Arch. Hist. Exact Sci. (2008) 62:469–487
DOI 10.1007/s00407-008-0020-3

From ultrasonic to frequency standards: Walter Cady's discovery of the sharp resonance of crystals

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Received: 11 November 2007 / Published online: 26 February 2008

Abstract In 1918–1919 Walter G. Cady was the first to recognize the significant electrical consequences of the fact that piezoelectric crystals resonate at very sharp, precise and stable frequencies. Cady was also the first to suggest the employment of these properties, first as frequency standards and then to control frequencies of electric circuits — an essential component in electronic technology. Cady's discovery originated in the course of research on piezoelectric ultrasonic devices for submarine detection (sonar) during World War I. However, for the discovery Cady had to change his research programme to crystal resonance. This change followed Cady's experimental findings and the scientific curiosity that they raised, and was helped by the termination of the war. Cady's transition was also a move from "applied" research, aimed at improving a specific technology, to "pure" research lacking a clear practical aim. This article examines how Cady reached the discovery and his early ideas for its use. It shows that the discovery was not an instantaneous but a gradual achievement. It further suggests that disinterested "scientific" research (rather than "engineering"

Communicated by J.Z. Buchwald.

I am very grateful to Chris McGahey for providing me with his research notes taken from Walter Cady's diaries kept by the Rhode Island Historical Society, henceforth *Diaries*. I would like to thank Aharon (Arkee) Eviatar for linguistic comments, Ido Yavetz for our helpful discussion and Jed Buchwald for his thoughtful comments and editorial work. I thank the Lemelson Center in the National Museum for American History for a grant that enabled me to study Walter Guyton Cady Papers, 1903–1974, Archives Center, National Museum of American History (henceforth, ACNMAH) and the staff of the center, especially Alison Oswald, for their help. The following abbreviations are used: NB — Cady's research notebooks kept at ACNMAH, AIP - Niels Bohr Library, American Institute of Physics, Cady's dossier.

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research) was needed in this process, while research aimed at design was required for the subsequent development of technological devices.

1 Introduction

Tiny and hidden from public attention, piezoelectric resonators are used to keep time in quartz clocks and watches, to control rates in integrated circuits in virtually every electronic instrument and to tune radio transmitters and receivers. Walter G. Cady in 1918–1919 was the first to recognize the significant electrical consequences of the fact that crystals resonate at very sharp, precise and stable frequencies. Cady was also the first to suggest the employment of these properties, first as frequency standards and then to control frequencies of electric circuits.[1] Cady's discovery originated in the course of research on piezoelectric ultrasonic devices for submarine detection during World War I. This paper, which is based on Cady's notebooks, describes the way in which Cady's work in that area coupled with his general interest in scientific phenomena moved him from his original research programme on ultrasonics to one on crystal resonance, which in turn led to the discovery of the sharpness of the concomitant electric effect, and then to the invention of basic ways for the latter's utilization.

Cady's transition was also a move from 'applied' research, aimed at improving a specific technology, to a 'pure' research lacking a clear practical aim. The former is sometimes called 'engineering science' or 'engineering research'. This kind of research shares the methods but not the aims of the natural sciences. It seeks knowledge for the sake of the design and improvement of practical devices and methods. Therefore, the questions asked and the results sought here differ from those of pure scientific research. The relationship between the two kinds of research, their significance and even their very existence, have been a subject of controversy among historians of technology and science.[2] It is thus interesting to examine their possible roles in Cady's research, which included both kinds in the study of one and same object — oscillating piezoelectric crystals. In Cady's research, knowledge was sometimes its own aim, sometimes it was a means for improving design (of a particular device or in general) and sometimes it was both, since questions of understanding and intelligibility were linked to possible practical uses. A close look is therefore required to plausibly reconstruct the goals of his research, whether of intelligibility or of design, at different stages in order to appreciate the contribution of and limitation imposed by each kind of research (and their combination). This investigation shows that although parts of the research cannot be neatly divided between the poles of "engineering" and

[1] During a legal procedure on patents, the American Telephone & Telegraph Company claimed for the priority of Alexander L. Nicolson in recognizing and utilizing the properties of resonance. This claim, however, does not seem to be supported by evidence. See Frederick V. Hunt, *Electroacoustics: the analysis of transduction, and its historical background* (Cambridge, 1954) 53–57, and more briefly in Katzir, "Between science and technology: the discovery of crystal frequency control," forthcoming.

[2] Edwin T. Layton, Jr., "Through the looking glass, or news from lake mirror image," *Technology and culture, 28*(1987), 594–607, and Walter G. Vincenti, *What Engineers know and how they know it: Analytical studies from aeronautical history* (Baltimore, 1990). For the controversial character of this definition see for example Sungook Hong, "Historiographical layers in the relationship between science and technology," *History and technology, 15*(1999), 289–311.

"pure" research, nevertheless at other instances the two different kinds of research led to investigations with significantly different immediate aims, examined phenomena and consequently results.

Ironically, the diversion from research related to ultrasonics towards more general questions remote from known practical aims (i.e. from "engineering" to "pure" research) eventually led to major applications of vast importance eclipsing those of ultrasonics. These applications, including frequency control circuits and clocks, were based on Cady's recognition that the electro-mechanical resonance of crystals is sharper than that of any tuning fork.[3] The transition from tuning forks to piezoelectric resonators, or more generally the use of the piezoelectric resonators for timekeeping, control of radio frequency, etc., is part of the transition from mechanical to electric and electronic technology,[4] arguably the most important development in twentieth century technology.

I begin with a brief discussion of the research on piezoelectric ultrasonics as a background to an examination of Cady's work in that field, the turn of his research to the study of crystals in resonance, his early findings and the initial ideas of their use. In another article I elaborate on the context of Cady's research and his invention of frequency control.[5] Later applications, which evolved within an established research programme on piezoelectric resonance and its possible uses (including piezoelectric frequency control), are beyond the scope of this paper.

2 Prelude: Piezoelectricity in the detection of submarines

At the beginnings of World War I, as the Entente powers recognized the threat imposed by German U boats, they invested much effort in finding ways to detect them. Constantin Chilowski, a Russian electrical engineer émigré in Switzerland, suggested sending ultrasonic waves and receiving the echo returned from the underwater vessels. Chilowski's suggestion was delivered to the French physicist Paul Langevin. Working together, by the end of 1915 the two developed an electro-mechanical device that transduced high frequency alternating current (simpler to produce than mechanical alternations) to ultrasonic, and they developed as well a microphone for the detection of the echos generated by the device's ultrasound. In early 1917, after his collaboration with Chilowski ended, Langevin designed a new ultrasonic transducer based on the piezoelectric effect in quartz.[6] Discovered by Jacques and Pierre Curie in 1880, the main properties of piezoelectricity were well known and accounted for by a

[3] In later years he mentioned the comparison with tuning fork several times, e.g. oral interview by R. Bruce Lindsay and W. J. King, 28, 29 August, 1963 (AIP).

[4] Since the piezoelectric resonator was always used with electronic amplifiers (vacuum tubes, transistors) piezoelectricity was an early electronic technology.

[5] Katzir, (note 1).

[6] Willem D. Hackmann, *Seek & strike: sonar, anti-submarine warfare and the Royal navy, 1914–1954* (London, 1984), 77–80, id., "Sonar research and naval warfare 1914–1954: A case study of a twentieth century establishment science," *Historical studies in the physical sciences, 16*(1986), 83–110, Hunt (note 1), 46–49, and Katzir (note 1).

phenomenological theory.[7] As a former student of Curie Langevin was familiar with the phenomenon and with its only practical use in a laboratory electrometer.

The piezoelectric effect is the phenomenon by means of which a change of pressure applied in particular directions in certain crystals generates electric polarization (and so a corresponding voltage difference); An electric field induces strain in the same direction. In proper conditions, the combination of electric field with mechanical strain can produce electro-mechanical oscillations. The application to the crystal of an oscillating electric voltage can, moreover, produce a periodic mechanical disturbance and vice versa. Thus, piezoelectricity offered a relatively simple solution for the most problematic elements in the Chilowski–Langevin's technology — the generation of high frequency mechanical oscillations, and their detection by electrical means. A piezoelectric crystal could be made to oscillate mechanically by applying to it an alternating electric voltage, producing thereby ultrasonic waves; the process could be used in reverse, with ultrasonic waves eliciting mechanical oscillations that generated alternating current. Such a transducer became the basis for underwater detection devices like sonar (originally known in Britain as asdic) as well as for medical ultrasonic scanners.

Constructing working piezoelectric transducers was hardly the trivial application of a simple principle to a new problem. Although the phenomenon had been studied, high-frequency piezoelectric oscillations had not been examined before Langevin thought about their technological use. The properties of the crystal under such conditions (e.g. possible changes in piezoelectric and dielectric coefficients) were one area of inquiry in the research for piezoelectric ultrasonic devices. Most questions, however, concerned design issues, such as the shape, size and availability of appropriate crystal bars, their mounting to metals, the connection between the (dielectric) piezoelectric plate and the electric circuits, the amplification of its electric signals and the effect of sea-water on the transducers. Another field of inquiry was underwater acoustics, which was entirely new. Langevin's breakthrough resulted from the construction of a crystal "sandwich" made of a few quartz plates and steel whose natural elastic frequency of vibration was in the range suitable for ultrasonic waves, and from the use of better vacuum tube amplifiers (based on De Forest's "audion") to detect the feeble echo signals.[8] Thus, a prerequisite for piezoelectric ultrasonic technology was the development of electronic amplifiers (and circuits) for radio transmission (and earlier for telephony). Indeed the development of radio technology continued to serve the study of piezoelectric oscillators and later became the first field of its application.

Detailed information about Langevin's devices was communicated quickly to other Entente powers, which thereafter pursued their own research and development programmes for piezoelectric ultrasonic echo detection. Despite the French exposure of their findings and the efforts undertaken by scientists and engineers in Britain, Italy

[7] Shaul Katzir, *The beginnings of piezoelectricity: a study in mundane physics* (Dordrecht, 2006).

[8] Lee de Forest's "audion" was an electronic valve with a grid between anode and cathode. Although it was invented primarily as a detector of radio waves, since 1911 a few individuals and companies designed circuits and "audions" for amplifying currents. See Sungook Hong, *Wireless: from Marconi's black box to the audion* (Cambridge, 2001), 178–189. On the ultrasonic research see, in addition to the sources mentioned in note 6, Pierre Biquard, "Les premiers pas dans les recherches sur les ultasons," *Journal de physique Colloque, supplement to 33*(1972), C6-1–C6-3.

and the United States, the French continued to lead the field. By the end of the war they had reached a detection range of about 1,000 m with their piezoelectric quartz transmitter and receiver. Still, the device did not go into service before the armistice. All in all, this WWI research involved at least 12 groups (not totally independent of each other) in 4 countries, involving many leading physicists and professors of electrical engineering from famous universities and from industry (including Langevin, Rutherford and Robert William Boyle in Britain, Michael Pupin, John A. Anderson and George W. Pierce in the US).[9] Significantly, only Cady investigated the special electric properties of piezoelectric resonance and suggested their utilization.

3 Cady's work on ultrasonics and resonance

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 MA. Encouraged by one of his teachers he continued his studies in Berlin, earning a PhD in 1900, on experimental research concerning the energy of cathode rays (electrons), on which he worked mostly with Walter Kaufmann, one of the experts in this field. He retuned for a more pragmatic research at the magnetic observatory of the US Coast and Geodetic Survey, and in 1902 he joined the small faculty of Wesleyan University, where he taught physics until 1946. At Wesleyan he continued studying magnetism, but divided his time between a few subjects. In 1908, in the wake of a student's finding (Harold Arnold) he began to investigate vibrations and rotations in electric discharges (like the electric arc). Many years later he pointed to that as "a good example of the fact that a chance observation can give rise to a long line of research." Wireless telecommunication also attracted his attention, and he examined a few related issues such as detectors for electromagnetic waves and high-frequency oscillations just before commencing his study of piezoelectricity. While constructing his own experimental devices Cady devised and patented a number of laboratory instruments.[10]

3.1 Ultrasonic research

In spring 1917 Cady "did little thinking and small-scale experimenting, especially in the use of magnetic methods" for detecting submarines. Most of the methods attempted to detect the electromagnetic effects of a metal submarine in water (e.g. a change in the magnetic field, or in conductivity between two points in water). These led to no

[9] Hackmann mentions ten American centres but one of these did not work on ultrasonics, Hackmann, *Seek & strike* (note 6), 41, 90–92, also in Hackmann, "Sonar Research" (note. 6), 95–97. Walter G. Cady, "Piezoelectricity and ultrasonics," *Sound: its uses and control, 2* (1963), 46–52, pp. 46–49. On the international exchange of knowledge see David Zimmerman, *Top secret exchange: the Tizard mission and the scientific war* (Montreal and Kingston, 1996), 8–11.

[10] Walter G. Cady, *Saving ancestors*, (unpublished manuscript a copy kept in AIP, 1963), 100–106, 116–118, 209–210, quotations on 100, 209, his papers in ACNMAH. For a short description of Cady's work see James E. Brittain, "Walter G. Cady and Piezoelectric Resonators," *Proceedings of the IEEE* 80 (1992).

practical results, except his invitation, among a few dozens American scientists and engineers, to a three-day scientific-technical conference on antisubmarine measures, held in Washington in June 1917. There, foreign envoys informed the audience about work in the field with emphasis on Langevin's piezoelectric method. Years later he wrote that "[a] principle so novel and so suggestive could not fail to excite the interest of many physicists."[11] Cady clearly was among those excited. Soon after returning to Wesleyan he experimented with piezoelectric crystals, and two weeks later he joined the General Electric laboratory in Schenectady, NY, where he "devised various forms of quartz and Rochelle salt [crystal] units for receiving ultrasonic signals."[12] "The research on piezoelectricity," Cady recalled half a century later, "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."[13] Indeed, his experience with vibrations, including electronic circuits for their generation was useful for his research on piezoelectric oscillations.

Cady did not stay long at General Electric laboratories. He left in October and a month later "began cooperation with Pupin, Wills and Morecroft at Columbia, though most of my [Cady's] share was done at Wesleyan [where he continued to teach during the war]."[14] The Columbia group made sea trials in the navy base of Key West Florida and from summer 1918 in the Navy experimental yard of New London, Connecticut (a location that enabled the participants short visits). In his research in Wesleyan Cady studied, among others, the basics of piezoelectricity from a German textbook by Woldemar Voigt, who formulated the general theory of the field.[15] Voigt's theory related the linear electric effect of pressure on electric polarization and its converse effect to crystalline structure; it also examined the relationship between piezoelectric and other crystalline characteristics, such as dielectric and elastic coefficients. Among others, Cady examined empirically the piezoelectric and electric properties of static and oscillating crystals, measuring capacity, dielectric coefficients, inductance and later resistance. By these studies Cady learnt general properties of piezoelectric crystals and acquired the skill to work with them in the laboratory. Another object of the investigation was to decide between the two crystal species suggested for use as ultrasonic transducers, Rochelle salt or quartz. Rochelle salt has a stronger piezoelectric reaction, but is soluble. Quartz is more stable as a crystal and in its piezoelectric reaction. The Europeans employed only the latter, probably because of these characteristics. The Americans, however, considered both and usually preferred the

[11] Earlier non-piezoelectric attempts to detect submarines, in NB 18, pp. 170–171, NB 43, pp. 81–87. First quote Cady, *Saving ancestors*, 210, second quote, id., *Piezoelectricity: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals*, 2nd edn. (New York, 1964), 676.

[12] W. G. Cady, "Outstanding dates relating to work of W. G. Cady in piezoelectricity," 2 pages manuscript written probably at the 1960s, kept in AIP.

[13] Cady, *Saving ancestors*, (note 10), 211.

[14] Cady, "Outstanding dates."

[15] Cady first mentioned its study on 29.7.1917, *Diaries*. He probably used Voigt's thorough *Lehrbuch der Kristallphysik* (Leipzig, 1910), to which he referred in his 1921 paper. Ironically, Cady used a German textbook in a way unexpected by its writer in an effort to fight Germany.

former. Most of Cady's work concentrated on questions of design: efficient sizes and cuts of crystals, their mounting, the material to which they were mounted in the transducer (tinfoil, steel, aluminum, rubber, wax, castor oil),[16] and so forth. The inclusion of the crystals as transducers (mostly as receivers) in the electric circuit was another central question of design.[17] Cady experimented with the transducers, which usually consisted of one or a few crystal plates (dimensions of a few to a few dozens millimetres). Since February 1918 he included them in electronic circuits with a triode valve amplifier ("audion"), inductance coil/s and capacitor/s, sources of power (dc batteries) and a detector in various settings and branches, some of them loosely coupled to the transducer's circuit.

Frequency was one among a few variables in Cady's experiments. It was induced by electromagnetic means, like a known LC circuit. He recorded its value and its influence on other magnitudes. Variations in frequency led to stronger changes in other variables near resonance frequencies, commonly exploited by workers in the field. As was well known for the elastic theory of vibrations, at these frequencies the crystal plates (or sandwiches) vibrate close to their 'natural' mode with small loses of energy (no mechanical friction). Since vibrating plates in resonance are energetically significantly more efficient than at other frequencies, researchers in the field exploited these frequencies both for transmitters and receivers (this was a major advantage of the "quartz sandwich"). Therefore, since Langevin's early works on the subject, they studied the behaviour of crystal transducers and circuits at and near resonance frequencies.[18] No Later than the beginning of 1918 Cady studied characteristics of resonance. For example, on February 12–15, he examined the resonance frequencies of rods of different lengths (from 14 to 28 mm with the same cross section) and their sharpness, i.e. how sensitive is the intensity of sound to changes in frequencies.[19] Still, like his colleagues, Cady neither took up an intensive research on the shape of resonance, nor studied closely its electric consequences. On August 15th while measuring capacity and resistance of new Rochelle salt plates, he calculated a negative capacity of plates at specific frequencies. Later he would associate it with the special electric properties of resonance, but in August he did not pursue the matter further.[20] As Cady was preoccupied with the engineering research on submarine he did not fellow, what

[16] Rochelle salt crystal had to be immersed in an isolating material since it is soluble.

[17] NB X pp. 14–64, NB 20, pp. 53–65, NB 23, especially 1–32.

[18] See Langevin, Paul, "Procédé et appareils d'émission et de réception des ondes élastiques sous-marines à l'aide des propriétés piézo-électriques du quartz", France patent FR505703, filed 17-9-1918, issued 1920, and his report from Oct 1918 published in David Zimmerman, "Paul Langevin and the discovery of active sonar or asdic," *Northern mariner, 12*(2002), 39–35. For other examples see the part of I. B. Crandall in "Report on the conference of physics and engineering divisions of the National Research Council, Washington, July 18, 1918" and Fuller and Ryan's report "Problem #324: Quartz supersound source projector" from 1.8.1918, both in The National Academies Archives (Washington), 1914–1918 CFP. I do not know of any examination of resonance electric properties before Cady's .

[19] NB 23, pp. 27–31. Cady mentioned "dull resonance" of two new receivers in his reports to the NRC, (under the title "problem 190 supersonic vibrations," in AIP) from 29.8.1918; on these see NB 23 pp. 107–111 (10-15/8/1918) in which, however, he did not refer to resonance.

[20] NB 23, pp. 107–111.

probably seemed to be an interesting behaviour that could not help improving ultrasonic detection.

In autumn 1918 Cady began paying more attention to the electrical properties of crystals near resonance. In October and November he employed a new, accurate measurement method that had been developed for capacitors in radio to probe the effect of the frequency of the circuit (among other variables) on the voltage, capacity and resistance of the transducers.[21] Apparently at that stage Cady suspected that interesting changes might occur to the electric properties near resonance. Still, the investigation was connected to his efforts to improve ultrasonic transducers, probably in an attempt to utilize properties of resonance for both senders and receivers (improving their energetic efficiency, and by using a narrow wavelength, perhaps thereby reducing their vulnerability to interference). Cady carried out important parts of this study in the New London Navy station, performing underwater experiments from a ship and comparing Rochelle Salt and quartz crystal transducers for the strength of their reaction and their sensitivity to changes of frequency. He examined transducers usually consisting of a few crystals mounted together as "senders" and "receivers" rather than individual crystal plates. In December he started calling them "plates", while intensively experimenting with their electric properties (resistance, capacity) in different settings. These included variation of capacitors, crystal plates, arrangements and frequencies.[22] Although, Cady's examination of the electrical behaviour of transducers in different settings and frequencies was not limited to the working of the plates as ultrasonic transducers, apparently (at least through November) that was one of his central aims. Cady gathered knowledge that might be useful for designing more efficient submarines' detectors

3.2 Crystal frequencies

Late December brought a break in Cady's research,[23] and probably helped him reorient his study from ultrasonic detection to crystal resonance, since he suspected that the electric reaction of crystals in resonance was responsible for peculiarities that he observed in his circuits.[24] He began 1919 studying intensively the influence of frequency on the electric behaviour of quartz and Rochelle salt, including a reappraisal of earlier results. On January 4th Cady observed a sharp minimum in current in a

[21] Frequency was induced by electromagnetic means.

[22] An early graph of capacity against frequency, which, however, did not show any peak, appeared on November 6th (NB 20, pp. 106–108). Other related entities: NB 20, especially pp. 66–74 (1-2.10.1918), 114 (14.11.18), NB X, p. 68 (before 16.10.18 – theoretical comparison of receivers at different frequencies, NB 12, pp. 76–81 (6-8.12.18), 82–87 (17–20.12.18). Cady's new method of measurement is first mentioned after 29.10.18 (NB 20, p. 100). It follows the one presented in *Circular of the Bureau of Standards, No. 74: Radio instruments and measurements* (Washington, 1918), 180–182, 190–193.

[23] Cady went to two scholarly trips in December one to New York (on the 9th) and the other to the American association for the advancement of science meeting in Baltimore (on the 26th), *Diaries*.

[24] E.g. 20.12.1918, NB 12, p. 84.

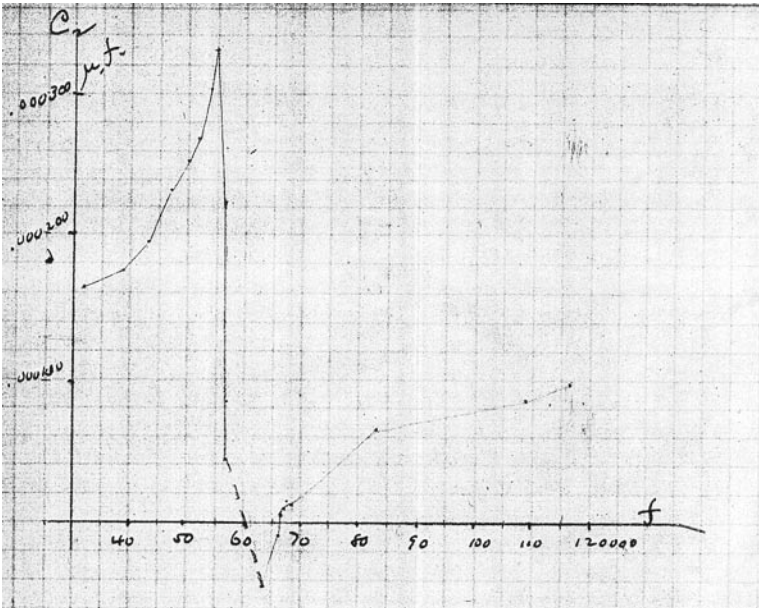

Fig. 1 A graph drawn by Cady on 11.1.1919 of capacity as a function of frequency. Notice the negative value around 65 KHz, (source NB 25, p. 29)

circuit that contained a Rochelle salt crystal, at "a critical frequency."[25] The association between a minimum in current and resonance had been observed before. In his report for an inter allied conference on submarine detection from 31 October 1918 Langevin described and explained the phenomenon: "The intensity of the high frequency current received by [a secondary oscillating circuit, Langevin wrote] passed thin [*sic*] a minimum at the moment of elastic resonance, because of the important subtraction of power which the supersonic emission produces at this moment in the electric circuit, or, in other words, because of the increase in the resistance of the emitting quartz condenser at this moment."[26] Like Cady, Langevin used a thermal ammeter to measure the current. Cady's observation was significant in two aspects: he probably found a sharper minimum than those previously observed (and certainly recognized its sharpness), and more importantly he followed this observation with an examination of the influence of frequency on current (in the circuits) and on the crystal's resistance and capacity.

Varying the settings by replacing Rochelle salt plates, capacitors, coils and their arrangement, Cady obtained a clear change in resistance with frequency and an even more conspicuous one for the capacity. Capacity near critical frequency had more than twice its "normal value." Moreover, its value dropped steeply to a negative value just near the maximum value, as Cady drew in a graph on January 11 (Fig. 1). As men-

[25] The term critical frequency appears in this context first on 20/12/1918 (NB 12, p. 84) and again on 9/1/1919. It appeared already earlier (e.g. on 15/2/1918, NB 23, p. 31), but probably without the full meaning acquired by January 1919.

[26] Langevin in Zimmerman (note 18).

tioned, he had observed a negative value 4 months earlier but did not make much of it then. Such a capacity now became meaningful as part of more general behaviour, and he verified theoretically that it has a physical meaning within the electric circuit. In analysing his findings about resonance Cady relied on a basic model of the crystal as a condenser and resistor in series (i.e. without considering inductance). In such a model the effective capacity and resistance vary with the frequency. At the end of the month and beginning of February he carried out a series of experiments on quartz plates like the ones that he had performed on Rochelle salt, finding even steeper curves near resonance. Subsequently, he investigated more closely the neighbourhood of resonance, narrowing the range of frequencies. In this research Cady sought the best arrangement to enhance the effect, as is common in designing a technological device, but also in experimental physics, where one looks for the clearest effects.[27]

Apparently, in early 1919, as the end of the war lifted the urgency of ultrasonic detectors, Cady felt free to deviate from his ultrasonic research programme to study instead resonance phenomena. His research was nevertheless still related to submarine detection. The crystal plates that he examined did not differ much from transducers; they were still compounds of a few plates (which have an advantage of resonating in frequencies most suitable for underwater detection). Moreover, he applied his findings to supersonic research, probably with a hope to utilize the conspicuous changes in the electrical behaviour of crystals for transducers. Thus, on January 13th he studied the behaviour of Rochelle salt crystal in a saltwater tank. A week later at the New London naval research station, with which Cady was still associated, he compared the sensitivity of Rochelle salt and quartz to ultrasonic waves of different frequencies, quantitatively and qualitatively, by listening to the sound produced by the electric circuit (probably through a telephone receiver). While the equations he used here had already appeared in his notebooks the previous October, in January he measured and calculated the magnitudes of capacity and current using these equations for the first time. This examination indicates his growing recognition of the crucial influence of frequency on piezoelectric plates; it also suggests that he considered the use of resonance frequency in submarine detection. Still, he attempted to exploit neither the specific changes in electrical properties nor the sharpness of resonance (or critical frequency, as we see in Fig. 1).[28] So while Cady continued investigating ultrasonics, his work on these detectors did not require comprehensive research with crystals. This suggests that his investigation of piezoelectric resonance was motivated by another factor, most likely by curiosity about nature and its laws. In other words, Cady's "engineering" research alone would not have allowed him this comprehensive study of resonance (and it probably prevented earlier examination of resonance effects). Still, his research at this point exemplifies the difficulty in drawing a dividing line between research aimed at improving technology and an investigation designed to probe unexplored areas of particular phenomena. It does not seem that Cady drew any such line himself.

[27] NB 12, p. 89 (3.1.19), NB 25, pp. 1–47 (4.1-5.2.19).

[28] NB 20, pp. 35 (13.1.19), 40–41 (20.1.19), quotation on 41.

Cady's research during January and early February 1919 showed that piezoelectric crystals have a sharp resonance with clear electrical consequences. From the intensity of his work on these days and its focus on the behaviour near resonance, it seems that Cady realized that he had discovered an interesting, novel phenomenon, although he still had much to learn about it. In later recollections he assigned the discovery to an earlier date:

> In the course of my tests of quartz and Rochelle Salt in 1917 and 1918, I had noticed that specimens cut from these crystals reacted in a peculiar way on the driving circuit when the frequency was close to that for a natural mode of vibration. In quartz the effect was extraordinary sharp. To me, this observation was like one of Sir Thomas More's "Diamondes and Carbuncles upon certain rockes," discovered by the dwellers in Utopia: "And yet they seke not for them: but by chaunce finding them they cutt and polish them."[29]

However, in this case the recognition that these are "diamonds" was far from obvious. Although Cady had observed a few "peculiar" behaviours of crystals during 1918 (such as negative capacity), at the time he had neither recognized the sharpness of resonance nor had he closely studied the phenomena before the beginning of the next year and the end of the war. The previous August he had not cared enough to examine the resonance, and neither did other researchers in the field (including Langevin), who most probably observed a few of these properties as they experimented with piezoelectric oscillators near resonance. Cady's discovery was accordingly a chance finding only in a qualified sense. Although initially he had not looked for any special behaviour of piezoelectric resonators, he was led by a few occasional unconnected observations to undertake an investigation only by which he forged a discovery. He began the investigation in late 1918 but carried it through in a concerted way only in the early part of 1919. Moreover, the stages described above suggest that "the discovery" was the retrospective outcome of a gradual, uneven process that cannot be fully reconstructed.

3.3 Frequency standards

The scientific interest in Cady's discovery of an unknown phenomenon is obvious. Yet, this discovery did not suggest the illumination of any central question in contemporary physics (unlike his dissertation on cathode rays). It suggested, however, possible, albeit unclear, future technological applications. In this sense it resembles

[29] Cady, "Piezoelectricity and Ultrasonics," (note 9), 49, the quotation from More appears without explanation also as an epitaph of the chapter on the piezoelectric resonator in his textbook, Cady, *Piezoelectricity*, (note 11), 284. Cady's choice of quotation is quite strange since More denies the value of these findings, as *Utopia* continues: "and with them [diamonds etc.] they adorn their children, who are delighted with them, and glory in them during their childhood; but when they grow to years, and see that none but children use such baubles, they of their own accord, without being bid by their parents, lay them aside." Thomas More, *Utopia*, in a common anonymous translation, book II (http://www.gutenberg.org/files/2130/2130-h/2130-h.htm) (Cady used a version with an older spelling).

much of Cady's work since his return to the United States.[30] Indeed, Cady was quick to consider the application of the sharp resonance for frequency standards. Still, this application was in a traditional domain of physics. At least since 1830, physicists and astronomers had been developing and defining standards and measuring devices.[31] Almost simultaneously the physicists Abraham and Bloch in France reported on a different method for measuring radio frequency.[32]

More than four decades later Cady recalled that the thought of using piezoelectric resonance came to him at one particular moment.

> I cut some thin bars from quartz crystals and set them into vibration by the current from a high-frequency vacuum tube oscillator. Each one vibrated strongly in resonance at a particular frequency, depending on its length. One night while I was getting ready for bed it suddenly flashed on me that these resonances were so sharp that such a rod could serve as a standard of frequency. It could be used to standardize, or calibrate, a frequency meter. At that time even the best frequency meters were not very accurate. It was in this way that the piezo resonator came to be invented.

Cady's notebooks, however, do not support his recollection of one "night of revelation."[33] In February he began devising circuits that could be used both to study crystal resonance and to exploit these 'piezo resonators' to other ends. These circuits were based on the discovery that the resonance of crystals is electrically sharp and the stability of its frequency, probably inferred from elasticity and supported by the results of Cady's electro-mechanical experiments. Yet, it is less clear if and in what sense Cady thought of resonating crystals as "frequency standards." It is possible that during this research the specific idea of using the resonators as "frequency standards" crystallized in Cady's mind in a way similar to his recollection. Even if so, Cady's

30 Cady himself characterized his early study of the piezo-resonator as "pure research in a new branch of applied physics." 'Pure' does not usually go with 'applied'. Yet, Cady's words can be interpreted as consistent (and in agreement with my finding here). By this interpretation, his research was connected through its subject (through questions and possible goals) to applications, but, unlike engineering research, did not aim directly at a better design and departed from questions of design. Cady, "Problems confronting the independent inventor," a manuscript dated August 6, 1963, held in AIP, p. 1. The relation of Cady's research to technology after his return to the US, fits common generalizations according to which American science was more practical and more atuned to application than European science.

31 Scientists (especially Gauss and Bessel) were active in reforms 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 M. Norton Wise, ed., *The values of precision* (Princeton, 1995), 103–134, on 117–125. On electrical standards see Simon Schaffer, "Accurate measurements is an English science," *ibid*, 135–172.

32 Henri Abraham and Eugène Bloch, "Amplificateurs pour courants continus et pour courants de très basse fréquence," *Académie des sciences* (*France*). *Comptes rendus, 168* (May 1919): 1105–1108. Abraham and Bloch's 'multivibrator' circuit produces 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 war work at the Military radio-telegraphy.

33 Cady, *Saving ancestors* (note 10), 211–212. The notebooks do not mention a list of such different bars at the relevant month of February – early March, when Cady described his plans for a patent (see below). He continued working on condensers made of a few plates also after starting working on a patent.

account disregards or downplays the central accomplishments needed for the invention: the observation that the resonance is sharp, that its electrical consequences are profound (which he probably established by early February) and the findings of proper means to detect it. The research on these questions was a more gradual process than suggested by Cady.

Perhaps in testing the resonance of a four plates quartz condenser during the first week of February, Cady attempted to examine its possible use for tuning wave meters. In these experiments, he employed a buzzer, and got a "min[imum] of sound . . . not very sharp" at resonance frequency, when the crystal "chokes." This resembles a known standardisation method for wave meters. At that time "[i]n its usual form a wave meter [was] essentially a simple radio circuit, consisting of an inductance coil and condenser in series, with an ammeter or other device to indicate either the current flowing in the circuit or the voltage across the whole or a part of the capacity or inductance. Either the inductance or capacity [was] made variable and sometimes both." The resonance wavelength of the device (observed by the indicating device) is $\lambda = k\sqrt{LC}$, where L is the inductance, C the capacity and k a constant. The calibration of the meter was based either on determination of capacities and inductance by their physical dimensions and dielectric constants or by electric measurement at low frequencies or on comparison with a known standard. Cady's experiment, however, included an unsuccessful attempt to generate oscillations from the circuits (disconnected from the electric source), which is hardly consistent with the aim of designing frequency standards.[34]

A day after completing these experiments, Cady examined another use of crystal resonance, or perhaps another way to detect it. That evening he attempted to receive a broadcast of electromagnetic waves (at 120 kHz) from the Navy station in Arlington Virginia (NAA) by coupling two circuits with Rochelle salt plates. A few days earlier he had received the station's signals by means of a known radio method of heterodyne detection.[35] However, the attempt with Rochelle salt failed, and Cady "gave up" receiving the faint signals from NAA, but not the idea to employ piezoelectric plates to detect radio waves.[36] Two days later, he employed crystals instead in order to couple two new circuits, so that they would be electrically connected only at resonance frequency, enabling the detection of signals of that wavelength. To this end, an assistant sent waves from a nearby room, varying the frequency of the sender while keeping

[34] Cady used buzzer coil whose sound would be "chopped" in resonance frequency, NB 43, p. 31 (7.2.1919). On wave-meters see D. B. Sullivan "Time and frequency measurement at NIST: the first 100 years," (2001): 4–17, p. 5, *Circular No. 74*, (note 22), 96–109, quotation on 98, on the "buzzer" method pp. 107–108.

[35] Cady returned to detection of NAA signals on March 21. This time his detection method was not based on piezoelectricity, but he examined the influence of inserting crystals on the received signals. NB 25 p. 48 (8.2.1919), p. 80–87 (21–25.3).

[36] He might have made an earlier attempt to receive electromagnetic waves by piezoelectric method on January 20th. On his way back from New London to Middletown at that evening, he carried an electrometer on his car's back seat, "A few miles later I ran machine off road while attending to electro[meter]." This suggests an attempt to detect electromagnetic waves. Yet, even in that case it is unclear whether he used a piezoelectric device for such an end. Cady's active interest in wireless communication was independent of and preceded his engagement with piezoelectricity; a week later he gave a talk in his local radio club on inducting coils. *Diaries*, 20.1.19, 28.1.19.

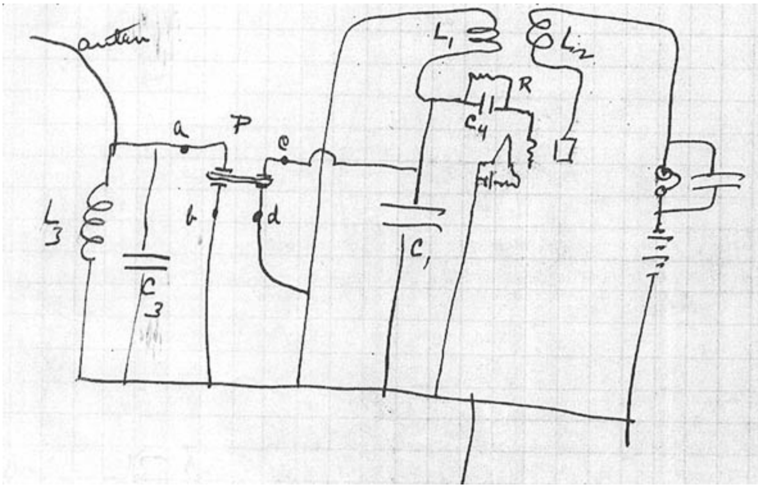

Fig. 2 Cady's first successful device to couple to circuits by a crystal plate (*P* in the figure). Near resonance the plate oscillated due to alternating voltage between *a* and *b*, induced by electromagnetic waved received by the antenna on the left size. The oscillation of the plates generate alternating voltage between *c* and *d* in the second circuit, which are amplified by the battery and audion in this circuit [source: NB 25, p. 48 (8.2.1919)]

a constant current. The receiving antenna induced oscillation at the frequency of the electromagnetic waves in a 'primary' circuit consisting of a capacitor, a coil (this is an RC circuit) and a Rochelle salt plate (Fig. 2). Metals coated the plate on its ends (near *a b* and *c d* in the figure), but not at the middle. One coated end was in the primary circuit; the other side was connected to a "secondary" circuit, which included a triode valve amplifier, a battery and a telephone receiver to detect the electric current in the circuit. A year later in his patent application Cady explained the mechanism beyond a simpler version of this circuit: "whenever an alternating current of the critical frequency flows in the circuit the [crystal] plate will be brought into energetic vibration through the agency of the alternating potential differences between the coatings [*ab* in Fig. 2]. These alternations will in turn generate potential differences in the coating [*c d*], which will cause an alternating current of the same frequency to flow in the second circuit."[37] In February 1919 he found that "when λ [the wavelength] = 3,025 m about, sound is max . . . and falls off in either dir.[ections]. . . [Yet] resonance [is] not at all sharp." Replacing the Rochelle salt by quartz a week later, he found that: "Results ca [circa] same as w. [with] RS, tuning somewhat sharper perhaps, but loudness at max. not as good."[38] As Cady later remarked this device is a kind of a (band pass) radio frequency filter, which transmits signals only at a particular range of wavelengths. However, at the time Cady did not use the term, and the electric circuits that he constructed were more complicated than those needed for a simple filter. Thus,

[37] Walter G. Cady, "The piezo-electric resonator," US patent 1,450,246, filed 28-1-1920, issued 1923, p. 3.

[38] NB 25, pp. 48–49 (8,10,17.2.1919).

he probably thought about coupling of two circuits rather than a filter, although the difference is quite subtle.

Coupling of two electric circuits by the resonance of piezoelectric plates was Cady's immediate aim. Unlike professional inventors he did not indicate the further goals of his researches. So the historian is left to speculate about them. Cady's later use of "the filter," his later recollection, and the similarity with common practice of the day with wave-meters suggest that he tried to apply the resonance for the purpose of establishing a device that could set frequency standards.[39] Simultaneously, these tests examined the sharpness and electric effect of crystal resonance, which he continued studying in the following weeks. In the latter studies he varied not only frequency but also the arrangement of the circuits and their components to enhance the effect and found sharper and narrower resonances. At the end of the month resonance in quartz (now as part of a "sandwich") was found "extremely sharp." Cady, thus, could focus on narrower ranges of frequencies, e.g. between 71,500 and 71,606 and then 73,600 Hz and between 57,288 and 57,373 Hz (less than 0.15%) with another crystal, while in the previous month he examined frequencies between 43,500 and 76,000 Hz in one experiment. The numbers that Cady recorded for the frequencies in the experiment exceeded the precision of current wave meters for high frequencies; in 1919 their precision was estimated not to exceed 1/100. Yet, absolute values were not important for these experiments, and differences between frequencies could be estimated to a higher precision, even if it did not reach a fifth significant digit.[40]

A few days earlier, on February 22nd, Cady "showed resonators to Arnold of Bell Labs, [George V.] Wendell of Columbia, and [Karl] Van Dyke of Wes[lean] [then a PhD student in Chicago]. Told them of the coupling device, also my observation of the negative capacitance of Rochelle salt plates at certain frequencies."[41] Cady's display of his results reveals a confidence about his findings and their significance. Indeed, on March 2nd, he talked about his plans for a related patent with Commander de Frees

[39] One might suggest that Cady considered the use of the filter for radio receivers. However, it does not seem to have any clear advantages on contemporary devices. That it is limited to a narrow frequency range, would be regarded as a disadvantage for a useful receiver since transmission frequency was not stable. To make the piezo-resonator a practical radio receiver much work was needed. In 1924 radio broadcast transmitters became the first application of the piezo-resonator beyond measurement.

[40] NB 25, pp. 52–59 (21-28.2.1919). The experiment also revealed in such cases a small plateau for the value of the electric magnitudes in resonance, which could be helpful for filters. For an earlier experiment from 10.Jan. see NB 25 pp. 20–21. On precision of wave meters Abraham and Bloch, (note 32), 1106. Cady might have used Abraham and Bloch's method which was developed during the war and was probably informed to the Americans. With this method the precision raised to 1/1,000 (still the state of the art in 1929), still below the accuracy in Cady's notebooks. See also Sullivan (note 34), 5.

[41] Since, Cady's memories of more than 40 years after the events, are the only source about this meeting, it is impossible to know exactly what Cady told his colleagues and former students, and what their reaction was, Cady, "Outstanding dates" (note 12). Cady consulted his notes in writing this report probably at the early 1960s. He mentioned the same occasion in the oral interview (AIP). There, he recalled that he asked Arnold "if there was anything his company might be interested in." However, he was not so clear about the year of the meeting (since it was Washington Birthday, the date was easier to remember) and he did not mention the other visitors, so his written testimony should receive more weight.

of the New London research station.[42] Obviously, at that point Cady's research was directed to the study and use of piezoelectric resonance.

Patents and possible applications were one goal of Cady's research; scientific knowledge and publications were another. To a large extent, these aims went hand in hand because more thorough knowledge and understanding of the resonator contributed to technological design. In particular, research that Cady carried out on variant cuttings and mounting of crystal plates and on new directions of oscillations helped improve the sharpness of the resonance, and in adjusting it to needed frequencies. Such a research on the relation between shape and crystalline vibrations was however less relevant for designing circuits for detecting and exploiting resonance frequency. "The filter" that Cady constructed in February was his only device for that purpose when he announced his plans for a patent. Eight months later, when he filed the patent, he suggested five additional circuits (or methods) to detect and use resonance.

Cady continued examining the electric behaviour of crystals in resonance, changing crystal plates, frequencies and varying settings and additional components of the circuits such as capacitors and coils. Among other results, close examination of quartz plates under forced oscillations clarified that the value of current and capacity near resonance is discontinuous. If resonance is approached from below the capacity rises, while approaching from higher frequencies causes it to decrease (see Fig. 3). This explains how the actual capacity of the resonating plates can acquire a value that puts the whole circuit at its resonant frequency. Apparently, for Cady, this observation made such behaviour intelligible, i.e. it supplied a reasonable explanation for phenomenon.[43] Yet, he still wondered why the capacity is capable of change in this way. Whatever was the cause, the observation leads to the conclusion that the resonant frequency is insensitive to a change in the capacity and inductance of auxiliary coils and capacitors, a conclusion of important practical consequences, which Cady exploited for frequency control 2 years later.[44] In March 1919, however, he did not make the conclusion explicit, although he implicitly assumed it in explaining to himself a few results.

During 1919 his research included general questions of piezoelectric behaviour, like possible variation in the value of piezoelectric coefficients (especially problematic with Rochelle salt, because of what was later known as its ferro-electricity) and the influence of other variables such as the temperature. Generalizing from his empirical finding, Cady developed a theory of the piezoelectric resonator and rules and methods for computation. To understand better the behaviour of the crystal rods, he worked also on the laws of their (damped) mechanical vibrations, which involves a complicated mathematical theory for which he provided a solution in autumn 1919. Like his theory of piezoelectric oscillation, this was a phenomenological theory that did not suggest

[42] Cady, *Diaries*, 2.3.19. In his "Outstanding dates" Cady mentioned that he talked with de Frees on March 30th. However, the contemporary evidence is more reliable.

[43] I agree with Dear that scientists often strive to make the natural world intelligible, i.e. to give an account that would explain the causes of the observed phenomena and regularities in manner that gives practitioners a sense of understanding, albeit according to changing standards. Peter Dear, *The intelligibility of nature: how science makes sense of the world* (Chicago, 2006).

[44] Katzir, (note 1).

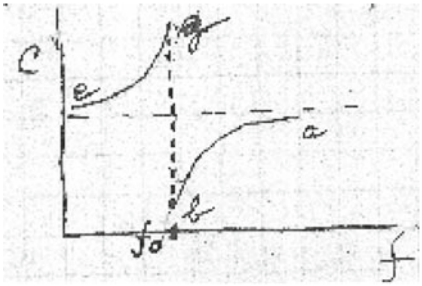

Fig. 3 Cady's schematic figure of the discontinuity in the value of the capacity, which become very high when approaching resonance frequency (f_0) from below and tends to zero when approaching from above [source NB 25, p. 74 (8.3.1919)]

a process or mechanism that underlies the phenomena.[45] This approach continued to characterize most theories in elasticity and piezoelectricity until the 1990s.[46]

Cady's studies of piezoelectricity, resonance and rods' oscillations were connected to questions of design. More thorough understanding of the behaviour near resonance was likely to help improve frequency-standards devices (although it happened to be more important for Cady's later invention of frequency-controlled circuits than to this one); articulated theory of rod oscillations was likely to help design the crystal–metal resonating plates. Notwithstanding, Cady's research went beyond the direct needs of design, suggesting that the latter was not its sole motivation. His work on the vibration of rods provides a good example of Cady's quest for knowledge that went beyond direct technological ends. For the design of plates a direct study of their behaviour would have been sufficient. Moreover, even if one chooses a mathematical–scientific approach one does not have to suggest a general solution, whereas Cady did.

4 Concluding remarks

Walter Cady liked to view his discoveries and inventions as results of chance and instantaneous insights. Indeed from the perspective of Cady's scientific career, World War I and the quest for underwater detection methods were contingent events that led to his work on piezoelectricity. In the next stage, his discovery of the sharp electric resonance was not only surprising, much like the discovery of any unexpected phenomenon or property (e.g. Geiger–Marsden experiment on atomic scattering); it

45 Cady, NB 25, pp. 68–110, especially 68–70, 72–75, NB P, p. 1-1a (analogy with synchronous motor), *Diaries* of 1919, "Note on the theory of longitudinal vibrations of viscous rods having internal losses," *Physical review, 15*(1920), 146–147." Cady's research on the piezoelectric resonator resembles in character that of Bell scientists after the discovery of the point contact transistor in 1947. In both cases, scientists developed novel theoretical understanding of an unpredicted phenomenon through an intensive experimental study, 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 An interest in "first-principles-derived approaches to investigate piezoelectricity" grew during the 1990s, Laurent Bellaiche, "Piezoelectricity of ferroelectric perovskites from first principles," *Current opinion in solid state and materials science, 6*(2002), 19–25.

was also accidental in the sense that it did not follow a program aimed specifically at the study of resonance. Indeed, piezoelectric resonance was only a secondary subject in his research programme concerning underwater transducers, and Cady's first observations of a peculiar electric behaviour near resonance were made while examining other questions. Yet, these few initial observations were insufficient for him to recognize the phenomenon. Moreover, the discovery was not a singular event but a process in which Cady realized that there was a connection between the scattered data, and then recognized the electric properties connected to the resonance and its sharpness. This, however, required the deliberate experimental examination of crystal oscillations near critical frequencies. Chance was perhaps important for getting the first hints (although other laboratories probably recorded similar results), but only Cady's subsequent research yielded anything like a true discovery.

This case shows that research programmes are often flexible, and that flexibility facilitates new and important findings. To follow the findings on resonance, Cady had to diverge from his research programme on ultrasonic transducers. Although the new interest was connected to the former, its further examination deviated from the original programme and gradually became the subject of novel research, which resulted in an altogether new programme by March 1919. Cady's move followed his experimental findings and the scientific curiosity that they raised. Thus, the laboratory findings shaped not only empirical and theoretical conclusions but also the direction of research. Still, they did not determine the directional shift in Cady's research programme. Nothing forced him to explore them. His move seems instead to be connected to a general elasticity that characterized his approach to research. Until 1919 he had examined quite a few areas. A decade earlier he showed similar plasticity, with considerable but less impressive results, when he followed a student's findings to the field of vibration in electrical discharge. During the war Cady was obliged to the research on ultrasonic transducers. With the end of the war, as a master of its own time and means, Cady was free to pursue a new project. Fortunately the new project could be studied by his modest means. In piezoelectricity he found a vein of rich ore, of which he became the most distinguish researcher and which he had not left.

Cady's flexibility is evident also in his bidirectional move from research aimed at applications ('engineering') to research aimed at knowledge and understanding of natural phenomena (and so more 'scientific' in the usual sense, rather than applied). Although Cady used knowledge for applications, his acquisition of it cannot be seen simply as a means to an end. This is clearest during his turn to the study of resonance, where Cady moved from applied research, with a specific technological end to a study whose technological implications were unclear. Yet also in other phases of his study, such as when he worked on transducers for ultrasonics, or on resonators for frequency standards, Cady showed an interest in the intelligibility of natural phenomena beyond the direct needs of the target devices. His work does not reveal a solid boundary between scientific and engineering research but, instead, a back-and-forth movement conditioned by his findings and by external circumstances (such as the war), and an interest both in the natural phenomena and their possible utilization. This movement enabled his discovery of the sharp electric resonance, the ability to use it as a frequency standard, and, although beyond the scope of this paper, its deployment for frequency control. While the technological origins of research into piezoelectric oscillation cannot be denied, ultrasonic study did not include the investigation of resonance. Thus, research aimed exclusively at the improvement of transducers did not and probably could not lead to the discovery of the properties of piezoelectric resonance. Disinterested 'scientific' research was required for this important discovery.