> If the observer had a choice it is not obvious that he would choose optical waves for the microscopic examination. . . . [F]or the most part the form, function, and growth patterns of cellular complexes do not depend on their optical properties. . . . Contrary to this the elastic properties are directly and intimately connected to the form and function of a cell. . . . In the new microscope acoustic waves in the form of propagating elastic waves—familiar as water waves in the oceans and sound waves in the air—are used in such a way that we can now monitor these elastic properties.[15]

Biomedical researchers were neither synesthetically nor cognitively familiar enough with ultrasonic radiation to be comfortable with acoustic microscopy: They knew what an optical micrograph of a cell meant, but images made with acoustic radiation required a difficult translation between senses:

> The training and background of such people as pathologists and histologists cannot be easily transferred in a way that will allow them to interpret the acoustic micrographs with the same facility that is now done with the optical photos. . . . [W]ork to date has been done in an electronic laboratory with people possessing a background in physics and electronics. No one in biology or in medical research has carried out a significant piece of research with this new instrument.[16]

Difficulties in interpreting acoustic micrographs stymied Quate's efforts to deepen collaboration beyond biomedical researchers' simply handing him samples.

Without those deeper collaborations, agencies balked at funding biomedical acoustic microscopy research. As an NIH reviewer told Quate in turning him down, "[T]his research will require a more definitive commitment and interaction with cell biologists, preferably one who can make a daily involvement."[17] By 1974, therefore, Quate was seeking alternatives to biomedical applications and the civilian agencies that funded them. This shift was aided by two changes in the political environment of American science. First, reconversion fervor had burned itself out. American universities were no longer overwhelmed by protests, sit-ins, teach-ins, or faculty strikes. Soul-searching publications like *The Grindstone* had petered out. While many Americans still wanted scientists to tackle society's problems in preference to the military's, few now vocally questioned the morality of researchers who took defense funding.

Second, the American public's laundry list of civilian problems that scientists should tackle began to converge with research problems relevant to the military. In the late 1960s reconversion proponents had pushed for research on environmental problems, urban housing, mass transit, and medical research. These were areas where applied physicists/electrical engineers like Quate were most out of their depth, as shown by his difficulties forging biomedical collaborations. After the oil crisis of 1973, those problem areas faded and were replaced by alternative energy research. The NSF's RANN budget, for instance, doubled from 1974 to 1975, due almost entirely to new funding for solar and geothermal energy research (WSF 1974). In these areas—particularly solar—physical scientists and electrical engineers could contribute without having to expand their horizons as broadly.

As the economy further deteriorated, a new problem area arose—national economic competitiveness, particularly with Japan in microelectronics. In the dynamic random access memory (DRAM) market—the microelectronics industry's barometer—the ratio of U.S. firms' share to that of Japanese firms went from 19:1 in 1971 to less than 5:1 in 1974 to 1.4:1 in 1977 (Macher, Mowery, and Hodges 1998). American policymakers, microelectronics manufacturers, and academic electrical engineers monitored this gap closing with alarm. The Japanese government's announcement in 1975 of a VLSI (very large-scale integrated circuits) crash program prompted calls for the U.S. government to aid domestic manufacturers by funding academic microelectronics research.

Here, applied physicists/electrical engineers like Quate could serve national needs without the complications of crossing many disciplinary boundaries. Moreover, in microelectronics the goals of military and civilian funding agencies coincided. The military wanted to stimulate domestic manufacturers to avoid dependence on offshore producers for advanced chips. Also, microelectronics research was perceived as more likely to have dual military-civilian applications than the biomedical and environmental research earlier favored by reconversion supporters. Thus, Quate could now propose to the armed services to use acoustic microscopy to inspect *both* microelectronic circuits and materials used in advanced airframes and naval vessels.[18] Perhaps the clearest sign that civilian and military interests aligned around microelectronics was a program that funded Quate from 1976 to 1978 on "Innovative Measurement Technology for the Semiconductor Industry"—run jointly by the National Bureau of Standards (part of the Department of Commerce) and the Advanced Research Projects Agency (the Pentagon's long-range research-funding arm).

Through that program, Quate had much more success finding collaborators than he had with biomedical applications. Samples of microelectronic devices for the acoustic microscope to inspect came to him from Hewlett-Packard, Avantek, IBM, Fairchild Semiconductor, and other companies. Many of the microelectronics researchers who sent samples found acoustic microscope images useful—much more so than biomedical researchers had. They were particularly pleased that the acoustic microscope could look through a thin film to see whether it completely adhered to its substrate, something other instruments could not do. Since applying thin films is an essential step in microelectronics manufacture, catching defective films could save firms millions.

For that reason, electronics firms—unlike biomedical researchers—built their own acoustic microscopes or bought them when they became commercially available: Bell Labs, Hughes Aircraft, IBM, Hitachi, DuPont, Westinghouse, Motorola, TRW, Intel, and others are all mentioned in this regard in Quate's correspondence.

This interest in turn meant that microscope manufacturers could foresee a market in a way that American Optical had not when the only customers were likely to come from biomedicine. With Quate's help, two firms, Leitz in West Germany and Olympus in Japan, developed commercial instruments for microelectronics customers.

Synesthesia, Conversion, and Awareness

With the return to electronics applications and defense funding, both reconversion and synesthetic conversion faded as drivers of Quate's research. To understand why, we need to delve into the reason these phenomena were paired in the first place. Here I will be extremely speculative. For now, the documentary record is too sparse to directly address this point. We can, however, approach the issue by asking, what was reconversion really about?

I would argue that reconversion aimed to bring researchers into a heightened state of awareness—of themselves and others and of connections between the two. Most narrowly, this meant making researchers aware of the consequences of their research for the people of Southeast Asia. It was on that narrow interpretation of reconversion that the debate became heated and occasionally violent. Nonetheless, many reconversion supporters sought a broader awareness. They wanted researchers not simply to be aware of society's problems (which many already were) but also to see themselves as agents that possessed the capacity to solve those problems.

Some reconversion proponents focused on institutional and political changes to facilitate this awareness. Lessening researchers' dependence on military funding, for instance, would make them more aware of civilian problems and of the agencies that fund scientists to solve those problems. Likewise, the creation of interdisciplinary centers would make researchers like Quate aware of "human problems" in the life sciences in such a way that they could envision how electrical engineering could solve those problems. Reconversion-oriented publications like *The Grindstone* pushed faculty to recognize their own political agency in effecting reconversion: "If the faculty truly desires to redirect the School, they must accept the inconvenience of lobbying the executive to changing budget priorities, and then follow through by providing advice and testimony, if necessary, for the Congress."[19]

Yet reconversion was not limited to institutional and political reforms. The counterculture encouraged many scientists and engineers to follow a technological and synesthetic path to awareness as well. For them, awareness could be expanded by developing new technologies for integrating the human mind with a greater range of perception and/or for making the perceivers more aware of their place within society and the environment.

One epicenter for this approach was Quate, Linvill, and Kompfner's former employer, Bell Labs. Matthew Wisnioski has detailed efforts in the late '60s to carve institutional space at Bell Labs for collaborations with artists and other ways to humanize engineering practice. One result was the Experiments in Art and Technology (E.A.T.) organization that brought Bell Labs engineers together with artists such as Robert Rauschenberg. As Wisnioski (2005, 300–301) describes it, most of E.A.T.'s few successful engineer-artist collaborations involved synesthetic extensions of their audience's awareness, such as "a glass-enclosed cube with a high-intensity light beam, which illuminated a pile of dust that responded to acoustic vibrations of recorded heart rhythms" or a sculpture "sensitive to changes in its environment, [which] consisted of vibrating steel rods illuminated by strobe lights, which modulated to the sounds in the room."

Kompfner worked with one of E.A.T.'s organizers, Billy Klüver, and provided advice for John Cage's contribution to E.A.T.'s "9 Evenings: Theatre and Engineering" shows (Klüver 1988), in which performers' movements tripped photocells, triggering sound sources all over New York—a true synesthetic symphony. Around the same time, he wrote an unpublished essay expressing his own, complex views on music, technology, and cognition:

> *Music represents the human mind. It is the representation by the human mind of itself.* . . . In depicting the processes, the states and the modes of operation of the human mind music at first did it simply and in a primitive way, limited perhaps by the technology which was available for its expression. As western technology developed and surpassed anything that existed before on this planet, it became possible to express music in ever increasing complexity, and to depict ever increasingly complex mental phenomena, so that finally music has achieved the power to represent all of the human mind, and perhaps even more than that. Music describes what human mind has not yet reached, and may perhaps never reach; it goes beyond the compass of the human mind just as mathematics does when it operates in many dimensions.[20]

Quite possibly Quate knew about E.A.T. through Kompfner. If not, he certainly knew about Bell Labs' collaborations in electronic and computer-aided music with Stanford's John Chowning since he played a role in Chowning's tenure case. Quate and Kompfner's old boss, John Pierce (to whom Kompfner sent his essay on music), connected Chowning with Max Mathews, another Bell Labs musician-engineer. Pierce also encouraged Chowning to patent his FM synthesis work (Reiffenstein 2006). Later Quate was instrumental in bringing Pierce and Mathews to faculty positions in Chowning's Center for Computer Research in Music and Acoustics.[21] Though there is no evidence Quate himself participated in synesthetic artist-engineer collaborations, his closest colleagues did so while he worked on acoustic microscopy.

The other epicenter of technophilic-synesthetic extensions of awareness was the San Francisco Bay Area. At Berkeley, for instance, physicist Don Buchla was building particle accelerator components for the Atomic Energy Commission when the free speech movement pushed him toward more humanistic, civilian, and synesthetic applications of his talent for electronics (Pinch and Trocco 2002, 33–36). Initially that meant developing a transistorized hearing aid, then a proprioceptive sensor for blind people that "changed pitch according to its proximity to objects." Most famously, he developed the Buchla Box, an analog synthesizer distinguished from its rivals by Buchla's interest "in involving as many senses as possible" (Pinch and Trocco 2002, 49).

Similarly, Buchla's patron, Ramón Sender Barayón, coorganized the Trips Festival of 1966 with (Stanford alumnus) Stewart Brand. "In venues like the Trips Festival, the hippies of Haight-Ashbury sought to demonstrate the ability of technologies such as LSD, stereos, and stroboscopic lights to amplify human consciousness" (Turner 2006, 178) by mixing those technologies into a single, transcendently synesthetic experience. Brand, in turn, was closely associated with techno-synesthetic experimentation at the Stanford Research Institute (SRI). Willis Harman, Quate's colleague in the Stanford electrical engineering department and an SRI researcher, introduced Brand to LSD, and Brand subsequently connected SRI to the counterculture. Though SRI's classified contracts were a critical focus of reconversion protests at Stanford, many SRI researchers drew on countercultural aspirations in devising technologies for expanding consciousness to integrate an ever-larger sensorium.

At the time, for instance, SRI's best-known research was its "Electronics and Bioengineering Laboratory's" 1972 experiments on parapsychological synesthesia. Spoon bending, remote viewing, telepathy, and ESP attempted to expand awareness until mental states could convert into physical actions (Kaiser forthcoming). Today SRI is most famous as the birthplace of the mouse and the graphical user interface (GUI), which debuted at the so-called mother of all demos in 1968, for which Brand served as videographer. Both those technologies originated in the same techno-synesthetic aspirations as the Buchla Box, Trips Festival, and acoustic microscopy. Thierry Bardini (2000) argues that their inventor, Douglas Engelbart, explicitly conceived them as synesthetic devices that would enable "augmentation of the human intellect" through feedback between proprioception (movement of the mouse) and vision (seeing the cursor on the screen).

I have no evidence that Quate knew Engelbart (much less Buchla or Brand), but they were geographically, socially, and intellectually proximate. All three had multiple connections to Stanford's School of Engineering. More generally, the two organizations that defined Quate's career—Stanford and Bell Labs—were places where reconversion and synesthetic conversion intertwined. Quate's boss at Bell Labs, John Pierce, was one of the first prominent engineers to publicly criticize the military-industrial complex for "alienating engineering education from the civilian economy" (quoted in Leslie 1993, 252). He was also a staunch proponent of artist-engineer collaborations that fused multiple senses into one synesthetic experience. Likewise, Quate's Stanford department chair, John Linvill, outlined a clear program for reconversion three years before the campus erupted in protest—at the same time that he was developing the Optacon.

While administrators like Pierce and Linvill outlined political and institutional reforms, engineers in Bay Area and Bell Labs workshops and laboratories focused on new synesthetic technologies as a complementary or alternative path to reform. Most of these engineers were not politically active. Kompfner, Quate, Buchla, Engelbart, Chowning, Mathews, Meindl, Klüver, and others had all worked on Cold War technologies funded by defense agencies, usually with great pride. Yet some of this group also were attracted to a more humanistic, socially conscious engineering practice geared to "maximizing how much good I can do for mankind" (Engelbart, quoted in Bardini 2000, 8). Technologies for expanding awareness offered a less overtly politicized way to maximize the good they could do. As Fred Turner (2006, 108) says of Engelbart, he "worked to create an environment in which individual engineers might see themselves as both elements and emblems of a collaborative system designed to amplify their individual skills." Technologies for translating among visual, auditory, haptic, tactile, and proprioceptive sensations offered a way both to amplify individual skills and create collaborative systems linking engineers to "representatives from different tribes—e.g. sociology, anthropology, psychology, history, economics, philosophy" (Engelbart, quoted in Bardini 2000, 16).

Linvill may have seen projects like Engelbart's as the intended outcome of the institutional reforms he proposed. The first two "representative areas" of research Linvill called for in his 1967 memo were "(a) education by teaching machines [and] (b) automation and cybernetics." Engelbart's whole program was a kind of educational teaching machine, and he and Brand were closely associated with the nearby Portola Institute's work in instructional technologies (Turner 2006, 70). Both were also deeply influenced by cybernetics; like many, they saw it as a bridge from engineering to biomedicine, art, and music (Dunbar-Hester 2010). Likewise, Linvill and Quate were in close contact in shaping how acoustic microscopy could further Linvill's institutional reforms.

So acoustic microscopy resembled other synesthetic technologies at Stanford and Bell Labs in that it aimed to extend perception by fusing different senses, to connect engineering to more humanistic fields (i.e., the life sciences), and to answer administrators' calls for institutional reform. All of these synesthetic technologies, including acoustic microscopy, experienced some collapse or deflation of their original ideals by the mid-1970s. The E.A.T. project dissolved due to lack of funding and a disastrous exhibit for the 1970 World Expo in Japan. Engelbart's group imploded, and his most creative engineers moved to Xerox PARC. Brand founded the *Whole Earth Catalog* to provide information to the commune movement, only to see the communes evaporate by 1973.

A common theme of these unravelings was that new forms of liberated communication and synesthetic consciousness were too difficult to sustain—especially once less-challenging alternatives became available. For instance, Buchla's Box, which required its operators to unlearn the entire framework of Western music, lost out to the mini-Moog synthesizer, which (with its preset patches and familiar keyboard) could be played like an ordinary piano. Similarly, Engelbart's five-finger keyboard, which required learning an entirely new system for inputting information, lost out to the familiar QWERTY keyboard. The mouse and the graphical user interface, which Engelbart conceived as a means to challenge and stimulate users to a new stage of "coevolution," were co-opted by Apple for their unchallenging "user friendliness" (a concept Engelbart detested).

Something similar befell acoustic microscopy. Quate's original ideal of working closely with biomedical researchers to better understand living cells became mired in life scientists' reluctance to use an entirely new imaging technology and interpret an entirely new contrast mechanism—at least while more familiar imaging technologies sufficed. Thus, Quate turned away from biomedical applications and toward materials science and microelectronics. There he found an audience that already understood how the acoustic microscope worked and what its images meant and who even wanted to build new microscopes for themselves.

Quate's return to audiences in engineering and the physical sciences coincided with his palpable frustration with civilian agencies. He criticized RANN for its tendency to "revolution and abrupt changes in course" that demoralized NSF staff, and he rebuked the NIH for its inability to understand his difficulties collaborating with life scientists.[22] Defense agencies, meanwhile, showed great interest in acoustic microscopy and related technologies. Thus, Quate began work on an acoustic array imaging system that would allow the army to "see" at night and the navy to "see" under water (a macroscale equivalent of the array detector scheme he rejected for acoustic microscopy). By 1980, he and his colleagues had come to view synesthetic conversion as a way to signal their alignment with traditions in the military itself. As Tony Siegman, the director of the laboratory where Quate worked, asked:

> Have you guys ever thought seriously about heterodyning some of your rf [radio frequency] or microwave acoustic signals down to audio frequencies, and letting some human ears simply *listen* to them? From what I've been told of the near-miraculous ability of human sonar operators to recognize, and pull out of the noise, audible signals which defy any kind of electronic signal processing, perhaps this facility could be usefully employed in acoustic microscopy or NDT also. [Now there's a good basic research topic that should really be salable to ONR!].[23]

CONCLUSION: BASIC SCIENCE TO NANOSCIENCE

Siegman's mention of "basic research" is telling, for it had been the *bête noire* of reconversion proponents. As one pro-reconversion student put it in *The Grindstone*:

> [S]ome engineers point out that they do basic research and if someone else uses it for something else, it is not their fault. This is a school of engineering—of applied science—not of physics. We are concerned with how to do things, not how the universe works. . . . The notion of "basic research" often acts as a smokescreen to hide what we are doing from others as well as to avoid facing the consequences ourselves.[24]

The final phase of acoustic microscopy, however, took place in a postreconversion environment where engineers no longer faced such criticisms for doing basic research.

The evolution of acoustic microscope design reflected that reality. In microelectronics, acoustic microscopy was successfully applied to nondestructive inspection of integrated circuits. Microscope manufacturers and microelectronics firms actively developed the technology for that application with only occasional input from Quate. In the life sciences, he accepted—perhaps grudgingly—that such applications would have to wait. Biomedical researchers provided him with samples but generally proved uninterested in acoustic micrographs of those samples. Though Quate initially justified acoustic microscope research on the basis of its routine use in clinical settings, biomedical researchers' indifference meant he made little progress toward that goal.

Quate therefore used their samples as test objects (Mody and Lynch 2010) to calibrate high-resolution versions of the microscope for basic biophysical research rather than clinical application. Quate's students of the early '80s focused on simply driving the microscope toward higher resolution. Cells and bacteria contained small features with which to demonstrate acoustic microscopy's improving resolution, but Quate made little attempt to generate new knowledge of those samples (figure 9.2). Partly this was because high-resolution acoustic microscopes operated in liquid nitrogen or liquid helium rather than water. In those conditions, cells and tissues would die, and any images generated would be too esoteric to be useful to life scientists. As one reviewer put it:

> the main advantage of acoustic microscopy, besides the ability to see below the surface, is the ability to observe biological specimens in their natural environment, or inorganic specimens without the need for etching or special preparation. The steps required to improve resolution seem to all require temperature changes or altered fluid couplant properties that would remove this advantage.[25]

Quate's research had become so basic that it had lost much of its relevance even to other basic researchers!

Ironically, the idea for this line of improvement arose from Quate's misunderstanding a biomedical colleague—the kind of misunderstanding that frustrated his original hopes for acoustic microscopy:

> "Gene Farber . . . said, 'Why don't you look at frozen tissues?' So we built a microscope that would look at frozen tissues." Actually, Farber was merely suggesting another use for the microscope. Tissue examined under an optical microscope is first frozen so that it can be cut. It is then placed on a slide where it warms to room temperature and stained to afford contrast for the viewer. [Says Quate,] "I thought they looked at it while it was frozen, so we build one at the liquid nitrogen level. Farber said, 'What the hell for?' But once you start looking at the properties of nitrogen, you soon realize it's a better instrument, it's a better resolving power." (Jacobson 1984, 135)

By 1982 Quate's students were almost exclusively operating the microscope in liquid helium-3, at the coldest temperatures in the universe.[26] Achieving acoustic

Figure 9.2 Cryogenic acoustic microscope image of myxobacteria (left) compared with transmission electron microscope image (right). The scale bar in both micrographs represents one micron (one-millionth of a meter). Reproduced with permission of University of California Press, from Edwin S. Boatman, Michael W. Berns, Robert J. Walter, and John S. Foster, "Today's Microscopy: Recent Developments in Light and Acoustic Microscopy for Biologists," ***Bioscience*** **37 (June 1987): 384–94. Permission conveyed through Copyright Clearance Center.**

microscopy's theoretical maximum resolution replaced biomedical collaboration and discovery as the end goal of Quate's research program.

So when he read an article (Schwarzschild 1982) that April about an entirely new microscope that used tunneling electrons to probe a metal or semiconductor surface, Quate abruptly moved into the area. Scanning tunneling microscopy (STM) was, in many ways, a natural extension of acoustic microscopy. Quate's students ported significant pieces of acoustic microscope technology to STM. The means of scanning an STM probe over a surface, for instance, resembled those for scanning the acoustic lens. The circuits for controlling the scan and outputting the microscopes' signals to a visual format were closely related. Quate was also confident that the STM could become a nondestructive testing tool for microelectronics manufacturing in the same way acoustic microscopy had.

The social relationships built around acoustic microscopy were also critical to Quate's success in STM. Indeed, Quate's introduction to STM came through an acoustic microscopy colleague—after reading that article, he obtained a meeting with the STM's inventors through Eric Ash, a British acoustic microscopist. As it happened, IBM, which had sponsored Quate's acoustic microscopy work, was also where the STM was invented—so Big Blue naturally funded Quate's STM research as well. Several of the students and postdocs who worked on acoustic microscopy had left Stanford for IBM in the early '80s; when these people learned their mentor had moved into tunneling microscopy, they followed. Moreover, once it became obvious that STM was not conducive to nondestructive testing, Quate convinced IBM to send one of the STM's coinventors to spend a year at Stanford so they could coinvent the atomic force microscope (AFM), a related instrument that *can* nondestructively test microelectronic components (Mody 2004).

Acoustic microscopy's deepest influence on Quate, though, may have been that it offered a new way to think about the objects of research. Before acoustic microscopy, Quate worked on *phenomena* (microwaves, surface acoustic waves) or areas of *application* (signals processing, nondestructive testing). In the late '70s, however, Quate began arguing that his expertise lay in a *size scale*—the submicron regime—that was critical to national security and economic competitiveness:

> We propose here a program of generic research in the field of acoustic microscopy . . . with a resolving power that approaches one-tenth of a micron. The realization of this goal will open new vistas in this field of "Microscience." . . . In the special issue on "Microscience" (*Physics Today*, November 1979) [and] . . . a report from the National Research Council ("Microstructure Science, Engineering & Technology") . . . the case is stated. . . . "Microstructure science, engineering, and technology are essential to . . . continued economic well-being."[27]

Expertise in "microscience" would not be pinned to any particular instrument but would range across all conceivable means of augmenting the senses:

> Unconventional methods for imaging in the microscopic world represent an emerging technology that permits us to go beyond what is possible with the optical or electron microscope. These technologies are based on other forms of radiation such as acoustic waves, tunneling electrons, ions and X-rays.[28]

Quate and his associates have lived this philosophy to the fullest. For several years in the '80s and '90s, for instance, his former postdoc, Kumar Wickramasinghe, was inventing a new microscope every six months.

As "microscience" morphed into "nanotechnology" in the '90s, veterans of the Quate group were therefore well positioned as the leaders in the field. For instance, when President Clinton gave a speech announcing the formation of the National Nanotechnology Initiative, the backdrop behind him was an STM image made by one of Quate's former acoustic microscopy students.[29] By focusing on size scale rather than phenomena or applications, Quate has retrieved some of the interdisciplinary aspirations that were stymied in the 1970s. When Quate first contemplated the STM, for instance, he waxed enthusiastic that it would ensure that "someday we should return to cells."[30]

Synesthesia, however, is largely missing from aspirations for nanotechnology. As I explain in the introduction, probe microscopists still listen to their data but with none of the utopian connotations of the late '60s. The moment when synesthesia and reconversion were two sides of the same reformist coin passed quickly. For a few years around 1970, though, these senses of conversion were intertwined in ways that shaped how (and why) scientists and engineers generated new knowledge. If we consider the role of the senses in research—and particularly the ways laboratory workers move from one sense to another—then we need to be mindful of the historical specificity of these conversions. What is simply the natural manipulation of data in one era can, in another, be the hook on which utopian reforms, unsettling convulsions, or appeals to new audiences are hung.

NOTES

SUA = Stanford University Archives
CQC = SUA, Calvin Quate Collection SC 347 (83-033), 1987 accession

1 Holt Ashley, "New Directions for Engineering Research," *Grindstone: A Forum for Controversial Issues of Special Interest to the Engineering Community* 1 (Feb. 22, 1971): 1–?, SUA, Collection Arch 3009 The Grindstone.

2 Integrated Circuits Laboratory, Integrated Circuits Technology: Opportunities for Graduate Study at Stanford University, 1973, SUA, Collection 3120/4 Electronics Labs.

3 Stanford Electronics Laboratories, Stanford University Electronics Research Review, 11, 12 (August 1969), SUA, Collection 3120/4 STAN.

4 Calvin F. Quate, Engineering Aspects of Acoustic Microscopy, 1979, CQC, box 1, folder Conferences 1979.

5 Calvin F. Quate, Improved Resolution in the Acoustic Microscope, April 1977, CQC, box 1, folder Contract ENG75-02028 NSF.

6 J. G. Linvill, memo to Committee for the Study of Stanford's Educational Program, Jan. 26, 1967, CQC, box 4, binder Electrical Engineering.

7 Calvin F. Quate, letter to John Dimmock, Feb. 9, 1977, CQC, box 1, folder Contract #N000014-75-C-0632 ONR (JSEP) correspondence 1974–1977.

8 Robert Lamar, Stanford University News Service press release, Jan. 15, 1975, CQC, box 1, folder American Optical Corporation.

9 Linvill memo to committee, 1967.

10 National Science Foundation, Appendix A: Background of RANN, 1976, National Archives, collection 307-130-37-16-(1–6) National Science Foundation, NSF Historian, box 30, folder RANN: Interviews.

11 Quate, Improved Resolution, 1977.

12 Calvin F. Quate, letter to J. Warren, Dec. 15, 1977, CQC, box 1, folder Contract—Hartford Foundation, Inc., Correspondence—Proposals (1970–1981).

13 Calvin F. Quate, letter to Eric Ash, Jan. 5, 1978, CQC, box 3, folder Correspondence 1978 January–June.

14 Neils Reimers, memo to file S73-46, May 20, 1976, re: Visit of Eli Snitzer, American Optical Director of Research, on May 3, CQC, box 1, folder American Optical Corporation.

15 K. Wickramasinghe, M. Hall, and C. Quate, Acoustic Microscopy for Biomedical Structures, 1977, CQC, box 1, folder Contract #N000014-75-C-0632 ONR (JSEP) correspondence 1974–1977.

16 Calvin F. Quate, memo to NSF/RANN re: Acoustic microscopy, Dec. 19, 1974, CQC, box 2, folder Contract APR75-07317, National Science Foundation, Apr. 1, 1975.

17 National Institutes of Health, report of Special Study Section on "Acoustic Microscopy for Biomedical Applications," July 26–27, 1978, CQC, box 2, folder NIH 25826 Renewal (January 1980).

18 Calvin F. Quate, letter to Capt. Stephen Wax, 1977, CQC, box 2, folder AFOSR 98 Correspondence 1978–1982.

19 Stanton A. Glantz, "Comments about Engineers for Engineering by an Engineer," *The Grindstone: A Forum for Controversial Issues of Special Interest to the Engineering Community* 1 (Nov. 30, 1970): 4–16. SUA, Collection Arch 3009 The Grindstone.

20 SUA, Rudolf Kompfner papers, SC 194 ACCN 86–125, box 1, folder "Music" personal reminiscences.

21 John R. Pierce, oral history conducted by Andy Goldstein, IEEE History Center, New Brunswick, N.J., Aug. 19–21, 1992.

22 Calvin F. Quate, letter to Dr. Richard C. Atkinson and letter to Dr. Suzanne Stimler, both Nov. 12, 1979, CQC, box 3, folder Correspondence 1979 July–December.

23 Anthony Siegman, memo to Quate et al., Nov. 12, 1980, CQC, box 4, folder GL [Ginzton Lab] Memoranda 1980–1982. Brackets and emphasis in original; "NDT" refers to nondestructive testing.

24 Glantz, "Comments," 1970.

25 National Science Foundation, referees' comments on ECS-8010786, NSF Automation, Bioengineering, and Sensors, Systems program, 1980, CQC, box 3, folder NSF 10786 Proposal January 1980.

26 John Foster, interview by author, Santa Barbara, Calif., May 15, 2009.

27 Calvin F. Quate, Research on Acoustic Microscopy with Superior Resolution, 1981, CQC, box 3, folder NSF 10786, Proposal December 1981.

28 Calvin F. Quate, flyer, UC Irvine School of Engineering, "Modern Microscopy," Nov. 28, 1984, CQC, box 1, folder Conferences 1984.

29 Dan Rugar, interview by author, San Jose, Calif., Mar. 14, 2001.

30 Calvin F. Quate, notebook, April–June 1983, SUA, Quate Collection SC 347 (04–117), 2004 accession, box 2.

REFERENCES

Bardini, Thierry. *Bootstrapping: Douglas Engelbart, Coevolution, and the Origins of Personal Computing*. Stanford: Stanford University Press, 2000.

Colyvas, Jeannette Anastasia. From Divergent Meanings to Common Practices: Institutionalization Processes and the Commercialization of University Research. PhD diss., Stanford University, 2007.

Crary, Jonathan. *Techniques of the Observer: On Vision and Modernity in the Nineteenth Century*. Cambridge, Mass.: MIT Press, 1990.

Daston, Lorraine, and Peter Galison. *Objectivity*. New York: Zone, 2007.

Devey, Gilbert B. "Ultrasonic Microscope." *Radio-Electronic Engineering* (February 1953): 8–9.

Dunbar-Hester, Christina. "Listening to Cybernetics: Music, Machines, and Nervous Systems, 1950–1980." *Science, Technology, and Human Values* 35 (2010): 113–39.

Helmreich, Stefan. "An Anthropologist Under Water: Immersive Soundscapes, Submarine Cyborgs, and Transductive Ethnography." *American Ethnologist* 34 (2007): 621–41.

Jacobson, Judith S. *The Greatest Good: A History of the John A. Hartford Foundation*. New York: The Foundation, 1984.

Jones, Caroline A., and Peter Galison, eds. *Picturing Science, Producing Art*. New York: Routledge, 1998.

Kaiser, David. *How the Hippies Saved Physics*. New York: Norton, forthcoming.

Klüver, Billy. "E.A.T. 9 Evenings: Theatre & Engineering, Variations VII by John Cage" (1988). http://www.9evenings.org/variations_vii.php (accessed January 6, 2010).

Kompfner, Rudolf. "Recent Advances in Acoustical Microscopy." *British Journal of Radiology* 48 (1975): 615–27.

Latour, Bruno. *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge, Mass.: Harvard University Press, 1987.

Lécuyer, Christophe. "What Do Universities Really Owe Industry? The Case of Solid State Electronics at Stanford." *Minerva* 43 (2005): 51–71.

Leslie, Stuart W. *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford*. New York: Columbia University Press, 1993.

———. " 'Time of Troubles' for the Special Laboratories." In *Becoming MIT: Moments of Decision*, ed. David Kaiser, 123–43. Cambridge, Mass.: MIT Press, 2010.

Macher, Jeffrey T., David C. Mowery, and David A. Hodges. "Reversal of Fortune? The Recovery of the U.S. Semiconductor Industry." *California Management Review* 41 (Fall 1998): 107–36.

Mody, Cyrus C. M. Crafting the Tools of Knowledge: The Invention, Spread, and Commercialization of Probe Microscopy, 1960–2000. PhD diss., Cornell University, 2004.

———. " 'A New Way of Flying': *Différance*, Rhetoric, and the Autogiro in Interwar Aviation." *Social Studies of Science* 30 (2000): 513–43.

———. "The Sounds of Science: Listening to Laboratory Practice." *Science, Technology, and Human Values* 30 (2005): 175–98.

———, and Michael Lynch. "Test Objects and Other Epistemic Things: A History of a Nanoscale Object." *British Journal for the History of Science* 43 (2010): 423–458.

National Science Foundation. "The Promise of Acoustic Microscopy: Aided by Gigahertz Sound, Acoustic Microscopists Add a Dimension to the Perception of the Very Small." *Mosaic* (March/April 1978): 35–41.

Nelson, Andrew J., "Cacophony or Harmony? Multivocal Logics and Technology Licensing by the Stanford University Department of Music." *Industrial and Corporate Change* 14(1) (2005): 93–118.

Pierce, J. R. "Rudolf Kompfner, May 16, 1909–December 3, 1977." In *Biographical Memoirs*, ed. Bryce Crawford Jr. and Caroline K. McEuen, 157–80. Washington, D.C.: National Academies Press, 1983.

Pinch, Trevor. "Towards an Analysis of Scientific Observation: The Externality and Evidential Significance of Observational Reports in Physics." *Social Studies of Science* 15 (February 1985): 3–36.

———, and Frank Trocco. *Analog Days: The Invention and Impact of the Moog Synthesizer*. Cambridge, Mass.: Harvard University Press, 2002.

Quate, Calvin F. "Acoustic Microscopy: Recollections." *IEEE Transactions on Sonics and Ultrasonics* SU-32 (March 1985): 132–35.

Reiffenstein, Tim. "Codification, Patents, and the Geography of Knowledge Transfer in the Electronic Musical Instrument Industry." *Canadian Geographer* 50 (2006): 298–318.

Roosth, Sophia. "Screaming Yeast: Sonocytology, Cytoplasmic Milieus, and Cellular Subjectivities." *Critical Inquiry* 35 (2009): 332–50.

Schwarzschild, B. M. "Microscopy by Vacuum Tunneling." *Physics Today* 35 (April 1982): 21–22.

Smith Hughes, Sally. "The First Major Patent in Biotechnology and the Commercialization of Molecular Biology, 1974–1980." *Isis* 92 (2001): 541–75.

Stanford Workshop on Political and Social Issues (SWOPSI). *D.O.D. Sponsored Research at Stanford.* Vol. 1, *Two Perceptions: The Investigator's and the Sponsor's.* Stanford: Stanford University, 1971.

Turner, Fred. *From Counterculture to Cyberculture: Stewart Brand, the Whole Earth Network, and the Rise of Digital Utopianism*. Chicago: University of Chicago Press, 2006.

Vettel, Eric J. *Biotech: The Countercultural Origins of an Industry*. Philadelphia: University of Pennsylvania Press, 2006.

Wisnioski, Matthew H. Engineers and the Intellectual Crisis of Technology, 1957–1973. PhD diss., Princeton University, 2005.

WSF. “NSF RANN Program Shifts Gears: Sun, Earth Core Energy Sources to Receive New Research Emphasis.” *Environmental Science and Technology* 8 (August 1974.): 704.

Yi, Doogab. The Recombinant University: Genetic Engineering and the Emergence of Biotechnology at Stanford, 1959–1980. PhD diss., Princeton University, 2008.