War and Peacetime Research on the Road to Crystal Frequency Control

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On 26 February 1921, Walter Cady, professor of physics at Wesleyan University, presented his findings on electrically driven resonance in crystals to the American Physical Society. In the audience was Harold Arnold, a former student of Cady's and the head of research at Western Electric, the manufacturing arm of American Telephone & Telegraph (AT&T). As Cady recalled many years later,

> [Arnold] said, "it would be awfully nice if you could find some way to make the crystals not only resonate like this [i.e., vibrate freely at a particular frequency], but also control frequency." Well, I hadn't thought of that and on the train going back to Middletown, I thought the thing over and instead of going home and going to bed as I should have done, I went right up to the laboratory and started setting things up and in a few days I began to get definite results.[1]

Cady succeeded in designing electric circuits that set the frequency of an electronic system to desired values. This proved useful for telephony and radio communication, AT&T's core markets. Later, crystal frequency control was implemented in quartz timekeeping, and today it is a ubiquitous

Dr. Katzir, Alexander von Humboldt Fellow at the Max Planck Institute for the History of Science, studies the history of physics and its related nineteenth- and twentieth-century technologies. The present essay is part of a larger project on early technological uses of piezoelectricity, and the consequent changes in the study of this phenomenon. He expresses his appreciation to the National Museum of American History's Lemelson Center for funding his study of the Walter Guyton Cady Papers (1903–1974) held by the museum's archives, and to Alison Oswald and other members of the center's helpful staff. He also thanks Chris S. McGahey for so generously sharing his notes on Cady's diaries, the *T&C* editor and anonymous referees for their helpful comments on earlier drafts of this essay, and Reed Benhamou for her thoughtful editing.

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[1] Walter G. Cady, interview by R. Bruce Lindsay and W. J. King, 28–29 August 1963, p. 18, Cady dossier, Niels Bohr Library, American Institute of Physics.

tool for controlling "smart" electronic circuits. Crystal frequency control was one of the essential inventions in the twentieth century's electronics revolution.[2]

Telephony, radio, and timekeeping were far from Cady's mind when he first began studying crystals and their vibrations in 1917 as part of a wartime crash program in submarine detection. This program involved physicists and engineers in academic, government, and corporate organizations (as well as independent inventors) in France, Britain, and the United States. When World War I ended, some participants continued with related projects. However, the armistice reoriented their research to new questions, a longer time horizon, and more varied outputs.

Historians of American science and technology have generally depicted the post-1918 period, at least in comparison to post-1945, as a quick return to the status quo ante.[3] Organizations created to aid the World War I effort were quickly disbanded or scaled back, whereas those created for World War II were largely retained and expanded. Cady's case shows that there was somewhat more "stickiness" to the World War I experience than we might think.[4] Having invested time and energy in learning the theory and practice of building high-frequency circuits with piezoelectric crystals, and in acquiring thorough and novel knowledge about their behavior, Cady was reluctant to abandon that work for his prewar research. In addition, his wartime collaboration with corporate researchers had intensified his awareness of the commercial applications of his work.

Cady's case shows that the return to peacetime can inform the content of

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[2] Historians interested in the origins of frequency control have tended to see it as a product of high science; see Carlene Stephens and Maggie Dennis, "Engineering Time: Inventing the Electronic Wristwatch," *British Journal for the History of Science* 33 (2000): 483, and David S. Landes, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge, Mass., 1983), 342. Histories by those who worked on frequency-control devices tend to focus on its technological origins; see Virgil E. Bottom, "A History of the Quartz Crystal Industry in the USA," in *Proceedings of the 35th Annual Frequency Control Symposium* (Adelphi, Md., 1981), 3–12.

[3] Compare, for instance, Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (Cambridge, Mass., 1995), 139–54, 324–92. World War I is widely seen as having affected U.S. science and technology in three ways: the postwar retrenchment of federal research funding allowed philanthropic foundations to dominate interwar research policy; the wartime experience contributed to increased appreciation of teamwork in research; and the success of physicists sponsored by the National Research Council and the failure of Thomas Edison's Naval Consulting Board contributed to an increasing appreciation of "pure" science. Cady's story accords well with the latter trend. See Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (New York, 1989), 118–26; Robert E. Kohler, "Science, Foundations, and American Universities in the 1920s," *Osiris* 3 (1987): 135–64; and Steven Shapin, *The Scientific Life: A Moral History of a Late Modern Vocation* (Chicago, 2008), 168.

[4] Eric von Hippel, "'Sticky Information' and the Locus of Problem Solving: Implications for Innovation," *Management Science* 40 (1994): 429–39.

science and technology almost as much as the initial wartime mobilization. The organizational boundaries between corporate and academic researchers that had blurred during the war remained blurry afterward, though Cady found that his interests were diverging from those of his corporate colleagues. The wartime submarine-detection program had been characterized by short time horizons and targeted goals. The armistice released that constraint, allowing participants to rededicate themselves to their home organizations and their own interests. For Cady, that meant a return to publishing articles in scientific journals and striving for recognition from fellow physicists; it also meant that he was freer to follow his curiosity.

Yet as the opening anecdote shows, Cady's interests went beyond discovering and publishing. His war work accustomed him to thinking about how to translate experimental and theoretical findings into commercially or militarily useful products in the near-term. His wartime contacts and network of former students enabled him to approach companies to commercialize his work when he chose to do so.[5] After the war, Cady became an "occasional" inventor. He explicitly rejected the notion that he was a professional inventor seeking a steady stream of patents, as did Thomas Edison or Elmer Sperry, but he pursued ways to translate his findings into inventions when he saw an opportunity for lucrative intellectual property, closer integration with such companies as General Electric (GE) and AT&T, or (as on that train to Middletown in 1921) intellectual stimulation.

Historians, sociologists, and management scholars have recently begun to reassess the role of independent inventors and the avocation of invention. Earlier, pioneering studies by David Hounshell and Thomas Hughes drew attention to the displacement of inventors like Edison and Sperry by large corporate research laboratories that occurred after World War I.[6] However, it is now becoming clear (if it was ever unclear) that independent inventors never ceased to exist, and that some firms built their innovation strategies around collaborations with these independent and often full-

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[5] There is a large literature on "research schools" and the ways in which scientific concepts and methods are diffused through networks of teacher–student relationships. See John W. Servos, "Research Schools and Their Histories," *Osiris* 8 (1993): 3–15, or David Kaiser, "Making Tools Travel: Pedagogy and the Transfer of Skills in Postwar Theoretical Physics," in *Pedagogy and the Practice of Science: Historical and Contemporary Perspectives*, ed. David Kaiser (Cambridge, Mass., 2005), 41–74, as well as the other articles in both volumes. Considerably less has been written about teacher–student networks that include both corporate and academic organizations. Cady's case shows that such networks may offer one pathway for commercialization of academic research; for a similar example, see Cyrus C. M. Mody, "Corporations, Universities, and Instrumental Communities: Commercializing Probe Microscopy, 1981–1996," *Technology and Culture* 47 (2006): 56–80.

[6] David A. Hounshell, "The Evolution of Industrial Research in the United States," in *Engines of Innovation: U.S. Industrial Research at the End of an Era*, ed. Richard S. Rosenbloom and William J. Spencer (Boston, 1995), 13–85; Hughes, 138–83.

time inventors whom Eric Hintz has termed "post-heroic."[7] Like Cady, though, others invented only occasionally.

Viewing Cady as an occasional inventor offers a fresh view of the relationship among universities, corporations, and independent inventors following World War I. As high-tech companies like General Electric and AT&T hired more Ph.D.s and encouraged their researchers to publish in scientific journals, their ties to academic science deepened;[8] at the same time, these companies could not shed their reliance on independent inventors.[9] This left an opening for academics such as Cady, whose networks of collaborators and former students extended into corporate labs and were willing to occasionally rethink their findings from a short-term, commercial perspective. Its relationship with Cady helped AT&T to be a major force in developing, employing, and spreading frequency-control technology in the 1920s. At the same time, the products of that relationship stimulated a lively scientific discussion of the new "piezo-resonators" among corporate and academic researchers. Although Cady later felt that AT&T had misappropriated his intellectual property, in the end, their interaction gave the company a solution to important technological problems and stimulated Cady to develop his most important invention.

The Application of Piezoelectricity to Ultrasonic Devices

Although developed during World War I, ultrasonic underwater echo-detection may be traced to the sinking of the *Titanic* in 1912, an event that led Constantin Chilowski, a Russian émigré in Switzerland, to consider a system for locating underwater objects from a safe distance. Since sound waves are five times longer in water than in air, his system would utilize the shorter ultrasonic waves to facilitate the detection of objects of only a few meters in length. When German U-boats threatened the navies of the entente powers during World War I, Chilowski contrived a method of producing and detecting the ultrasonic waves and sent it to the French authorities. In February 1915, they in turn forwarded it to physicist Paul Langevin.[10]

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[7] Eric S. Hintz, "Portable Power: Inventor Samuel Ruben and the Birth of Duracell," *Technology and Culture* 50 (2009): 24–57.

[8] See Lillian Hoddeson, "The Emergence of Basic Research in the Bell Telephone System, 1876–1915," *Technology and Culture* 22 (1981): 512–44; Leonard S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge, 1985); Ronald R. Kline, *Steinmetz: Engineer and Socialist* (Baltimore, 1992); and George Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (New York, 1985).

[9] Tom Nicholas, "Spatial Diversity in Invention: Evidence from the Early R&D Labs," *Journal of Economic Geography* 9 (2009): 1–31.

[10] Little is known about the training and earlier work of Chilowski (Chilowsky). According to one contemporary source, he studied with Nikolai Zhukovski (Joukowski), who was a Russian pioneer of aerodynamics, but it is unclear when and where he might

It is doubtful that without the war Chilowski's idea would have received serious consideration, or that Langevin would have turned his attention to improving military technology. Until the outbreak of the war, the French physicist stood for disinterested scientific research. Like scientists on both sides, however, Langevin participated enthusiastically in research to improve military technology.[11] Even under these circumstances, as a foreign independent inventor, the Russian émigré had to prove his ability in the field to two French professors in Geneva before they would deliver his proposal to the Paris "high committee for inventions," chaired by Paul Painlevé, the mathematician and politician who "became the direct interlocutor of inventors by granting them audiences or connecting them with scientists." The Chilowski–Langevin partnership was the most famous (and successful) match of the over 800 (of 45,000) proposals that Painlevé's committee moved into development.[12]

Although he doubted the feasibility of Chilowski's method for producing ultrasonic waves, Langevin thought the idea of underwater echo-detection was worth a try. Consequently, Chilowski joined him in Paris, and by the end of 1915 they had constructed an electromechanical transducer—a device that converts high-frequency, alternating electric current (simpler to produce than mechanical vibrations) to ultrasonic mechanical waves by using a mica dielectric. With a carbon microphone designed for detecting the waves' echo, they had an ultrasonic-detection system. In other words, the principles of the technology were suggested by the inventor, but the means to achieve them were developed in the physicist's research. Further work on the encouraging results from underwater experiments in Paris and Toulon continued during 1916. The collaboration between Chilowski and Langevin was "less than entirely serene," however; in the spring of 1916, Chilowski left to investigate other military technologies, and Langevin took full responsibility for the direction of the ultrasonic research.[13]

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have done so; see Claudine Fontanon, "L'obus Chilowski et la soufflerie balistique de Paul Langevin: Un épisode oublié de la mobilisation scientifique (1915–1919)," in *Deux siècles d'histoire de l'armement en France: De Gribeauval à la force de frappe*, ed. Dominique Pestre (Paris, 2005), 81–109. Chilowski did not complete his studies at Moscow University, having fled to Switzerland and France after being arrested for political activity in 1904; see I. I. Klyukin, *Sound and the Sea* (Arlington, Va., 1974). His early work is unknown, but the many devices he invented after 1915 qualify him as a "professional"; on these, see Frederick V. Hunt, *Electroacoustics: The Analysis of Transduction, and Its Historical Background* (Cambridge, Mass., 1954), 45–46.

[11] Langevin studied ballistics prior to his work on ultrasonics; see Bernadette Bensaude-Vincent, *Langevin, 1872–1946: Science et vigilance* (Paris, 1987), 85–86.

[12] Gabriel Galvez-Behar, "Le savant, l'inventeur et le politique: Le rôle du sous-secrétariat d'état aux inventions durant la première guerre mondiale," *Vingtième Siècle* 85 (2005): 105. The establishment was much more successful than its U.S. counterpart, the Naval Consulting Board, which developed 110 "inventions" out of 110,000; see Hughes (n. 3 above), 119–24.

[13] On the Chilowski–Langevin partnership, see Hunt, 46–49; on Langevin, see Be-

In early 1917, Langevin devised a new ultrasonic transducer based on the piezoelectric effect in quartz.[14] The piezoelectric effect is the phenomenon by which a change of pressure applied in particular directions in certain crystals generates electric voltage difference (i.e., opposite charges), and the converse effect where electric voltage induces mechanical pressure. Placing the crystal under alternating electric voltage could induce mechanical oscillations in the crystal, which could produce sonic (or ultrasonic) waves; the process could be used in reverse, with ultrasonic waves eliciting mechanical oscillations that generated alternating current. Piezoelectricity thus offered a relatively simple solution for the most problematic elements in the Chilowski–Langevin technology: the generation of high-frequency mechanical oscillations and their detection by electrical means. The new piezoelectric transducer was the most promising of the techniques suggested for detecting submarines,[15] and it later became the basis not only for sonar, but also for medical ultrasound scanners.

The utilization of piezoelectricity for underwater detection seems a classic case of "applied science," in which knowledge gathered through disinterested research is applied to technological development. Here, knowledge of piezoelectric phenomena, cultivated for its own sake for some thirty-five years, was employed to answer an urgent need; until then, the phenomena were regarded as irrelevant to technology. As the "dean of piezoelectricians" Woldemar Voigt said in 1905 about the field of crystal physics that included piezoelectricity, "it is old-fashioned physics in the stronger sense; its laws are hardly meager attempts at technical application, and only the quest for scientific knowledge drives and guides it."[16] In 1880, Jacques and Pierre Curie had discovered the phenomenon, whose existence they had conjectured in an attempt to understand the origin of a related phenomenon, pyroelectricity. By 1895, scientists reached a consensus about the central properties of piezoelectricity, including its basic characteristics; moreover, Voigt's confirmed mathematical theory accounted for its phenomena. After 1895, research in the field continued on a small scale, and

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noît Lelong, "Paul Langevin et la détection sous-marine, 1914–1929: Un physicien acteur de l'innovation industrielle et militaire," *Épistémologiques* 2 (2002): 205–32; and on Chilowski's later work, see Fontanon. On Langevin's work see his report of October 1918, which appears in David Zimmerman, "Paul Langevin and the Discovery of Active Sonar or Asdic," *Northern Mariner* 12 (2002): 39–52.

[14] Willem D. Hackmann, *Seek & Strike: Sonar, Anti-submarine Warfare and the Royal Navy, 1914–54* (London, 1984), 77–80.

[15] Willem D. Hackmann, "Sonar Research and Naval Warfare 1914–1954: A Case Study of a Twentieth-Century Establishment Science," *Historical Studies in the Physical Sciences* 16 (1986): 90–94.

[16] Woldemar Voigt, "Rede," in *Die physikalischen Institute der Universität Göttingen* (Leipzig, 1905), 39. Voigt contrasted his own instruments to those of Ludwig Prandtl, whom Walter G. Vincenti portrayed as a central figure in the establishment of "engineering science" in his "Control-Volume Analysis: A Difference in Thinking between Engineering and Physics" (*Technology and Culture* 23 [1982]: 145–74).

piezoelectricity was not widely known outside of physics. That was probably one reason why engineers and inventors did not apply it to practical ends. A small number of physical laboratories employed the effect in a precise measurement instrument, for either charge or pressure, that was designed by the Curies in 1881.[17] Langevin's dynamic transducer worked on different principles than their static instrument, however; an unexpected benefit of research into piezoelectricity was thus the ability to employ it beyond the laboratory.

Nevertheless, constructing working piezoelectric transducers was hardly the trivial application of a simple principle to a new problem, as a naive view of "applied science" may suggest. Although the phenomenon had been studied, no one examined high-frequency piezoelectric oscillations before considering their technological use. The properties of the crystal under vibrations were one area of inquiry in the research for piezoelectric ultrasonic devices. While exploring these properties ultimately aimed at improving design, most questions more directly concerned such design issues as shape, size, availability of appropriate crystal bars, their mounting to metals, the connection between the piezoelectric plate and the electric circuits, the amplification of the electric signals in the circuit, and the effect of seawater on the transducers. Another field of inquiry was the entirely new area of underwater acoustics.[18]

Obstacles relating to such questions probably account for an early failure of Langevin, independently of Ernst Rutherford in Britain, to utilize piezoelectricity in 1915 and 1916.[19] Langevin's breakthrough resulted from the use of crystal bars whose natural elastic frequency of vibration was in the range suitable for ultrasonic waves. A natural (or resonance) frequency is the one in which an object would vibrate of its own accord for a long time, like the tone of a piano string. At resonance frequency, less energy is lost to the resistance of the crystal plate itself. To obtain a plate of appropriate resonance frequency, Langevin first used a pure crystal slab but replaced it in February 1918 with a steel-quartz-steel parallelepiped sandwich of 20 cm^2 on 4 mm, in which small pieces of quartz were cemented to the steel.[20] Another important factor in Langevin's success was his use of better vacuum "valve" amplifiers for high frequency, which had been developed for radio communication during the war by French military radio-telegra-

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[17] The use of this instrument motivated two measurements of quartz piezoelectric constants during the first decade of the twentieth century; on the measurements, see Shaul Katzir, *The Beginnings of Piezoelectricity: A Study in Mundane Physics* (Dordrecht, 2006), 214–17. I know of no attempt to use piezoelectricity outside the laboratory before 1915.

[18] Hackmann, *Seek & Strike*, 80–94.

[19] Ibid., 79, 83–85; David Wilson, *Rutherford, Simple Genius* (Cambridge, Mass., 1983), 373–76; Paul Langevin, "Echo Sounding," *Hydrographic Review* 2 (1924): 75.

[20] Langevin, in Zimmerman (n. 13 above); Hackmann, *Seek & Strike* (n. 14 above), 80–82.

phy in collaboration with physicists and engineers.[21] To be detectable by contemporary methods, the weak electric signals generated by piezoelectric receivers required amplification. Since ultrasonic waves are of radio frequencies (tens of thousands of cycles per second—kHz), amplifiers for wireless communication fitted the needs of echo-detectors. Indeed, the development of radio technology continued to serve the study of piezoelectric oscillators, which later became the first field of its application.

Detailed information about Langevin's devices was communicated quickly to other entente powers, which consequently pursued their own research and development program for piezoelectric ultrasonics. Despite earlier British work on the subject and the wartime efforts of scientists and engineers in Britain, Italy, and the United States, the French continued to lead. Even their device did not go into service before the armistice, however. In June 1917, foreign envoys explained the work in detail to a few dozen American scientists and engineers during a three-day Washington conference on antisubmarine measures. Subsequently, many of the attendees were mobilized to the ultrasonic research coordinated by National Research Council director of research Robert Millikan, who, because of the importance of the issue, also headed its antisubmarine committee. Millikan, a distinguished experimental physicist, achieved a close cooperation between academy and industry and among different companies.[22] One of the central figures Millikan mobilized was Walter Cady, who, though collaborating with a few research groups, worked mostly alone or with an assistant in his small university.

Cady's Work on Ultrasonics and Resonance

Cady's work on piezoelectric transducers led him to the discovery that piezoelectric crystals have an electrically sharp and steady resonance,[23] and

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[21] These amplifiers were based on an improvement of Lee de Forest's "audion," an electronic valve with a grid between anode and cathode. Although invented primarily as a detector of radio waves, it was first used in the United States in 1911, and later in France and Germany for amplifying currents; see Sungook Hong, *Wireless: From Marconi's Black Box to the Audion* (Cambridge, 2001), 178–89, and Guy Hartcup, *The War of Invention: Scientific Developments, 1914–18* (London, 1988), 129–30.

[22] Willem Hackmann mentions ten U.S. centers for research on submarine detection (none of which was totally independent of the others), of which nine worked on ultrasonics. The groups involved such academic scientists as professors of electrical engineering Michael Pupin (Columbia) and Harris J. Ryan (Stanford); the astronomer John A. Anderson (Mount Wilson Observatory); and physicists Albert P. Wills (Columbia) and George W. Pierce (Harvard). They also involved industrial scientists from the laboratories of General Electric, Western Electric, and other telecommunication companies and a group from the American Bureau of Standards. See Hackmann, *Seek & Strike*, 41, 90–92; Hackmann, "Sonar Research" (n. 15 above), 95–97; and Walter G. Cady, "Piezoelectricity and Ultrasonics," *Sound: Its Uses and Control* 2 (1963): 46–49.

[23] For a closer analysis of Cady's discovery of sharp resonance and its employment

thus to its use as a frequency standard. Cady's discovery differed from Langevin's on how to utilize piezoelectricity for ultrasonic detection: Langevin's starting point was an acute technological problem, for which piezoelectricity provided a solution, or at least a promising path; Cady, on the other hand, found a solution and looked for problems it could solve. Unlike the case of the high-frequency transducer, Cady did not set out to look for a new standard of frequency. Like other "technologies that sought problems," the initial design of frequency-standard instruments resulted more from an interest in the working principles of their components than in their application for other ends.[24] The development of ultrasonics is an example of a kind of technological change that stems from a particular social need, although its implementation may depend on the machinery of modern physics and engineering. This kind of technology can be called "necessity-driven," as the effort for its development originates in needs identified by the developers themselves. It stands in contrast to "knowledge-driven" technology, where similar efforts originate from a wish to exploit a familiarity with a particular phenomenon or behavior. The research on frequency standards and control is an example of such knowledge-driven technology, a type that became more common as scientific knowledge advanced in the nineteenth century. In the case of early piezoelectric technology, we have a clear example of both the necessity- and knowledge-driven kinds. In other cases, as with most classifications, the demarcation line between the two kinds is blurred.

Until the events discussed here, Walter Cady had had a quiet and undistinguished career. Born in 1874 in Providence, Rhode Island, he "decided on pure physics instead of engineering" during his college years at Brown University, where he stayed for his M.A. Encouraged by one of his teachers, he continued his studies in Berlin, conducting experimental research concerning the energy of cathode rays (electrons) and earning a Ph.D. in 1900. He returned to work at the magnetic observatory of the U.S. Coast and Geodetic Survey, and in 1902 he joined the faculty of Wesleyan University in Middletown, Connecticut, where he taught physics until 1946. "In one way," Cady recalled, "it was my good luck to be at a small college where I had no superiors to direct me, and where I had to choose my own subjects for research and devise my own equipment. For instance, my first patent was for an improved form of electrical connector." This innovation of an "occasional inventor" was atypical of Cady's later inventions, as it followed a particular

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for frequency standards, see Shaul Katzir, "From Ultrasonic to Frequency Standards: Walter Cady's Discovery of the Sharp Resonance of Crystals," *Archive for History of the Exact Sciences* 62 (2008): 469–87.

[24] For examples from other technologies, see Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (Philadelphia, 1982), and Nicolas Rasmussen, *Picture Control: The Electron Microscope and the Transformation of Biology in America, 1940–1960* (Stanford, Calif., 1997), 25–35, on the electron microscope.

need rather than a finding. Dividing his interest into a few areas and assisted by graduate students and "an expert mechanician," Cady also continued his study of magnetism. In 1908, following a finding of his student Harold Arnold, he began investigating vibrations and rotations in electric discharges such as the electric arc. Before beginning his study of piezoelectricity, he had investigated wireless telecommunication and related issues, which included detectors of electromagnetic waves and high-frequency oscillations. His research on electromagnetic waves was linked to his practice as a radio amateur, a link that continued with his professional interest in electric rotation and his later work on piezoelectric devices, where, like all researchers in the field, he employed methods and devices from the study of radio. Cady was an amateur musician as well, and his lifelong interest in ornithology also led to publications in that field. His students remembered him as "a splendid, generous and kind man" with a wide education.[25]

From Ultrasonic to Resonance

Early in 1917, Cady's nascent exploration of ways of detecting submarines resulted in an invitation to the June 1917 Washington conference on this problem. There, he was excited by Langevin's piezoelectric method,[26] and upon returning home he began experimenting with crystals. Two weeks later, he became an employee of the General Electric (GE) research laboratory in Schenectady, New York, where he joined the group led by physicist Albert Hull and devised crystal-metal receivers for ultrasonic signals. As he recalled a half-century later, "[t]he research on piezoelectricity was practically thrown at me. Fortunately the way had been somewhat paved by my previous work on vibrations, and it lay in my range of general interest. Anyway it has been my principal scientific concern ever since."[27] Cady left GE in

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25. Walter G. Cady, "Saving Ancestors," unpublished manuscript, 1963, pp. 100–6, 116–18, 209–10, Cady dossier (n. 1 above); Walter Cady diaries (meetings about radio), Rhode Island Historical Society, Providence; Gerald Holton, personal communication, 17 April 2007. For short descriptions of Cady's work, see James E. Brittain, "Walter G. Cady and Piezoelectric Resonators," *Proceedings of the IEEE* 80 (1992), and Sidney B. Lang, "Walter Guyton Cady" and "A Conversation with Professor W. G. Cady," *Ferroelectrics* 9 (1975): 139–40, 141–49. On Cady's character and later work, see Hans Jaffe, "Professor Cady's Work in Crystal Physics," in *18th Annual Frequency Control Symposium* (Fort Monmouth, N.J., 1964), 5–11; on radio amateurs, see Susan J. Douglas, *Inventing American Broadcasting, 1899–1922* (Baltimore, 1987), 144–86.

26. In his *Piezoelectricity: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York, 1946), Cady wrote that "[a] principle so novel and so suggestive could not fail to excite the interest of many physicists" (pp. 675–76). He recorded earlier nonpiezoelectric attempts to detect submarines in research notebooks (hereafter RNB); see Cady, RNB 18, pp. 170–71, and RNB 43, pp. 81–87. The notebooks form part of the Walter Guyton Cady Papers, 1903–1974, Archives Center, National Museum of American History, Smithsonian Institution (hereafter ACNMAH).

27. Cady, "Saving Ancestors," 211; W. G. Cady, "Outstanding Dates Relating to Work of W. G. Cady in Piezoelectricity," unpublished manuscript, circa 1965, Cady dossier.

October 1917 and a month later "began cooperation with Pupin, Wills and Morecroft at Columbia, though most of my [Cady's] share was done at Wesleyan."[28] The Columbia group made sea trials first in Florida, and from the summer of 1918 in the navy experimental yard at New London, Connecticut. Cady studied the fundamentals of piezoelectricity from a German textbook[29] and experimented with basic piezoelectric properties, but most of his work dealt with questions of design: efficient sizes and cuts of crystals (usually in dimensions of a few to a few dozen millimeters), their mounting, the material to which they were mounted in the transducer, and so on.

Cady's research included an examination of the crystals' electric properties—capacitance, dielectric constant, inductance, and resistance—and their dependence on the electric circuits, on one another, and on additional variables such as frequency.[30] Frequency variations had their most conspicuous effect near resonance. Following Langevin, most researchers, including Cady, exploited resonance frequency for efficient transmission, and thus took notice of transducer behavior at frequencies near that of resonance. It seems, however, that its electrical consequences had not been seriously investigated before the autumn of 1918.[31] At that point, Cady began experimenting with the electrical properties near resonance of Rochelle salt and quartz—the two crystals used in transducers—examining composed crystals of the kind used as transducers. Between October and December, he examined the effect of varying the frequency of the circuit on voltage, capacitance, and resistance, performing most of the research in his laboratory and the rest—including underwater experiments—at the New London navy station.[32] Cady's examination of the electrical behavior of transducers was not limited to how the device functioned as an ultrasonic transducer; yet apparently at least through November, he directed his research to gathering knowledge that might result in more efficient submarine detectors.

Cady's wartime research had been focused on improving military tech-

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[28] Cady, "Outstanding Dates."

[29] Cady diaries, 29 July 1917; Cady used a book by Voigt. The irony in using a German textbook in a way unexpected by its writer in an effort to fight Germany originates in the open character of scientific knowledge.

[30] Katzir, "From Ultrasonic to Frequency Standards" (n. 23 above); Cady, RNB X, pp. 14–64; RNB 20, pp. 53–65; RNB 23, esp. pp. 1–32.

[31] Paul Langevin, "Procédé et appareils d'émission et de réception des ondes élastiques sous-marines à l'aide des propriétéés piézo-électriques du quartz," French patent FRD505703, filed 17 September 1918. See, for example, the part of I. B. Crandall, in "Report on Conference of Physics and Engineering Divisions of the National Research Council, Washington, July 18, 1918," and Leonard F. Fuller and Harris J. Ryan's report, "Problem #324: Quartz Supersound Source Projector," 1 August 1918, both in the National Academies Archives, Washington, D.C., Central Policy files, 1914–1918. I know of no examination of resonance properties prior to Cady's.

[32] Cady, RNB 20, esp. pp. 66–74 (1–2 October 1918), 106–8 (6 November 1918), and 114 (14 November 1918); RNB X, p. 68 (before 16 October 1918); RNB 12, pp. 76–81 (6–8 December 1918) and 82–87 (17–20 December 1918); Katzir, "From Ultrasonic to Frequency Standards," 475–76.

nology; the armistice led to a reorientation. As a well-informed contemporary observed, "[w]ith the sudden termination of hostilities the problems confronting the scientific workers have to a large extent either suddenly changed their nature altogether or have been considerably modified."[33] Suspecting that the electric reaction of crystals in resonance was responsible for the peculiarities he observed in his circuits, Cady moved from a focus on ultrasonic detection to crystal resonance. Still, his new area of research depended on the body of knowledge about piezoelectric vibrations developed as wartime research. Cady began 1919 with an intensified study of the influence of frequency on the electric behavior of crystals near their resonance frequencies, investigating, among other things, the meaning and significance of findings made the previous August that the pressure of the technological objectives of his wartime research had caused him to set aside. This investigation revealed sharp decreases in current, in resistance, and, most conspicuously, in the capacitance of electric circuits at the resonance frequencies. Figure 1, which Cady drew on 11 January 1919, illustrates the sharp change in capacitance. Changes in resonance current had been observed previously, but Cady was the first to follow this observation with an examination of electric properties at these frequencies. By mid-February, his experiments revealed that resonance in piezoelectric crystals shows not only the strong, and well-known, elastic effect, but also a hitherto unknown sharp and steady electrical effect marked by rapid changes in the values of resistance and capacitance.[34]

That others' research on underwater detection had failed to discover the same properties suggests that a focus on ultrasonic research was insufficient for the discovery of the electric resonance of piezoelectric crystals. To make this discovery, Cady had to carry out a special investigation to elucidate and connect a few scattered, unexpected observations made the previous year. Although Cady was still associated with the New London ultrasonic group and conducted a few experiments there, attempting to exploit the special electric values at resonance frequencies for ultrasound receivers,[35] his

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[33] O. E. Jennings, "Proceedings of the Baltimore Meeting of the American Association for the Advancement of Science," *Science* 49 (1919): 11. Jennings, general secretary of the American Association for the Advancement of Science, based his judgment on the December 1918 meeting of the society, which Cady attended, and noted that the society chose Baltimore "partly because war conditions had brought together at Washington scientific men from all over the country" (p. 11).

[34] Cady, RNB 12, p. 89 (3 January 1919); RNB 25, pp. 1–47 (4 January, 1–5 February 1919). On reference to resonance by others, see for example Langevin, in Zimmerman (n. 13 above); on differences between Langevin and Cady, see Katzir, "From Ultrasonic to Frequency Standards." For an observation by others of changes in electric properties near resonance, see for example L. B. Crandall, "Notes on Rochelle Salt Piezo Crystals" (undated, from summer 1918), in Paul Langevin's papers at La Centre de resources historiques de l'ESPCI, L134/08.

[35] Cady, RNB 20, pp. 35 (13 January 1919) and 40–41 (20 January 1919).

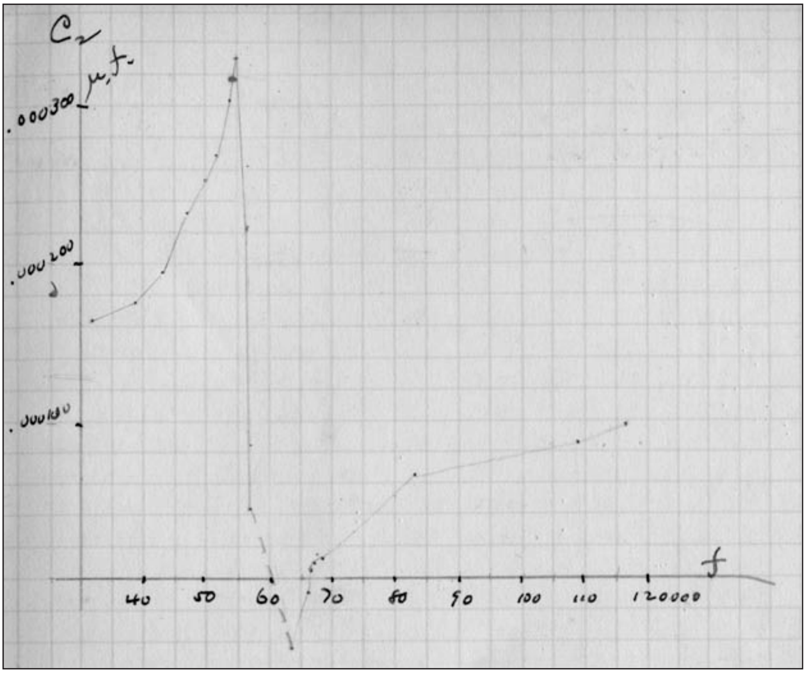

FIG. 1 Graph of capacity as a function of frequency, drawn by Cady on 11 January 1919. Notice the negative value in "resonance" at around 65 kHz. (Source: Research notebook 25, p. 29, Walter Guyton Cady Papers, Archives Center, National Museum of American History, Smithsonian Institution.)

work on ultrasonic detectors did not require such comprehensive research on crystal resonance, and he did not integrate his primary discovery—sharp resonance—into ultrasonics. Since neither his contemporary research notes nor his later recollections suggests any other technological goal, I conclude that his interest in the behavior near resonance was motivated not by a practical end, but by a physicist's curiosity about an unknown phenomenon. Still, Cady's research at this time exemplifies the difficulty in drawing a clear line between goal-oriented research and disinterested investigation, and it does not seem that Cady himself made so clear a distinction.

Frequency Standards

The discovery of the sharp electric resonance of crystals is an example of the finding of a general physical, hence scientific, phenomenon in a particular technological artifact. In this sense, the turn from ultrasonic transducers to resonance phenomena was one from technology to science. The discovery suggested a novel field of research—far from a trivial accomplishment—and in addition possible, albeit unclear, future technological applications. In its relationship to technology, it resembled much of Cady's work after he returned to the United States from Germany.[36] Cady was quick to utilize sharp resonance for a frequency standard, but the application he suggested fell within the traditional domain of physicists, even if it did move beyond the boundaries of the scientific laboratory. Physicists and astronomers had developed and defined standards and measuring devices since at least the 1830s, and they generally did so under the auspices of national institutes. In fact, contemporaneously with Cady's discovery, two French physicists reported an alternative method for radio-frequency measurement to the French Academy of Science.[37] In a variety of institutional settings, it was the physicists (and occasionally scientists from other disciplines) who improved measurement instruments not only for governments and industry, but also for the scientific community to which they themselves belonged and that usually had the highest requirement for precision. Scientists thus served as both users and builders of these devices. Indeed, since the seventeenth century and Christian Huygens's pendulum clock, a few of these laboratory technologies had turned to wider markets, usually with the cooperation of artisans and engineers.[38]

Many years later Cady recalled that the idea of using crystal resonators as standards of frequencies suddenly "flashed on him."[39] His notebooks suggest a more complex and gradual process. After he recognized the sharp piezoelectric resonance of crystals, he looked for different ways to exploit it. One obvious direction for a scientist was to broaden one's understanding of the phenomenon, which Cady did while simultaneously examining paths for applications. In February 1919, he began devising circuits that could be used both to explore the phenomenon and to search for possible ap-plications. Although not a professional inventor, Cady had enough

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[36] Cady's study of issues related to application after his return from Germany fits the common generalization that U.S. science was more practical and attuned to applications than was European science.

[37] Henri Abraham and Eugène Bloch, "Amplificateurs pour courants continus et pour courants de très basse fréquence," *Comptes rendus de l'Académie des sciences* 168 (1919): 1105–8. Abraham and Bloch's "multivibrator" circuit produced a wave whose frequency was an exact fraction of the original. The lower frequency was compared to a pendulum clock standard. They developed the method during their work with military radiotelegraphy.

[38] Scientists, especially Carl Friedrich Gauss and Friedrich Bessel, were active in the reform of weights and measurements in Germany; see Klaus Hentschel, "Gauss, Meyerstein and Hanoverian Metrology," *Annals of Science* 64 (2007): 41–75; Kathryn M. Olesko, "The Measuring of Precision: The Exact Sensibility in Early Nineteenth-Century Germany," in *The Values of Precision*, ed. M. N. Wise (Princeton, N.J., 1995), 103–34, esp. 117–25; and Simon Schaffer, "Accurate Measurements Is an English Science," in *The Values of Precision*, 135–72.

[39] Cady, "Saving Ancestors" (n. 25 above), 212.

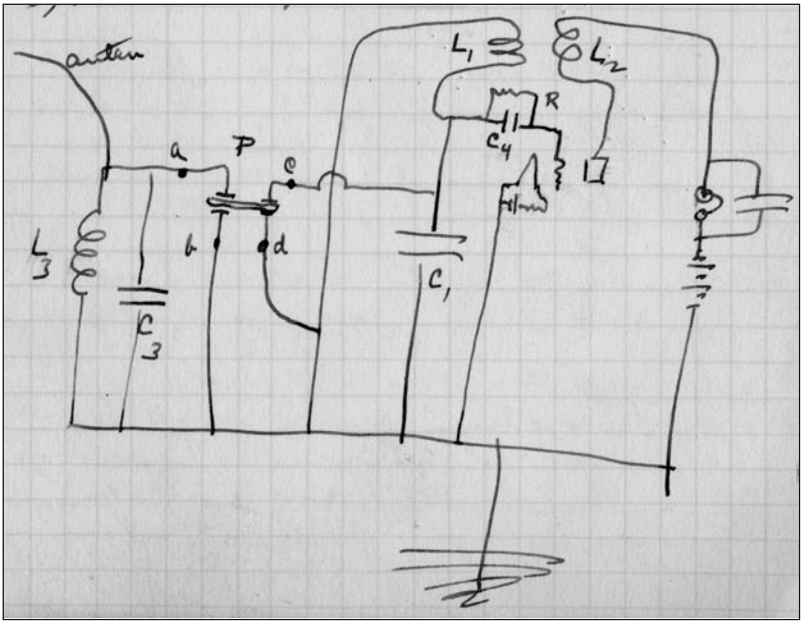

FIG. 2 Circuits coupled by a crystal plate (P); 8 February 1919. At resonance, the crystal transfers alternating electric current from the left branch of the circuit to the right branch. (Source: Research notebook 25, p. 48, Walter Guyton Cady Papers, Archives Center, National Museum of American History, Smithsonian Institution.)

interest in practical applications to seize the opportunities offered by the unique effect he discovered. In this sense, he was an occasional inventor. Unlike professional inventors, he did not indicate the goals of his experiments, and since his experiments could be used for more than one objective, it is unclear if and when he had a particular application in mind.

Whatever the ends he had in view, the key to exploiting resonance frequency was to find conspicuous and easy ways to observe it. Cady took a big step toward solving this problem in mid-February, when he coupled two circuits to a crystal plate in such a way that the circuits were electrically connected only at the plate's resonance frequency (fig. 2).[40] As he later remarked, this device was a kind of (band-pass) "radio-frequency filter"—that is, a device that transmits signals only at a particular range of wavelengths. At the time, however, Cady did not use that term, and the electric circuits he constructed were more complicated than were needed for a simple filter. It is probable that he was not yet thinking along these lines when he designed the experiment, but his recollections and his later use of "the

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40. Cady, RNB 25, pp. 48–49 (8, 10–17 February 1919); Katzir, "From Ultrasonic to Frequency Standards" (n. 23 above).

filter" suggest that, at least when finishing these experiments, he tried to use the apparatus as a frequency standard or meter, which transmits waves only at a particular frequency. At the time, a few months before the advent of public broadcasting, frequency meters were mostly used in radio to determine transmission and reception wavelengths. Such meters used an AC electric circuit consisting of an induction coil, capacitors (one of them variable), and resistors—all common radio components. Such devices were also used for standards, though they were not regarded as particularly accurate for this purpose.[41]

On 22 February 1919, Cady presented his findings on resonance "to Arnold of Bell Labs, [George V.] Wendell of Columbia, and [Karl] Van Dyke of Wes[leyan]." Cady's openness differs from the behavior typical of professional inventors or employees of commercial companies. Arnold, who had been Cady's M.A. student and assistant before moving to the University of Chicago for his Ph.D., "came very close to [him] in the laboratory," and they had maintained a scientific connection over the intervening decade.[42] But, as previously mentioned, Arnold was also a high-ranking employee of AT&T, and Cady may have informed him not only as a colleague, but also to learn whether his findings might be of interest to Arnold's company.[43] Unlike academic physicists who are free to share their ideas within their community, industrial scientists and engineers were often restricted by corporate policy, and Arnold did not inform Cady of associated research done under his supervision (see below). Still, Cady did not dismiss the possibility of financial gain from his invention. On 2 March 1919, he mentioned plans to patent a wavelength standard, and he did so in January of the following year before publishing his findings from a related study. A year later, however, he publicly presented his method of crystal frequency control a month *before* filing a patent on the subject.[44]

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41. In 1919, Abraham and Bloch claimed that current instruments barely exceeded an accuracy of 1 percent (Abraham and Bloch, 1106).

42. Cady interview (n. 1 above), p. 19. Cady's meeting with Arnold was not in itself unusual. Among other former students who maintained contact with him after leaving Wesleyan were Karl Van Dyke, who returned to the university as a lecturer and helped Cady build a strong center for the study of piezoelectricity, and Gerlad Holton, who dedicated his second book to him. Cady's diaries mention meetings in December 1918 and October 1919, as well as several later meetings that appear to have been related to professional concerns.

43. Cady, "Outstanding Dates" (n. 27 above); Cady interview, pp. 18–19.

44. For the print version of a paper presented in November 1919, see Walter G. Cady, "Note on the Theory of Longitudinal Vibrations of Viscous Rods Having Internal Losses," *Physical Review* 15 (1920): 146–47; for another, presented the following April, see Walter G. Cady, "New Methods for Maintaining Constant Frequency in High-Frequency Circuits," *Physical Review* 18 (1921): 142–43. See also "The Piezo-Electric Resonator," U.S. patent 1,450,246, filed 28 February 1920, issued 1923, and "Methods of Maintaining Electric Currents of Constant Frequency," U.S. patent 1,472,583, filed 28 May 1921.

From mid-February or early March 1919, Cady's research had two objectives: patents and possible applications on the one hand, and scientific knowledge and publications on the other. Because a better understanding of the resonator contributed to better design, these pursuits partly coincided. In particular, the research that Cady conducted on various cuts and mountings of crystal plates and on new directions of oscillations helped improve the sharpness of the resonance and adjust it to the frequencies needed for its use. These studies could hardly suggest approaches for detecting and exploiting resonance frequency, however. In addition to a command of the properties of the resonators, designing methods to exploit resonance frequency required ingenuity in combining electric—in modern terms, electronic—components into a useful circuit. The "filter" that Cady constructed in February was his first means to that end. In the patent filed nine months later, he suggested five additional methods to detect and use resonance. During 1919, his research included general questions of piezoelectric behavior, among them possible variations in the value of piezoelectric coefficients and the influence of other variables such as temperature. Generalizing from his empirical findings, Cady developed a theory of the piezoelectric resonator and a set of rules and methods for computation. To better understand the behavior of the rods, he elaborated on the laws of their (damped) mechanical vibrations—a complicated mathematical theory for which he provided a solution in the autumn of 1919.[45]

Cady's studies of piezoelectricity, resonance, and rod oscillations were connected to questions of design. Although it was actually more important to Cady's later invention of frequency control, this increased understanding of crystal electric behavior near resonance was likely to improve frequency-standard devices; an articulated theory of rod oscillations was likely to advance the design of the crystal-metal resonating plates. Notwithstanding, Cady's research went beyond the needs of design and led to scientific publications, suggesting that the former was not his sole motivation.[46] For Cady-as-academic, publication indicated more than his wish to

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45. Like his theory of piezoelectric oscillation, Cady's theory of rod oscillations was phenomenological; it did not suggest a process or mechanism that produced the phenomena. See Cady, RNB 25, pp. 68–110, esp. 68–70, 72–75; RNB P, 1–1a; Cady diaries for 1919 (n. 25 above); and Cady, "Note on the Theory of Longitudinal Vibrations." The character of Cady's research on the piezoelectric resonator resembles that of Bell Labs scientists following the discovery of the point-contact transistor in 1947. In both cases, scientists developed a novel theoretical understanding of an unpredicted phenomenon through an intensive experimental study. See Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Invention of the Transistor and the Birth of the Information Age* (New York, 1997), chaps. 7–9.

46. Cady's work on elastic vibration well exemplifies his quest for knowledge beyond direct technological ends, because for plate design, a direct study of the plates would have been sufficient. Moreover, even if one chooses a mathematical-theoretical approach, one does not have to suggest a general solution. Cady not only proposed such a solution, but elaborated it for publication.

share his findings; it also brought recognition from his peers. Industrial researchers had additional, important ways to evaluate the merits of their work, such as patents, position and rank in the hierarchy of their company, and financial reward; scientists in industry often clashed with their supervisors over their desire to publish.[47]

In October 1919, while Cady was pursuing his patent, Alexander Mclean Nicolson presented his findings on the behavior of Rochelle salt crystals near resonance. Nicolson, under Arnold's directorship at AT&T, replicated some of Cady's primary results, although he did not report so sharp a resonance. Moreover, he neither elaborated on the electric properties of the crystal near these frequencies nor indicated either the steady frequency of resonance or its possible use as a frequency standard. Furthermore, Nicolson's research may have built upon Cady's, since Arnold is likely to have informed his subordinate of what the Wesleyan professor had found up through February 1919. Still, parts of Nicolson's research were probably original, as he had begun his study of piezoelectric transducers soon after the 1917 inter-allied meeting on submarines. While the other American groups worked on submarine detection, Nicolson's was investigating possible applications of piezoelectric oscillators to telephony. This was, of course, the main business of AT&T. Although Nicolson's group contributed to the war effort by growing Rochelle salt crystals, in general, it was the company rather than the state or its military that benefited from the information shared at the inter-allied meeting.

With telecommunication in mind, Nicolson studied crystals and resonance in sonic rather than ultrasonic frequencies, exploring possible applications of piezoelectric transducers in the telephone system as microphones and loudspeakers of sound and as amplifiers for long-distance calls. By April 1918, he had applied for a patent for such devices. That Nicolson's research was directed toward immediate applications could explain why he did not pursue his, or Cady's, findings about the electric properties of resonance. Unlike Cady, Nicolson—a junior researcher in an industrial laboratory—was obligated to follow a research program that fit the company's commercial goals.[48] Before 1925, "the AT&T laboratory initiated very little research that was not concerned with some type of technology already under development. This greatly limited the scope of its research effort and

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[47] On the conflict between scientists and managers regarding publications, see for example Reich (n. 8 above), 186–96.

[48] Hackmann, *Seek & Strike* (n. 14 above), 92; Hunt (n. 10 above), 51–52; Alexander M. Nicolson, "The Piezo Electric Effect in the Composite Rochelle Salt Crystal," *Proceedings of the American Institute of Electrical Engineers* 38 (1919): 1315–33; Nicolson, "Piezophony," U.S. patent 1,495,429, filed 10 April 1918. Nicolson utilized the property of crystals to "respond in a greater degree to currents of some frequencies than to currents of other frequencies" (patent, p. 2), as had Langevin, but Nicolson proposed the use of several crystals (rather than the particularity of resonance frequencies) to achieve the wider spectrum needed for sound transducers.

often stood in the way of those conceptual leaps that led to major breakthroughs in technology."[49] Nicolson's case suggests that Cady's academic status freed him to follow his own path, and that his "scientific" attitude (i.e., independent of a particular technological objective) encouraged his exploration of the properties of the piezo-resonator. By defining the research that led him to the discovery as "pure research in a new branch of applied physics," Cady implied that unlike what applied research (or "engineering science," to use a later term) might suggest, he did not aim at providing tools for improving useful devices.[50]

Crystal Frequency Control

Notwithstanding Cady's frequency-standard devices, sharp, stable electric resonance remained a solution in search of a problem. Frequency standards had a very limited market—primarily researchers and regulatory agencies.[51] The American National Bureau of Standards, for example, used them to measure wavelengths of radio transmitters and to force commercial broadcasting at a narrower and steadier frequency, thereby opening a small, fixed market for such devices.[52] In the same vein, in 1923, Cady himself compared wavelengths of radio transmitters in Italy, France, and Britain.[53]

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[49] Reich, 215.

[50] Walter G. Cady, "Problems Confronting the Independent Inventor," unpublished manuscript, 6 August 1963, p. 1, Cady dossier (n. 1 above). On the history of the term "applied science," its use by contemporaries, and its connection to the "linear model" of technological development, see Ronald R. Kline, "Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880–1945," *Isis* 86 (1995): 194–221; and Paul Forman, "The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology," *History and Technology* 23 (2007): 1–152. Later historians, objecting to the implied hierarchy of "pure" and "applied," suggested the term "engineering science" for research aimed at improving design. See for example Edwin T. Layton Jr., "Through the Looking Glass, or News from Lake Mirror Image," *Technology and Culture* 28 (1987): 594–607; Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore, 1990); and Kline, *Steinmetz* (n. 8 above).

[51] In the 1930s, the piezoelectric filter, which Cady suggested in his 1920 patent, found itself a problem in telephony, where it enabled the transmission of more than 480 conversations over one pair of conductors, and in radio. The piezoelectric filter, however, was based on further developments in piezoelectricity and electronics; see W. P. Mason, "Quartz Crystal Applications," in *Quartz Crystals for Electrical Circuits: Their Design and Manufacture*, ed. Raymond A. Heising (New York, 1946), 11–56, esp. 14–15.

[52] Christopher Shawn McGahey, "Harnessing Nature's Timekeeper: A History of the Piezoelectric Quartz Crystal Technological Community (1880–1959)" (Ph.D. diss., Georgia Institute of Technology, 2009), 131–73.

[53] That Cady omitted Germany, where he himself had studied, suggests that he joined the post–World War I boycott. See Cady, "Saving Ancestors" (n. 25 above), 220; and "The Use of the Piezo-electric Effect for Establishing Fixed Frequency Standards," Radio Laboratory, Bureau of Standards, 11 September 1920, Cady dossier.

Yet controlling the frequency of electric circuits was the major problem for which piezoelectric resonance eventually found a solution.

The technological advantages of controlling frequencies, rather than merely measuring them, was obvious even in the 1920s. The immediate beneficiary of narrower and more precise wavebands was radio, the most exciting technology of the time. As recounted in the introduction to this essay, Cady invented circuits for frequency control two years after discovering sharp resonance. Relying on his previous studies and stimulated by the question Arnold posed in February 1921, he began intensive research on the theoretical and experimental aspects of circuits to stabilize frequency, and he filed a patent three months later.[54]

The interaction between Cady and Arnold began before the New York meeting and continued after it was over. Arnold and his staff came "often" to meet Cady and see his resonators, and they loaned Cady equipment. In January 1921, Cady began sending them (and a few other companies) piezoelectric resonators. This collaboration left Cady bitter: in May 1923, AT&T claimed the rights to Cady's patent by filing a divisional application of Nicolson's 1918 patent based on a circuit in which a crystal is used to modulate frequencies. The company also made a claim for crystal control, although there is no indication that its researchers worked on it before February 1921. Until AT&T filed the divisional application, Cady had every reason to suppose that the corporation would buy the patent rights from him.[55]

The relationship between Cady and AT&T may be considered in a number of ways. First, we may ask what Cady gained from Arnold's stimulation that enabled his use of crystal resonance for controlling frequency, especially when Cady's own notebook reveals that he had recently aban-

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[54] Cady, RNB 25, pp. 237–87; Cady, "Methods of Maintaining Electric Currents of Constant Frequency" (n. 44 above). Cady relied on his unpublished explanation of the electric behavior near resonance from March 1919; on this point, see Katzir, "From Ultrasonic to Frequency Standards" (n. 23 above), 484. This was probably not the first circuit to be crystal controlled, but it was the first result of a deliberate attempt to construct such a circuit.

[55] Cady diaries (n. 25 above); the frequency of visits is mentioned on 17 December 1920. On 28 March 1922, Cady "sent off amplifier to West. Electric Co." Since amplifiers were not Cady's area of expertise, this could indicate that they had been loaned to him. Cady recalled that he had asked Arnold "if there was anything his company might be interested in" (Cady interview [n. 1 above], p. 18). Legal and financial considerations and corporate prestige probably led AT&T writers to claim for Nicolson's priority; see Raymond A. Heising, "Introduction," in *Quartz Crystals for Electrical Circuits*, 1–9, and M. D. Fagen, ed., *A History of Engineering and Science in the Bell System—The Early Years* (Murray Hill, N.J., 1975), 988–90. AT&T's divisional application began a legal procedure about the patent rights for crystal frequency control that continued until 1953. Cady, who could not fight the corporation, sold his patent to the Radio Corporation of America (RCA) for a relatively modest sum in January 1925. Although the court eventually decided that Cady's discovery preceded that of AT&T, it nonetheless awarded patent rights to AT&T; see Hunt (n. 10 above), 53–57.

doned attempts to do so after an initial failure.[56] The answer seems to lie in the relationship the two men had developed since their work in a small college laboratory some ten years earlier. That relationship also seems at play in the anecdote that introduces this essay: Arnold's comment that it would be "awfully nice" if Cady could make crystals control frequency as well as resonate. Arnold's statement implies a belief that his mentor's experience with the piezo-resonator made him more qualified to solve the technological problems than were AT&T's own staff, who had conducted no comparable research on crystal resonance, and this evident faith may well have prodded Cady to reexamine the question. More broadly, the personal connection between professor and former student signals an obvious truth that personal relationships are important to the flow of information about science and the technological needs of industry.[57] That the connection did not end well signals the limitations of personal relationships in the corporate world, not necessarily because of the individuals involved, but because these individuals are company employees. Arnold was not involved in AT&T's decision to claim Cady's patent, but he was informed about it.[58] Their prior relationship allows us to surmise that Arnold considered Cady's research a kind of outsourcing and assumed (or wished to assume) that his former professor would profit if the technology proved to have commercial value. Still, that this particular relationship could lead from a professor's discovery to the invention of a useful device reflects the continuum that exists not only between pure and applied research, but between the academy and industry as well. In any case, the advantage of Cady's expertise suggests that even after the discovery of the basic effects such as resonance, simple knowledge of the phenomenon and laboratory experience with it were still conducive to novel applications. Lastly, the interaction between Arnold and Cady shows the understandable value industry places on products, and that even a scientifically trained industrial researcher was more inclined to concrete technological goals than was a college professor. Despite these differences, Cady and Arnold were not mirror images of each

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56. Cady reported on an "attempt at using F13 [a quartz rod] as oscillation generator" (RNB 25, 22 January 1921, p. 225); he sent the same specimen to Arnold five days later (Cady diaries). Then he tried unsuccessfully to induce electric oscillations in resonance frequency by vibration of a quartz rod in a feedback circuit. Following the New York meeting, however, he no longer tried to produce oscillations by the crystal but used it merely to control the frequency of oscillation generated by other electronic means. The move from induction to control was not requisite for Cady's invention, however, since in May 1921 he designed a circuit that induced oscillations in its resonance frequency.

57. Arnold's Western Electric laboratory had a close connection with Robert Millikan, who sent a few graduates of the physics department at the University of Chicago, including Arnold, to AT&T; see Hoddeson, "The Emergence of Basic Research" (n. 8 above), 526, 532–33.

58. See the documents in the folder "Research Materials: Crystals, Nicolson-Cady Interference, 1923–1925" at the Warren, N.J., branch of the AT&T archives, Loc: 79 10 01 05.

other;[59] rather, their mode of expressing interest in both natural phenomena and the design of useful devices places them in different locations along the continuum that runs between science and technology, pure and applied research.

Subsequent Research on Piezoelectricity

Following the discovery of sharp resonance and the application of piezoelectricity for ultrasonics and frequency control, interest in the field expanded. Moreover, while Americans contributed virtually nothing to the field until 1918, they became dominant after that year. A bibliography of piezoelectricity cited 208 publications (excluding patents) between 1918 and the beginning of 1928, while there were approximately half that number during the previous thirty-eight years. Piezoelectric research spanned the spectrum from the general and abstract to the practical. For example, examinations of frequency variation, especially those related to changes in temperature, were required for resonators whose frequency variations were negligible.[60] AT&T took an active part in this research, as did researchers at GE. A number of solutions to the practical (and primarily electronic) problem of generating stable vibrations at low frequencies appeared from 1924 onward. In 1927, Joseph Horton and Warren Marrison of AT&T used one of these solutions to design the first quartz clock, and "[s]oon after . . . the idea was studied and applied in many places notably in America and Germany."[61] The quartz clock exceeded the precision of the pendulum clock, which had been the standard timekeeper for more than 250 years.

Notwithstanding the significance of the quartz clock during the 1920s and 1930s, the most important application of piezoelectricity was in telecommunications. Starting around 1924, radio transmitters began to use crystal frequency control to stabilize and narrow transmitted wavebands,[62] and within a few years that use had become universal. In the summer of

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[59] Layton (n. 50 above) views science and engineering as "mirror image twins." Arnold was not an engineer, but his work was directed at technological design and was, in Layton's terms, closer to engineering than to physical science. If Layton includes Louis Navier with the engineers, Arnold can also find his place there.

[60] This research did not originate solely from design needs. Variations with temperature could supply information related to the nature and causes of piezoelectricity. Practical aims could not have directed W. Lissauer to study the variation in piezoelectric behavior with temperature (between +19° to –192°C) in 1907; see Woldemar Voigt, *Lehrbuch der Kristallphysik* (Leipzig, 1910), 862.

[61] Warren A. Marrison, "The Evolution of the Quartz Crystal Clock," *Bell System Technical Journal* 27 (1948): 510–88.

[62] Narrow bands reduced problems of atmospheric interference and enabled the transmission of more signals in the same physical space (in wire communication) or ether waves (in radio). AT&T also played a central though not exclusive role in this field. It probably installed the first crystal controller in a public broadcast station, initially in an experimental way in June 1924 and in 1926 on a permanent basis.

1924, Cady and Van Dyke helped the U.S. Navy construct a crystal-controlled high-voltage transmitter, work analogous to that of World War I scientists in that the physicists employed their experimental and theoretical knowledge of crystal behavior toward a defined technological end. A year later, research conducted by the navy resulted in a patent for using the piezo-resonator in radio receivers.[63]

Researchers did not confine themselves to potentially practical applications of piezoelectricity. Among post-1918 publications, fifty-six were classified under "fundamentals [and] theory," and forty-three under "general articles on the piezoelectric resonator and oscillators" (with duplications), which reveals an increased interest in the laws of the phenomena compared to the pre-application period.[64] As expected, understanding piezoelectric oscillations and behavior near resonance was at the forefront of research in which scientists required greater rigor than was needed for any technological application. Cady began developing a theory of piezoelectric vibrations in 1919. The German physicist Max von Laue offered a different theoretical approach, supposedly more exact, but one whose use on approximated calculations created controversy.

A theoretical effort of particular interest for the relationship between scientific and engineering knowledge was the quest for an electrical equivalent that would accurately represent a piezoelectric oscillator by means of better-known electrical components. Probably first suggested by Hermann Helmholtz in 1853 and developed largely by scientists, equivalent circuits were usually used by engineers. Their simplicity was also appreciated by physicists like Cady.[65] Since an equivalent circuit is a kind of model, it could also be useful in making the phenomenon intelligible.[66] Cady had posited

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[63] Marrison; Fagen (n. 55 above), 319; Bottom, "A History of the Quartz Crystal Industry" (n. 2 above); Linwood S. Howeth, *History of Communications Electronics in the United States Navy* (Washington, D.C., 1963), chap. 28, sec. 10, available online at http://earlyradiohistory.us/1963hw28.htm#28sec10 (accessed 11 September 2009); Albert Hoyt Taylor and Edwin White, "Signal-Receiving Circuits," U.S. patent 1,669,217, filed 17 October 1925, issued 1928. Interest in the field led to additional minor applications (not based on resonators), such as a high-pressure measuring device.

[64] Walter G. Cady, "Bibliography of Piezo-Electricity," *Proceedings of the Institute of Radio Engineers* 15 (1928): 521–35. Fifty items about piezoelectricity were published between 1880 and 1899, while fewer seem to have appeared between 1900 and 1918; see Katzir, *The Beginnings of Piezoelectricity* (n. 17 above), 253–54.

[65] D. H. Johnson, "Origins of the Equivalent Circuit Concept: The Voltage-Source Equivalent," *Proceedings of the IEEE* 91 (2003): 636–40; Kline, Steinmetz (n. 8 above), 112–13. In "Engineering Knowledge in the Laser Field" (*Technology and Culture* 27 [1986]: 798–818), Joan L. Bromberg suggests that maser and laser engineers applied the method of equivalent circuits, which was not useful for many physicists, perhaps because of their lack of experience with its application. A systematic examination is necessary to learn when and in which fields physicists became as familiar with the method as Cady and Van Dyke were.

[66] Physical models are often unrealistic, in the sense that they do not claim to represent the real process beyond the phenomena; see Shaul Katzir, "From Explanation to

an equivalent circuit in January 1919, but he could not formulate a completely equivalent circuit—that is, a circuit with constant electric magnitudes at relevant ranges. That was developed in 1925 by Van Dyke. Like Cady, Van Dyke was not aware of Stephan Butterworth's 1915 general theorem of the equivalence network of any "electrically-maintained vibrations," a theorem that underlay David Dye's 1926 suggestion for a similar network for piezoelectric crystals.[67]

Another area of inquiry within piezoelectricity was the measurement of electric, elastic, and piezoelectric constants. Although crystal frequency control was independent of the precise values of these constants, the study of crystal oscillations often included such measurements. During World War I, John Anderson, Nicolson, and Cady had observed the abnormal electric behavior of Rochelle salt crystal, first noted by Friedrich Pockels in 1894, but because they were focusing on ultrasonic and telephone technologies, they did not pursue the matter. Following their findings, Joseph Valasek's study of the electric behavior of this crystal, conducted at the University of Minnesota between 1920 and 1924, revealed an analogy between permanent magnetism and its electric behavior, an area later known as ferroelectrics. In the 1930s, ferroelectricity, a hitherto unknown state of matter, became a dynamic field of investigation in which active research has continued unabated.[68] In various ways, then, the *technological* interest in piezoelectricity has stimulated *scientific* study. Technology originating in science has thus fostered scientific investigation through the questions it raised and the phenomenon observed during its development.

Concluding Remarks

The large-scale mobilization of science for World War II is well-known. World War I research on submarine detection, and on ultrasonic methods in particular, displays a similarly concentrated effort of scientists and engi-

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Description: Molecular and Phenomenological Theories of Piezoelectricity," *Historical Studies in the Physical and Biological Sciences* 34 (2003): 69–94.

[67] Stephan Butterworth, "On Electrically-Maintained Vibrations," *Proceedings of the Physical Society of London* 27 (1915): 410–24. Butterworth was a mathematical physicist ("M.Sc. Lecturer in Physics, School of Technology, Manchester"), not an engineer; David Dye, head of the division of electrical standards and measurements at the British National Physical Laboratory, did study engineering. See Cady, *Piezoelectricity* (n. 26 above), 305–37, esp. 333–34; Albert B. Wood, "Stephan Butterworth, OBE: An Appreciation," *Journal of the Royal Naval Scientific Service* 1 (1945–46): 96–98; E. V. A., "David William Dye. 1887–1932," *Obituary Notices of Fellows of the Royal Society* 1 (1932): 75–78.

[68] Cady, *Piezoelectricity*, 514–15; L. E. Cross and R. E. Newnham, "History of Ferroelectrics," in *Ceramics and Civilization*, ed. W. D. Kingery, vol. 3: *High-Technology Ceramics: Past, Present, and Future* (Westerville, Ohio, 1986), 292–93; Jan Fousek, "Joseph Valasek and the Discovery of Ferroelectricity," in *Proceedings of the 9th IEEE International Symposium on Applications of Ferroelectrics* (Piscataway, N.J., 1994), 1–5.

neers, albeit on a smaller scale. As in the later war, scientists worked with engineers, dedicating their knowledge, skills, and time to finding practical solutions to critical military needs (e.g., submarine detection and radio amplifiers). The results were impressive. Ultrasound-detection technology could not have been developed in that period without the large-scale investment of effort, money, and scientific expertise. Indeed, measured by the number of scientists and engineers involved, this was probably the greatest scientific-technological project ever conducted up to that point. It is difficult to imagine such an effort in another context. War-related piezoelectric ultrasonic research considerably extended knowledge of the phenomena involved, leading to the discovery of sharp electric crystal resonance and to the invention of crystal frequency control. This development resembles the impact of World War II radar research on the invention of the transistor. In both cases, concentrated research paved the way not only for an unexpected and immensely useful technology, but also for pure knowledge of the physical world and subjects studied by scientists. In contrast to the post–World War II period, however, the sharp decrease in funding for military research that followed the armistice diminished physicists' wartime influence. Still, Cady's work suggests that the Great War also had the effect of awakening physicists to the practical applications of their findings, whether military (the navy in Cady's case) or commercial (telecommunications). The war also affected methods: Cady's use of an equivalent circuit suggests that, as in World War II, the collaboration between engineers and scientists in the earlier war promoted the adoption of "engineering tools" in physics. Still, this did not lead to sweeping changes in the practice and style of physics, such as those that Peter Galison attributed to World War II.[69]

Although the war brought researchers, laboratories, and organizations together, it left room for traditional, small-scale experimental work. The American emphasis on coordination rather than direction of research (as was practiced, for example, in industrial laboratories) probably allowed for this to occur. Like many pioneers in radio, the technology closest to his research, Cady arrived at his most important findings and inventions alone. He was an independent inventor in a time of industrial engineering depart-

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69. Lillian Hoddeson, "Research on Crystal Rectifiers during World War II and the Invention of the Transistor," *History and Technology* 11 (1994): 121–30. On the scale of the scientific-technological World War I effort, see Hartcup (n. 21 above). His claim that "most of the devices [of the war] originated in the decade or so before the war" (p. 189) is nominally true but misleading, since it conceals the novel ideas and designs that emerged during the war such as the application of piezoelectricity to ultrasonics, which did not originate in Chilowski's prewar ideas; see Paul Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940–1960," *Historical Studies in the Physical and Biological Sciences* 18 (1987): 149–229, and Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, 1997), 293–97, 304–11.

ments and the growth of research laboratories.[70] This suggests that the lone inventor continued to characterize new fields and new methods. Yet Cady was not an Edison. When he was described as an inventor, he commented: "I would rather have 'inventor' omitted, and just say 'physicist.' I am not a professional inventor." He did not behave like a professional inventor; for example, he neither kept a patent notebook nor recorded his intentions.[71] Cady's self-image reflects a significant difference from that of the "professional": he sought neither devices to invent nor areas requiring technological solutions. His investigations were sparked by observed phenomena, and although inventions sometimes followed, they were not his primary goal. This attitude probably describes many twentieth-century scientists. Langevin presents another kind of an occasional inventor.[72] He became an inventor only for the duration of the war, but his inventions of the dielectric (with Chilowski) and piezoelectric ultrasonic transducers stemmed from technical-social needs rather than from the phenomena themselves. In this sense, they better resembled the purposeful inventions of engineers than the occasional inventions of Cady.

Cady's research on piezoelectric vibrators reveals his oscillation between the poles of science and technology, a movement with no obligation to gain either disinterested knowledge or insights useful for practical designs. Many investigations of piezoelectric crystals aimed to reveal information that could be instrumental for both understanding the phenomena for its own sake and improving artifacts and methods. Other questions were more restricted to specific applications or were irrelevant for design. Cady's choice of research direction was mostly practical; he followed his findings, choosing research he believed would lead to the most fruitful and interesting results, whether in new devices, phenomena, methods, or fundamental understanding. Often, as in the case reported here, the richest vein of research emerged from tacking between the scientific and technological poles: from the basics of piezoelectricity to its utilization in transducers, from the

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[70] "Without question . . . World War I led to a widespread quickening of interest in and enthusiasm for industrial R&D in the United States" (Hounshell [n. 6 above], 34). By 1917, when research began on ultrasonics, the three major electric and telecommunication companies in the United States—GE, AT&T, and Westinghouse—had independent research laboratories, as did DuPont and Eastman Kodak; see Ronald R. Kline and Thomas C. Lassman, "Competing Research Traditions in American Industry: Uncertain Alliances between Engineering and Science at Westinghouse Electric, 1886–1935," *Enterprise & Society* 6 (2005): 601–45.

[71] Cady's letter to the president of the Academy of Applied Science, Robert H. Rines, 25 October 1963 (Cady papers, ACNMAH [n. 26 above]). The patent notebook opened by Charles Steinmetz in early 1891—before he had filed any patent whatsoever—both symbolized and established his new professional identity as an engineer; see Kline, Steinmetz (n. 8 above), 37.

[72] Shaul Katzir, "Scientists as Occasional Inventors," paper presented at the SHOT 2008 conference in Lisbon, Portugal.

properties of the transducers as emitters and receivers of ultrasonic waves to their unique behavior in resonance, and from sharp electric resonance to its utilization in frequency meter and frequency control.

Even if it is sometimes impossible to assign a particular investigation purely to the realm of science or to that of technology, we cannot doubt that both poles influence the thinking of the researcher. “Pure” science had maintained a relatively low profile during the war, but once the war ended, Cady and others could return to research for its own sake. Practical applications were not absent from Cady’s postwar horizon, however; like many of his fellow scientists, he was ready to exploit his discovery. It is difficult to see how sharp electric resonance—and, consequently, frequency-control technology—would have been discovered and invented without this approach that combined the scientific and technological. This kind of research differed from the disinterested study of piezoelectricity that prevailed until 1915—research that was a prerequisite to, but insufficient for, the development of ultrasound and frequency-control technologies. The postwar application of piezoelectricity shifted the nature of research in the field so that it ranged between the dual poles of science and technology: from resonator theory, through a circuit for dividing the resonator’s frequency, to specific crystal cuts.