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Hermann Aron's Electricity Meters: Physics and Invention in Late Nineteenth-Century Germany

ABSTRACT

This paper examines how Hermann Aron, a well-trained physicist, exploited his multilayered knowledge of science for technological innovations, innovations upon which he built a successful industrial company with more than 1,000 employees. In his academic training, research, and teaching, Aron gained expertise in electromagnetic theory and experimentation, which he later put to use to invent a new electricity meter for the emerging electric power industry of the 1880s. While Aron employed established physical laws and data, particular methods and techniques were central to his development of technology. Moreover, these and the scientific ethos of precision, which he adopted from his training in the Neumann School, were crucial to his invention of a pendulum electricity meter. Contrary to a recent claim about the lack of a scientific basis to the electrical industry, Aron's case shows a direct transformation of knowledge from physics to technology. Still, his work also displays the influence of technology on many topics of scientific research. The relevance of Aron's particular scientific expertise to the technological questions he examined was a central factor in his unusual move from academic physics to his own industrial firm. The move also benefited from sharing ideas, methods, and interests between scientists and engineers. Berlin, in particular, provided a nexus for such an interchange. On the other hand, Aron's poor prospects for a professorship in physics (further reduced by being Jewish), made him more receptive to opportunities outside the academy.

KEY WORDS: Hermann Aron, Neumann school, measuring instruments, electricity meters, science-technology relations, electric industry, precision, pendulum

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The following abbreviations are used: *AP*, *Annalen der Physik und Chemie*; *ETZ*, *Electrotechnische Zeitschrift*.

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INTRODUCTION

In 1883 Hermann Aron, a physics lecturer at Berlin University, founded a company to develop and produce electricity meters of his own invention. Aron's company was a great success. Twenty-five years after its founding, it employed more than a thousand employees in four countries. Even in the electrical industry, where many participants were trained in physics, Aron's background was exceptional. Engineers and inventors rarely held a PhD in physics (although this was more common in the chemical industry). Aron's academic background was even rarer among company owners. The depth of his knowledge and, more importantly, his experience in physical research could hardly be matched in the industry. This was not merely a biographical difference. Aron's experience in the study, research, and teaching of physics made his commercial inventions possible and shaped them. Practices of experimentation, theory, and styles of work, including those of the particular scientific tradition to which he belonged, were of special value in the success of his invention and consequently of his *Aron-Elektrizitätszähler-Fabrik*.

While scientific research traditionally has been regarded as central to the emergence of a strong and growing electrical technology at the end of the nineteenth century, more recently Wolfgang König has argued that electricity was not a science-based-industry. His claim can be seen as a part of a current tendency to diminish the importance of science in the development of technology. The electrical and chemical technologies of the time are an especially interesting basis for examining the relations between science and technology, since their introductions commonly have been viewed as the first extensive practical applications of science. König denies that science was a major source of knowledge for the electrical industry, however. He bases his statement on two claims. One, he shows that, among workers in the industry, the share of university graduates was small compared to graduates of engineering from the *Technische Hochschulen* (technical colleges). He argues that education in the latter institutes was based in industry rather than in science, and he concludes that they did not teach scientific knowledge to their students. Two, he claims that a "transfer of [recent] research results from the universities to industry" did not exist. Contrary to König, I show here that Aron did transfer knowledge from physics to technology, and that this knowledge was indispensable to his success.[1] This, of course, does not

1. In this inference König explicitly excludes the contribution of fundamental scientific "discoveries from which later technological developments in industry originated" and

eliminate the crucial role of specific research in finding a viable design, including the use of trial-and-error methods in Aron's development of technology.

While a career trajectory from physics university lecturer to technology and industry was not common in the twentieth century, it was quite exceptional in the late nineteenth. Aron's was not the case of a newly qualified doctor hired by industry. He was an experienced *Privatdozent* (lecturer) who had earned the *venia legendi,* teaching privilege, a few years before founding his own enterprise to exploit his own inventions. Like most other scientists (perhaps excluding chemists), physicists generally were not involved directly in the development of specific technologies beyond laboratory apparatus. Even those who developed commercial technologies did not become independent entrepreneurs, but rather joined extant or new partnerships, became consultants, or sold their patent rights to firms. For example, in the 1850s William Thomson was first a consultant and later a director of and advisor to a telegraph company. Forty years later Ferdinand Braun was introduced to the radio by industrialists and entrepreneurs, who asked for his technical help, drew him into research and development on related devices, and made him a partner for his patents and technical advice. Walther Nernst developed a new incandescent lamp on his own initiative but sold the patent to AEG, which undertook the necessary development to produce a working commercial device with his help.[2]

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research "performed at industrial research departments" from his interpretation of science-based industry. Paul Forman has pointed out that for his first claim "König had to ignore the stated fact . . . that in the crucial founding decade of the 1880s most of those appointed to electrical engineering chairs were physicists entirely without prior experience in industry." Wolfgang König, "Science-Based Industry or Industry-Based Science? Electrical Engineering in Germany before World War I," *Technology and Culture* 37 (1996): 70–101, on 73; Wolfgang König, *Technikwissenschaften. Die Entstehung der Elektrotechnik aus Industrie und Wissenschaft zwischen 1880 und 1914* (Chur: G+B Verlag Fakultas, 1995); 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, quote on 122 (n392).

2. Crosbie Smith and M. N. Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge University Press, 1989), 661–64; Friedrich Kurylo and Charles Susskind, *Ferdinand Braun, A Life of the Nobel Prizewinner and Inventor of the Cathode-ray Oscilloscope* (Cambridge, MA: MIT Press, 1981); Florian Hars, *Ferdinand Braun (1850–1918): Ein wilhelminischer Physiker* (Berlin: Verlag für Geschichte der Naturwissenschaften und der Technik, 1999), 131–52; Diana Kormos Barkan, *Walther Nernst and the Transition to Modern Physical Science* (Cambridge: Cambridge University Press, 1999), 91–109. A case similar to Aron's is that of Carl Auer von Welsbach, who invented a successful incandescent mantle for gas light in 1885, and later a metal filament with osmium and wolfram. Auer was an active research chemist after receiving his PhD, and even during the years that he worked on his technological devices. However, unlike Aron he did not embark on an academic teaching career. In any case, chemists had closer connections with

Aron's special path deserves an explanation. Why did he move from academic physics to inventions and industry? What led to his success in those fields? At the time industry was not a common choice for a physicist, even for one who could not obtain an academic position.[3] A private venture in technology was even rarer, and clearly could not provide an immediate income. Teaching at a secondary school or in other institutes of higher education (as Aron did) was much more common. Those who left (or considered leaving) an academic career for industry were often driven by external factors. For example, in 1888 Carl (Charles) Steinmetz fled Germany due to anti-Socialist persecution, abandoning his dissertation project in mathematics. In exile he embarked on a highly successful electrical engineering career as a means of earning his living. In 1904, after he was dismissed from teaching because he was a Social Democrat, his comrade Leo Arons began the commercial development of a mercury arc lamp, which he had invented twelve years earlier for experimental purposes.[4] Hermann Aron's transition, however, did not follow such a unique event. At most one can point to the fact that Aron was Jewish, and as such was vulnerable to discrimination with respect to securing an academic position. While there is no direct evidence that Aron suffered directly from anti-Semitism, his knowledge of its existence might have caused him to drift toward fields he believed were more sheltered from it, such as the study and later development of technology. Elsewhere I elaborate on the possible influence of Aron's Jewishness and how Aron's career bears on the historiographical discussion of Jewish scientists in Germany.[5]

Here, however, I explore the main causes of Aron's move within his scientific and early technological career and its context. Although such a move

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industry than physicists. Ronald Adunka, "Carl Auer von Welsbach: Das Lebenswerk eines österreichischen Genies," *Plus lucis* (2000): 24–26.

3. University graduates (regardless of degree) constituted only a small share of technical staff in industry, although many joined the civil service. König, "Industry-Based Science" (ref. 1), 78–79; König, *Technikwissenschaften* (ref. 1), 252–55.

4. Unlike Aron, Steinmetz and Arons did not start their own companies. Ronald R. Kline, *Steinmetz: Engineer and Socialist* (Baltimore: Johns Hopkins University Press, 1992), 17–21. Arons was also motivated by the way others developed his invention. Stefan Wolff, "Die Quecksilberdampflampe von Leo Arons," in *Circa 1903: Artefakte in der Gründungszeit des Deutschen Museums*, ed. Oskar Blumtritt, Ulf Hashagen, and Helmuth Trischler (Munich: Deutsches Museum, 2003), 329–48.

5. Shaul Katzir, "From Academic Physics to Technology and Industry: The Course of Hermann Aron's (1845–1913) Career," *Max Planck Institute for the History of Science preprint* 370 (2009): (online at http://www.mpiwg-berlin.mpg.de/Preprints/P370.pdf; last accessed on 21 Aug 2009).

from the lectern to the management of an industrial firm was exceptional, a few fields of the natural sciences had close connections with technology and industry. The introduction of chemical and electrical technologies in the so-called "second industrial revolution" during the last third of the nineteenth century raised both scientific interest in and enthusiasm for associated technologies.[6] It also raised the interest of industrialists and entrepreneurs in scientific findings and education. In particular, the spread of electrical technology at just the time when Aron made his move was directly relevant to the shift in his focus. Local conditions also played their role, as Berlin was an important nexus of science and technology. Beyond the personal dimension of Aron's specific roles in the communities of science and technology, his involvement in both sheds light on the complex relationship between and characteristics of science and technology.

In order to account for Hermann Aron's move from the academy to industry and the roots of his technological success, this paper relates the central stages in his intellectual biography up to circa 1891, when his transition was complete. In particular it examines the kinds of work in which Aron was engaged in physics and electrical technology, and the role of his experience in physics in his inventions. Table 1 complements the discussion with a chronology of relevant events in Aron's life. A more detailed discussion of Aron's biography and his research on science and technology is given in another publication (see footnote 5). The central sections of this paper examine the electricity meter and its origin and the establishment of a commercial company for its production. These lead to a discussion of the major factors contributing to Aron's transition from academic science to invention and industry. The lessons of this transition regarding the relationship between science and technology are discussed in the conclusion.

6. Despite their connections and some overlapping, science and technology were (and are) different human endeavors with different aims, and were recognized as such at the time. While knowledge is the goal of science, artifacts and products are the goals of technology. Research in technology also leads to knowledge, but this knowledge is not an end in itself, but a means to improve design (by either the researcher or others). Indeed it is not always easy to differentiate between means and ends, and some research aims at both knowledge and aiding design, which blurs the boundary between science and technology. Yet, this analytic definition serves well in differentiating between the two human endeavors. In particular, it is useful in understanding Aron's research. On design as an end of technological or engineering research, see Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies From Aeronautical History* (Baltimore, MD: The John Hopkins University Press, 1990).

TABLE 1. A Chronology of Hermann Aron

1 Oct 1845	Born in Kempen in the Pozen "Duchy" of Prussia
1861–1867	Studies at Köllnisches Realgymnasium
1867–68	Medical studies at Berlin university (two semesters)
1868–71	Physics, mathematics, and chemistry studies in Berlin and spring semesters 1869 and 1870 in Heidelberg
Apr 1872–?/73	Assistant to Paalzow at *Gewerbeakademie*
Oct 1873	Awarded doctorate at Berlin university (dissertation on elasticity)
1873–1910	Teacher of physics at *Vereinigte königliche Artillerie– und Ingenieurschule* (combined royal artillery and engineering school)
Jul 1876	Habilitation at Berlin university (on electric discharge)
Apr 1877–Mar 1895	*Privatdozent* for physics at Berlin university
Dec 1879	A founding member of *Elektrotechnische Verein*
1880	First paper on practical question (telegraph cables in powder magazine). Begins research on storage batteries
1881	Marries Betty Landsberger
Jan 1882–Nov 1884	First secretary of the *Elektrotechnische Verein*
Jun 1882	Patent (first) on storage batteries, and publications on the subject until 1884
1883	Alleged attempt at wireless telegraphy
1883	Final two papers on nontechnical physics (on symmetry in elasticity)
Oct 1883	Begins development of electricity meter, founds company
Jun 1884	Patent on electricity meter
Dec 1884	Patent on electric clock
Fall 1885	Berlin's choice of Aron's meters and sale of first 100 meters
Jun 1886	Patent for mercury-alkaline (primary) battery
1888	*Titularprofessor*
1890	Opens factory and company in Paris
1890	Reduces teaching at university to one hour weekly, free of charge
1891	Patent on "three-phase" electricity meter
1893	Opens factory and company in London
1894	*Geheimer Regierungsrat*
1897	Opens factory and company in Vienna and factory in Schweidnitz in Silesia (Germany)
1912	Manfred, Hermann Aron's son, replaces his father as director
1913	Death of Hermann Aron
1935	Purchase of Aron's company by Siemens (through Deutsche Bank)

EDUCATION, SCIENTIFIC RESEARCH, AND ACADEMIC CAREER

Hermann Aron was born on October 1, 1845, the fourth child of six to a traditional Jewish family of modest economic means, in Kempen, a small town in the Prussian Grand Duchy of Posen (now Kapno, Poland). Aron first attended a local Jewish municipal school, until at 16 he went to Berlin to study at the Köllnisches Realgymnasium, where he was three to four years older than his classmates. Although not common practice, leaving home to study at a Gymnasium in a foreign city was not rare.[7] In October 1867, at the age of 22, Aron completed his secondary education and enrolled to study medicine at the University of Berlin, a typical choice for a young person of his background. However, after one year he left medicine and switched to the faculty of philosophy, where he studied physics, mathematics, and chemistry. Unlike medicine, physics did not suggest a clear source of future income; in this sense Aron's move was impractical. Just as other students at the time, Aron divided his studies between Berlin and Heidelberg. In Heidelberg he studied in the mathematical-physical seminar of the physicist Gustav Kirchhoff and with the mathematician Leo Königsberger, taking honors in both. The seminar was dedicated to independent experimental and theoretical exercises beyond the lectures. Arguably, it provided the best education in the practice of scientific research. Problems posed in seminars led to quite a few doctoral dissertations, including that of Kirchhoff, who had studied at Franz Neumann's seminar in Königsberg.[8]

Kirchhoff's teaching left a clear mark on Aron's early independent research. His 1873 dissertation, "The Equilibrium and Motion of an Infinitely Thin Arbitrarily Curved Elastic Shell," is a mathematical study of elasticity following Kirchhoff's 1858/9 theory of the motion of infinitely thin rods, further elaborated by

7. Manfred Aron, "Rede zur Gedächtnisfeier für Hermann Aron am 12.3.1922," unpub. msc in the Leo Baeck Archives, New York, 1–2. I thank Hans-Christian Förster for providing me the manuscript. Ludwig Geiger, "Geh. Reg.-Rat. Prof. Dr. H. Aron," *Allgemeine Zeitung des Judentums* (1913): 448–49. Aron, vita in the dissertation in the Humboldt University Archive UA, Phil. Fak Nr. 247. Another famous Gymnasium student who was sent alone was Paul Ehrlich; see Shulamit Volkov, "Jewish Scientists in Imperial Germany," *Aleph: Historical Studies in Science and Judaism* 1 (2001): 215–81, on 266.

8. I am grateful for Kathy Olesko for the information on Heidelberg's mathematical-physical seminar and Aron's part in it taken from the Generallandesarchiv Karlsruhe Signatur 235/3228: Universität Heidelberg, Mathematisches Seminar (1823–24), Mathematisch-physikalisches Seminar (1869–1901). I thank Thomas Schraven for the information from the registry of the University of Berlin. On Neumann's physical seminar see Kathryn M. Olesko, *Physics as a Calling: Discipline and Practice in the Königsberg Seminar for Physics* (Ithaca, NY: Cornell University Press, 1991).

Franz Eduard Gehring in 1860 and Alfred Clebsch in 1862.[9] Elasticity was also the subject of Aron's last publications on pure science in 1883. In these, he showed how the elastic constants of all crystal classes can be derived from considerations of physical symmetry, and compared the results of a specific case with extant observational data. Once again Aron extended one of Kirchhoff's methods, which the latter applied to a subgroup. Further, in this research Aron proved himself to be a true member of Franz Neumann's school, to which Kirchhoff likewise belonged. The experimental results that he used were obtained by Gustav Baumgarten at Neumann's laboratory. More significantly, the so-called principle of symmetry he employed was applied systematically only by members of the Neumann school (who later named it after their teacher). In this work, Aron followed the approach of the school in seeking new, more rigorous general, secure, or elegant derivations of known relations, an approach that seems far removed from technological applications. Moreover, the Neumann school emphasized mathematical and experimental precision, far beyond the needs of industry. Exact measurements were thus more common at this school than exploratory research, which might lead to the discovery of applicable effects. Much of the research concerned subjects far remote from industrial applications like elasticity and crystallography. This kind of study is generally unlikely to lead to novel devices.[10]

Nevertheless, Neumann's followers also studied subjects that could be more useful to technology, such as electromagnetism. Within electromagnetism the issue of unsteady currents (i.e., charging and discharging conductors) was suitable for application, since, among other issues, it could describe telegraphic signaling. Kirchhoff had studied unsteady currents since 1857. In 1864

9. Hermann Aron, "Das Gleichgewicht und die Bewegung einer unendlich dünnen, beliebig gekrümmten elastischen Schale," *Journal für die reine und angewandte Mathematik* 78 (1874): 136–74; On the earlier works, see I. Todhunter and Karl Pearson, *A History of the Theory of Elasticity and of the Strength of Materials From Galilei to the Present Time,* vol. 2 "From Saint-Venant to Lord Kelvin," part 2 (Cambridge: Cambridge University Press, 1893), 53–68, 154–62, 181–83.

10. Hermann Aron, "Ueber die Herleitung der Krystallsysteme aus der Theorie der Elasticität," *AP* 20 (1883): 272–79; Hermann Aron, "Ueber die elastischen Eigenschaften der Krystalle," *Verhandlungen der Physikalischen Gesellschaft zu Berlin* (1883): 59–61. On the role of the Neumann School in the development and use of symmetry see Shaul Katzir, "The Emergence of the Principle of Symmetry in Physics," *Historical Studies in the Physical and Biological Sciences* 35, no. 1 (2004): 35–66; on Aron's contribution and its context, see p. 51. On the Neumann school, Olesko, *Physics as a Calling* (ref. 8), and Shaul Katzir, *The Beginnings of Piezoelectricity: A Study in Mundane Physics* (Dordrecht: Springer, 2006), esp. chap. 5. This apparent discordance between the research in the Neumann school and technology prompted my study of Aron's transit to technology.

he elaborated a theory for discharge of condensers, a subject which Aron picked up a decade later for his Habilitation thesis that was submitted to the University of Berlin in May 1876 (postdoctoral work being a prerequisite to teaching in Germany). The subject provided an opportunity to show both mathematical skill (this time coupled with physical interpretation) and experimental expertise. Aron studied the mathematical relations among current, capacity, and voltage in rapidly charging and discharging cables, and experimentally verified some of his results.[11] Aron's basic equation was similar to what Oliver Heaviside employed to deduce the so-called telegraph equation for the transformation of signals along cables. However, Aron's question was very different from the issues that occupied the discussion about telegraphy. Consequently, his results neither aspired to nor supplied new tools for the design of telegraphic lines or their use.

Aron's academic career had been launched before he submitted his dissertation. In April 1872 he became an assistant to Adolph Paalzow, the professor of physics at the *Gewerbeakademie* (trade academy), which would merge with the *Bauakademie* (academy of architecture) to form Berlin's *Technische Hochschule* in 1879. Paalzow was probably instrumental in securing Aron a teaching position in the *Vereinigte königliche Artillerie- und Ingenieurschule* (the combined royal artillery and engineering school) after the latter was granted a doctoral degree in 1873.[12] Aron continued teaching physics to cadet officers until his retirement in 1910. While Aron taught at the school, it introduced instruction to experimentation for small groups of artillery officers. The university physical seminar was probably a model for this new laboratory course, and it is likely that Aron designed the course.[13]

In the summer semester of 1877, Aron became a *Privatdozent* (a lecturer who earns only students' fees). He taught theoretical and mathematical courses on a wide range of subjects: electrodynamics, hydrodynamics, elasticity, optics, mechanical theory of heat, and mathematical methods. Apparently Aron made a name for himself as a teacher, for in 1884 the faculty requested his promotion

11. Hermann Aron, "Zur Theorie der Condensatoren," *AP* 159 (1876): 587–601.

12. Paalzow taught at the combined school until 1873, so he probably recommended his new doctoral assistant to replace him. A. Rubens, "A. Paalzow," *Verhandlungen der deutschen physikalischen Gesellschaft* 10 (1908): 451–62; Aron, vita (ref. 7).

13. These courses were introduced sometime between 1868 and 1889, probably around 1876. Aron was one of the school's two physics teachers. Bernhard Poten, *Geschichte des Militär-Erziehungs- und Bildungswesens in den Landen deutscher Zunge*, vol. 4, *Preussen* (Berlin: Hofmann, 1896), 388–546, esp. 388–89, 438–39, 446–49, 459, 461, 465–67, 546.

to an extraordinary professorship for theoretical physics. The Prussian Ministry of Culture, however, denied the request.[14] Aron had to be content with the title of a professor, without any practical implications (i.e., a professor only by name but with the rights and duties of ordinary or extraordinary professors), which he received in 1888. Six years later he was awarded the state's high honorary title of *Geheimer Regierungsrat* (usually translated as privy councilor), but this honor was probably granted for his technological and industrial accomplishments. By 1894 he was fully immersed in industry, and in the invention and improvement of technological devices. Even a full decade earlier, when the faculty requested his promotion to extraordinary professor, most of his research concerned technological questions. In retrospect, 1884 seems to have been the crucial year in Aron's shift, not only from science to technology, but also from the academy to industry. Both transitions, which were intimately connected, were gradual, as Aron was not quick to cut his connections with the search for pure science (in the cognitive realm) and with the community of physicists (in the social realm).

RESEARCH ON TECHNOLOGY

Aron's first publication on a technological device was a brief paper on the theory of microphones written over a short period in late 1878. It addressed the validity of Helmholtz's color acoustics theory of hearing, which was questioned in the wake of the scientific interest in understanding the telephone (invented in 1876). Aron analyzed the action of the conversion of sound waves to electrical signals by the microphone of the telephone and pointed out that his results complemented Helmholtz's analysis of the hearing piece and how the two combined to support the latter's acoustic theory.[15] While the subject matter of Aron's paper was technological, the issue at stake was not. The question was the validity of a physical theory, which could be applied to natural and artificial objects and their phenomena alike. Like his theory of condensers published two years earlier, Aron's analysis of the microphone was not intended to assist

14. "Fakultät an Minister mit dem Gesuch von Aron um Berufung zum Extraordinarius," 15 Jul 1884, Geheimes Staatsarchiv Preußischer Kulturbesitz Berlin- Dahlem, Rep. 76, Kultusmin., Va Sekt. 2, Tit. IV, Nr. 47, Bd. 19, Bl. 247f. I thank Aleksandra Pawliczek for kindly providing this document.

15. Hermann Aron, "Zur Theorie des Mikrophons," *AP* 6 (1879): 403–07; Katzir, "Academic Physics" (ref. 5), 14.

in the design of instruments. Thus, it was not engineering science directed at improving artifacts or methods, but part of the study of physical phenomena. The cognitive aspect of this research was reflected in its social acceptance as a contribution to physics by its publication in *Annalen der Physik,* the major journal of German physics.

Aron's first research with direct implications for technological design was an 1880 examination of the risk from atmospheric electricity in using telegraphic cables in powder magazines. Unlike Aron's earlier papers, this one did not include any mathematical deduction. Instead the author examined the question by means of an experiment on a model of telegraphic cables and their insulators. An immediate context for this research can be found in the combined military school where Aron taught. Beyond the apparent interest of engineering officers in the use of telegraphy, the experimental course at the institution likely prompted Aron to study the issue, as the course included inspection of telegraphic equipment.[16]

The technological content of Aron's research on cables was also reflected in the audience he chose. He published its results in a journal on technology, rather than in one of the physical or mathematical journals in which he had previously published. The *Elektrotechnische Zeitschrift*, in which Aron's article appeared, was the organ of the *Elektrotechnischer Verein* (Association for Electrical Technology) founded in December 1879. Aron was an active founding member of the association: its First Secretary from 1882 to 1884, a frequent lecturer, and a member of its first two inspection committees.[17] Beyond the participation of scientists, which was also common in other societies for the development of technology, the association called for a combination of science and technology, scholars and industrialists, technicians and officials. The task of the *Elektrotechnischer Verein* was "the cultivation of the whole field of electric technology [*Elektrotechnik*] in its scientific research as well as in

16. Hermann Aron, "Zur Frage der Influenz der Kabel durch atmosphärische Elektrizität und der Gefährlichkeit ihrer Einleitung in Pulvermagazine," *ETZ* 1 (1880): 94–97; Poten, *Geschichte des Militär-Erziehungs- und Bildungswesens* (ref. 13), 461.

17. List of founders in *ETZ* 1(1880): 3. Aron was appointed First Secretary in January 1882, and signed the reports of the association until November 1884 (in 1884 there was no distinction between First and Second Secretary), *ETZ* from 1882 to 1884 especially 3 (1882): 51 and 5 (1884): 51. Aron gave four lectures in the first five years of the association and published five papers in its journal. After 1884 he continued lecturing and publishing, but infrequently. He was a member of the committee on ground currents established in 1881 (with nine members), and from 1885 on a committee for protection from lightning (with eleven members). Emil Naglo, *Die ersten 25 Jahre des Elektrotechnischen Vereins* (Berlin: Hermann, 1904), 58–64.

its practical application."[18] The founders saw the association as a meeting place that would encourage electrical engineers to advance their scientific, technical, and commercial interests, the application of electricity for the improvement of daily life, and the utilization of technology for the advancement of science. As such, they regarded the union of science, technology, and industry as a powerful strategy for the advancement of all three. The relations that they prescribed were not symmetrical, however. Science was the source of knowledge, while technology only provided the former with equipment and experience. No commercial influence on science was considered (unlike the case for technology). The founders' view that scientific knowledge can be instructive for technology, and that helping technologists should be among the objectives of scientists, was the dominant one at the time.[19]

The proposed link connecting science, technology, industry, and government had a distinct personal dimension in the relationships among practitioners from the different realms. Werner Siemens, in particular, was instrumental in the establishment of the *Elektrotechnischer Verein*. Siemens himself embodied the ideal: an inventor who became a highly successful industrialist and who also contributed to the scientific study of questions related to technologies that he used. Like a considerable share of the *Verein's* active members (including Aron), Siemens also participated in the events of Berlin's physical society. Unlike Siemens, most of the active participants with dual membership came from academia. That physicists were prominent among them shows the interest in the new electric technology and its development among members of the discipline.[20] Thus the association both promoted and presented a vibrant network

18. K. Ed. Zetzsche, "Unser Ziel," *ETZ* 1 (1880): 1–2, on 1. Participation of scientists was important to an organization like the British Society for Telegraphic Engineers, yet the latter did not aspire to the cultivation of scientific research. Other kinds of societies such as the British Association for the Advancement of Science showed a more complex attitude toward technology. W. J. Reader, "'The Engineer Must Be a Scientific Man': The Origins of the Society of Telegraph Engineers," *History of Technology* 13 (1991): 112–18; Jack Morrell and Arnold Thackray, *Gentlemen of Science: Early Years of the British Association for the Advancement of Science* (Oxford: Clarendon Press, 1981), 256–66.

19. Robert Fox and Anna Guagnini, *Laboratories, Workshops, and Sites: Concepts and Practices of Applied Research in Industrial Europe, 1800–1914* (Berkeley: Office for History of Science and Technology, University of California, Berkeley, 1999), chaps. 1 and 4.

20. Among the eleven persons with dual membership who gave more than two lectures in the years 1880–82, nine were associated with an institute of higher learning. These persons contributed thirty-one of the sixty-eight lectures in the *Elektrotechnischer Verein*. Horst Kant, "Zu einigen Aktivitäten von Physikern im Berliner Elektrotechnischen Verein zwischen 1880 und 1890," in *Wissenschaft und Technik—Humanismus und Fortschritt (XVI. Internationaler Kongreß für*

of teachers of physics and engineers, inventors, practicing engineers, and industrialists. Its location in Berlin was not accidental. Berlin was not only the capital of Germany (and thus the seat of governmental ministries) but also a center of higher education and the electric industry. This combination of strong industry and research in the natural sciences was rare, especially with such vibrant communities of natural scientists, engineers, and industrialists.[21] Through his functions at the association, and probably through many unofficial channels, Aron was in contact with leading engineers and industrialists, but had stronger connections with scientists, both senior and junior, like himself.[22]

In the early 1880s most of Aron's research was aimed at improving technology. The study of the danger of telegraph cables was followed by a long-term, threefold research project on storage batteries (accumulators): (1) an attempt to produce an improved battery, i.e., an invention; (2) a study of the mechanism of the batteries and the causes of their deterioration; and (3) the development of general criteria to compare the efficiency of batteries regardless of their mechanism. This research could have been conducted as three separate projects, as some researchers did. Yet the links are obvious: Aron presented elements from the three kinds of research together, and made use of his understanding of the mechanism in inventing a new battery. This connection between different kinds of knowledge and the construction of new devices reflects the aim of the *Elektrotechnischer Verein*.[23]

Wissenschaftsgeschichte), Kolloquienheft Nr. 22 des Institut für Theorie, Geschichte und Organisation der Wissenschaft (Berlin: Akademie der Wissenschaften der DDR, 1981), 59–63 (on the lectures, see p. 61); Horst Kant, "Werner Siemens und sein Wirken im Berliner Elektrotechnischen Verein sowie in der Preußischen Akademie der Wissenschaften," in *Werner von Siemens: Studien zu Leben und Werk*, PTB–Texte, vol. 2, ed. D. Hoffmann and W. Schreier (Brunswick: Physikalisch–Technische Bundesanstalt, 1995), 117–34.

21. Bernal mentioned six European university cities that had strong industry: Glasgow, London, Copenhagen, St. Petersburg, Moscow, and Berlin. Among these, London and Berlin had by far the largest scientific communities. Wolfgang Girnus, "Zwischen Reichsgründung and Jahrhundertwende 1870–1900," in *Wissenschaft in Berlin: Vor den Anfängen bis zum Neubeginn nach 1945*, ed. Hubert Laitko (Berlin: Dietz Verlag, 1987), 174–304, on 228–53.

22. Katzir, "Academic Physics" (ref. 5).

23. Hermann Aron, "Die sekundären Elemente und ihre Anwendung," *ETZ* 3 (1882): 222–28; Hermann Aron,, "Theorie der Akkumulatoren und Erfahrungen mit denselben," *ETZ* 4 (1883): 58–60, 100–107; Hermann Aron, "Herstellung eines neuen Stoffes aus Metall und Cellulose für elektrotechnische Zwecke," German patent DE21957, filed 22 Jun 1882, issued 1883. Hermann Aron, "Zur Berechnung des Nutzeffektes von Akkumulatoren," *ETZ* 4 (1883): 342–44. For more details about Aron's research see Katzir, "Academic Physics" (ref. 5).

Regarding the major shortcomings of the contemporary lead-acid storage batteries, Aron searched for a simpler and quicker method of preparing the battery for use (formation) that would result in a battery of higher capacity. In developing his methods, Aron systematically analyzed the battery, employing chemical knowledge to interpret his observations. Yet overall his search was a kind of trial and error (though instructive). Beyond the question of methods, the aim of the research was directly technological: the design of a device and method, in this case, of a more efficient storage battery. An efficient battery could not be defined by a scientific understanding of its mechanism, but from its supposed functions in contemporary technologies, and thus in society. As such, the contemporary changes in the production and use of electricity explain the interest in the storage battery and the simultaneous invention of new principles for its formation by at least four researchers, among them Aron. The German physics lecturer was not the first to make the suggestion public nor were the details of his suggestion adopted.[24]

Unlike the other pioneers in the field, Aron did not have any experience with related technologies. However, he did have experience with the scientific study of electrochemistry. As an assistant to Paalzow in 1872–73, Aron had taken part in a research project on the electromotive force of liquids. The central aim of Paalzow's research was to clarify the relationship between the chemical and contact sources of the electric current. This scientific aim did not prevent him from applying his results to a laboratory (primary) battery. The research provided Aron with an intimate knowledge of metallic and acid solutions and their behavior in different conditions and settings. These were solutions similar to (some of them even the same as) those used in the storage battery. Aron's experience in Paalzow's laboratory gave him not only articulated theoretical rules of electrochemical phenomena, but also know-how about such phenomena and the experimental methods used in their study, a few of which he applied in his own technological research. In his study of the mechanism of the storage battery he applied a physical examination of the solutions, thus continuing Paalzow's approach in studying the relationships between metals and solutions.[25]

24. Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (Philadelphia, PA: American Philosophical Society, 1982), esp. 51–57. Schallenberg, however, does not mention Aron's research on the subject.

25. A. Paalzow, "Ueber die elektromotorische Kraft von Flüssigkeitsketten," *AP* Jubelband (1874): 643–49. Rubens, "Paalzow," (ref. 12).

In this way, Aron's experience in the scientific study of electrochemistry provided him with tools for the research and development of the storage battery. Moreover, this experience seems to have been crucial to his decision to carry out research for its improvement, as Aron apparently thought that it would help him solve the central shortcomings of the storage battery. In this he showed a belief in the usefulness of scientific knowledge and methods in the development of technology. This view was shared by most of his colleagues and many other contemporaries, as expressed, for example, by the *Elektrotechnischer Verein* and the eventual foundation of the *Physikalisch-Technische Reichsanstalt* (in 1887).[26] The belief that scientific knowledge can instruct technological development was a major force beyond Aron's attempt to implement science in improving the battery, and consequently in his move to technological research.

The year 1883 was fruitful for Aron: he published an analysis and theory of technology (storage batteries), suggestions for improving technology (batteries and incandescence lamps), and scientific papers on symmetry in elasticity. His scientific teaching won him respect at the university and his research and suggestions on technology were discussed both at home and abroad.[27] However, his ideas did not prove of value in practice. In November 1884 there were reasons to think that, unlike his previous suggestions, his "new work will luckily pass this difficult challenge." Aron's new work was the electricity meter, which he had been developing since October 1883 in a new laboratory established for this purpose.[28]

26. The benefit of scientific research to technology and economy was a central theme among the promoters of an institute to unite physics and technology, David Cahan, *An Institute for an Empire: The Physikalisch-Technische Reichsanstalt, 1871–1918* (Cambridge: Cambridge University Press, 1989), 29–39.

27. Hermann Aron, "Ueber künstlichen Graphit," *ETZ* 4 (1883): 248–49. The French *La lumière électrique* gave long reports on Aron's publications. Aron's main papers were also published in the journal of Berlin's physical society *Verhandlungen der Physikalischen gesellschaft zu Berlin* and the *Journal of the Society of Telegraph Engineers and Electricians* (London). Aron's research was discussed in books and papers on the subject such as Edmund Hoppe, *Die Akkumulatoren für Elektricität* (Berlin: Springer, 1888) 118, 150–54, 2nd ed. (1892): 182–83, 187–90; Frank Geraldy, "Sur un essai de locomotion par lémploi des accumulateurs," *La lumière électrique* 9 (1883): 422–25; and later (more critically) Franz Streintz and G. Neumann, "Beiträge zur Theorie des Secundärelementes," *AP* 41 (1890): 97–112.

28. Hermann Aron, "Ueber einen neuen Elektrizitätszähler," *ETZ* 5 (1884): 480–89, on 489.

THE ELECTRICITY METER

The Device

Like many good ideas, the principle behind Aron's electricity meter was quite simple. He took the pendulum clock, the most exact meter of his day, and modified it to measure electric charge and energy. The period of a pendulum depends on the force applied to its bob. A known alteration of the force would lead to a predictable change in the period of the pendulum, and consequently in the movement of the clock's mechanism. Aron conceived that the electric current in the system could induce a magnetic field and thus a force on a magnetic bob. A coil below the bob (R in Fig. 1) became an electromagnet when a current passed through it. The coil was connected to the system, whose consumption of charge the coil measured by having the entire current pass through it. The coil reacted to the passage of current by exerting a magnetic force on a permanent magnet (M in Fig. 1) that replaced the regular pendulum's bob. The consequent change in the period of the pendulum and therefore in the retardation or advancement of the clock's dials was thus approximately proportional to the electric charge (multiplication of a current by time) that went through the coil.[29] To determine the amount of charge consumed, one only need compare the reading of the modified clock with that of a regular clock. In an advanced model the two clocks were connected by a differential gear that showed the charge consumption directly. (Fig. 2) By replacing the permanent magnet in the bob with another coil connected to the measured circuit, the same principle could be used to register the electric energy consumed by the system (which is proportional to the square of the current).

The details were not as simple as the principles, however. While the change in the number of pendulum vibrations is approximately proportional to the charge, Aron's more exact mathematical analysis showed that in some cases it

29. The number of the pendulum's oscillations n at a time t under gravitational force alone is $n = t/\pi\sqrt{PL/M}$, where M is the moment of inertia, P the weight and L the distance between the axis and center of mass. When a magnetic force is applied to the pendulum by a current J in the coil, the number of oscillations N under a current is $N = t/\pi\sqrt{(PL + aH\ .\ J)/M}$, where H is the magnetic moment of the pendulum's magnet and a is a constant of the device (dependent on the coil and its relation to the magnet). With simple algebra this becomes $N = n\,(1 + J/C)^{1/2}$ where $1/c = aH/PL$; this leads in the first-order approximation to $Q = nJ = 2C(N - n)$, where Q is the total charge that passed through the coil. Ibid., 484.

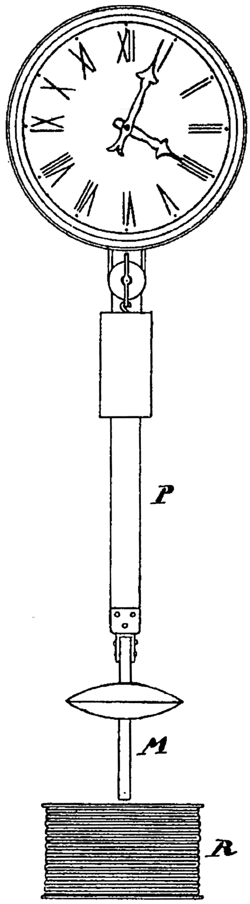

FIG. 1 A simple pendulum clock meter. The pace of the hands is changed in proportion to the total current that passed through the coil A. M is a permanent magnet. *Source*: Aron, "Elektricitäts-Zähler" (ref. 31).

led to a deviation of 2.5 percent between the calculation from the modified clock and the actual consumption.[30] Aron thought that this error made the meter impractical. Consequently for a few months he occupied himself with its correction. He sought a secondary effect that would compensate for the deviation from the

30. The second approximation (second-order Taylor series) gives $N = n\,(1+(J/2C - J^2/8C^2))$, which leads to $2C(N-n) = Q(1-J/4C)$. So the deviation from the linear rule is $J/4C$. Although C can be modified according to the current to be measured, it cannot be too large, since in that case the meter would not be sensitive enough to low currents. Aron found that for a desirable range (current of 1 to 24) the devation is 2.5. Ibid., 484–85.

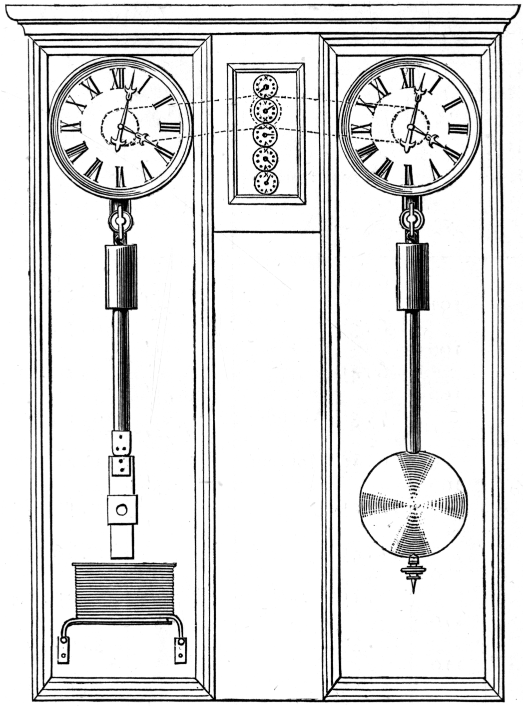

FIG. 2 Pendulum electricity meter with differential mechanism, which show the difference between the pace of regular and electrified clocks. The right is a normal pendulum clock; the left is modified by the electric current. *Source*: Aron, "Elektrizitätszähler" (ref. 28), 488.

linear relation. One possibility was to use a temporary magnet, i.e., an object that becomes a magnet in the presence of a magnetic force but loses its magnetization immediately after the force is removed. The electromagnetic coil would induce such a temporary magnetism in proportion to the strength of the current, so the magnetic effect would be of the second order, as needed. Yet his initial attempts to add a small soft iron horseshoe led to results opposite to those desired. Removing the iron did not help either, as the meter continued to exhibit an error in a direction opposite to the one predicted by the theory. Aron tried other means to no avail, until he stumbled upon the answer when he replaced the magnet with one of harder steel and found that "the temporary magnetism of this very hard steel is exactly adequate to produce uniformity [*Gleichmässigkeit*], as good as I could have wished for." In his laboratory test, results of which he cited in the publication, the precision was 0.2% when the meter was used for a relatively wide range (1:24 between minimum and maximum current). In other words, Aron found that the theory was inadequate since it considered only permanent magnetism. Fortunately for his technological aims, the induced temporary magnetism (not considered by the theory) compensated exactly for the difference between the theory and the linear rule required to make the electricity meter practicable.[31]

Aron detected the initial error in his meters theoretically by rigorously applying the known laws of the mutual action of permanent magnets and electromagnets. Thus, articulated scientific knowledge led to a search for a correcting effect. Physical theory could also suggest the kind of effect sought. However, scientific theory was hardly instructive in finding the means to produce the desired temporary magnetic force. The solution was specific for a particular design. In order to reach it, Aron had to return to trial and error. He could not rely on theory in determining the exact design of new models, which differed in their particularities of magnet design.[32] This is a good example of the interplay between theory and practice and the benefit of their combination in such knowledge-based technologies. The theory was needed to point out the problem, the practice for its particular solutions.[33] Aron's trial-and-error search, and the time and effort it consumed, was common in technological design. Still, such a pursuit was not completely remote from the practice of the physical laboratory, where one often works hard to improve an apparatus or locate a problem.[34]

So, in November 1884, after a year of development, Aron presented new precise electricity meters for both current and energy. As he concluded in his lecture at the *Elektrotechnischer Verein*, the future of his invention was unclear. Its high precision and wide range of current strengths, as well as the relative

31. Ibid. Aron described his effort and success to reach precision in this paper, which is based on a lecture of November 1884. Interestingly, in the patent, which he filed on June 15th, he mentioned only the first order (linear) approximation, without a hint of its limits. Hermann Aron, "Elektricitäts-Zähler," German patent DE30207, filed 15 Jun 1884, issued 1885. Aron had probably already worked on this problem before filing the patent, since in the published paper he told that he had worked on the problem for a long time, and by the end of July he had a precise instrument.

32. In the electric energy meter (watt-meter) the static electromagnetic coil should encircle the pendulum's bob, and iron is placed inside the pendulum's coil (ibid., 486–87). Later models had different designs, like two magnets in a U shape in the pendulum (in meters from 1897 and ca. 1900). I thank Thomas Schraven for the information on these meters, which he inspected personally (personal e-mail communication, 22 Jan 08).

33. A similar combination, of theory and practice, albeit by two persons, helped my historical reconstruction of Aron's work. See Katzir, "Academic Physics" (ref. 5), 40.

34. E.g., Riecke and Voigt's measurements of piezoelectric constants. Katzir, *Beginnings of Piezoelectricity* (ref. 10), 195.

simplicity of its use and the clarity of its reading (at least in the differential mechanism models), were clear advantages. Eventually they led to its success. On these merits, Aron's meter won the attention and approval of experts. For example, the French journal *Lumière électrique* described Aron's meter twice within two months. Excusing the duplication, the reporter referred to a major reason that Aron had for optimism. "Indeed," he wrote, "given the rapid development of the electric industry and its applications, which multiply from day to day, the question of an electricity meter . . . is of extreme importance from a practical point of view."[35]

Public distribution of electricity to homes and businesses had just begun in urban areas. With the development of the electric incandescent lightbulb, and the system of generation and distribution of electricity needed for its successful introduction, starting in 1882 public central stations were constructed all over North America and Western and Central Europe. These electrical systems needed convenient and reliable electricity meters to charge customers according to their consumption (other methods of charging, e.g., flat rates, were considered problematic by consumers and companies alike). Contemporary meters, however, did not satisfy many. They had problems with precision, reliability, and the range of currents measured. Probably the most exact device before Aron's was Edison's. Yet, Edison's electrolytic meter could not be read on-site. A company technician had to take its electrode to the station where its weight was measured. It is no wonder that this opaque and costly process was not popular with customers or electricity suppliers.[36]

Notwithstanding the potential of Aron's invention, in late 1884 a few obstacles still lay along the path to commercial success. The working prototype

35. B. Marinovitch, "A propos d'un nouveau compteur d'électricité," *La lumière électrique* 15 (1885): 83–90, quote on 83, a previous description in Hugo Michaelis, "Chronique de l'étranger—Allemagne," *La lumière électrique* 14 (1884): 219–21, on 220. Other examples: in a series of articles on electricity meters in 1888, Hospitalier in France found Aron's charge meter "a very simple and highly practical instrument" (p. 391), E. Hospitalier, "Les compteurs d'énergie électrique," *L'électricien* 12 (1888): 273–76, 289–93, 307–11, 328–30, 340–43, 360–63, 390–93, 403–08, 418–25, 450–54, 469–71, 498–504, 551–54. Siemens considered Aron's to be the only contemporary system to measure electric consumption well; see Werner Siemens, "Ueber Elektrizitätsmesser für Stromlieferungs-Anlagen," *ETZ* 8 (1887): 269–71.

36. On contemporary meters see Aron, "Elektrizitätzähler" (ref. 28), the references in this note, and C. N. Brown, "Charging for Electricity in the Early Years of Electricity Supply," *IEE Proceedings. Part A, Physical Science: Measurement and Instrumentation, Management and Education Reviews* 32 (1985): 513–24; Graeme J. N. Gooday, *The Morals of Measurement: Accuracy, Irony, and Trust in Late Victorian Electrical Practice* (Cambridge: Cambridge University Press, 2004), 232–39 for the professional and public attitude.

was not yet a workable commercial device, and the meter had not been examined in practice. Furthermore, industrial production of the device (even by artisans, let alone in a factory) could introduce new problems that might harm the functioning of the instrument (especially a delicate one like the meter, which is sensitive to the material used). Due to its special function, the meter had to be protected against attempts to change its reading manually. The device also had disadvantages compared to other proposed solutions, price probably being the most serious. Since Aron's meter consisted of two pendulum clock mechanisms plus an electromagnetic part, it was relatively expensive.[37] The number of meters sold supports the assumption that they were first used at the station and their junctions and only later installed at customers' homes and businesses. Possible improvements to competing devices and the invention of new ones posed other threats to the success of Aron's device. This threat was more visible since the distribution of electricity from central stations was just beginning, and the market only just emerging. Due to the relative infancy of the market, Aron could not count on mass sales in the short term. Berlin did not open its first central station until August 1885, three years after the first stations that supplied electricity to a tiny number of buildings in New York and London.[38]

Business Moves

In autumn 1885, a year after he had presented his electricity meters, Aron was waiting for Berlin's municipal commission to choose between his and Edison's meter. The commission decided that the electrical distributor of the city would use Aron's device; consequently, Berlin's Städtische Elektrizitätswerke bought one hundred meters by the end of the year, the first that Aron sold.[39] Yet it

37. Hirst recalled that in spring 1887 Aron "offered a price of £15 each meter, and it turned out the cost was only £6 [120 marks]" (an electric lamp cost about 1.5 marks). Hugo Hirst, "The History of the General Electric Company Up to 1900—Part 2," *GEC Review* 14, no. 2 (1999): 147–57, on 148. From the estimations of the total cost of meters by Edison's staff it seems that they estimated a meter at about £1. Edison papers, Menlo Park notebooks # 112, p. 261 (11-8-1880), #129 p. 109 (n.d., 1880), #172, p. 83 (n.d., 1880); see http://edison.rutgers.edu (last accessed on 20 Aug 2009).

38. Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore, MD: Johns Hopkins University Press, 1983), 72–73 (on Berlin).

39. B. Weinstein, "Bericht über die von Elektrotechnischen Vereine zu Ehren der internationalen Telegraphen-Konferenz am 3. September veranstaltete Ausstellung," *ETZ* 6 (1885): 409–73, on 456 (on waiting for the decision); Hermann Aron, "Ueber Elektricitätszähler für elektrische Centralstationen," in *Die Versorgung von Städten mit elektrischem Strom: Nach Berichten elektrotechnischer Firmen über die von ihnen verwendeten Systeme*, ed. Friedrich Uppenborn (Berlin: Springer, 1891), 17–26, on 25.

seems that at least until fall 1885, Aron's own plans were unclear. At an industrial exhibition in September he showed another invention—an electromechanical clock, which he patented in December 1884—while other commercial companies presented his meters. Aron continued to work on improvements in the clock during 1885. Like his meters, Aron's clock employed the uniform oscillation of the pendulum. In his clock Aron replaced the regular mechanical escapement (which moves the clock's wheels and gives an impulse to the pendulum) with an electromechanical escapement. He thereby eliminated the need to transform motion between the gear and the pendulum, which was a source of error. In addition, he eliminated the need to wind the clock, which was powered by a battery.[40] The similarity in the mechanism, if not in the purposes and markets, suggests that the electric clock originated in the electricity meter, which was, technically, a modified clock. Some electric timekeepers, like the popular Hip Clock, even employed an electromagnet below the pendulum, as in Aron's meter, although for a different function. Additionally, the need to compare the readings of his electricity meters with reliable clocks stimulated Aron's interest in timekeeping. In particular he employed master/secondary clock systems. These systems synchronized distant secondary clocks with a precise master clock, like the one in Berlin's observatory, employing electric signaling and electromechanical methods similar to those Aron applied. The application of electromechanical means to the pendulum clock in order to achieve higher precision, to facilitate use, or to connect different clocks was well known at the time.[41]

Aron's patent and his communications between 1884 and 1886 display his interest in the invention and improvement of technological devices and methods. In addition to the electric clock and the meters, he filed patents for protecting electromagnets from electromagnetic induction (most probably a follow-up to his work with electromagnets in the clocks and the meters) and a patent on a primary mercury alkaline battery. In the *Elektrotechnischer Verein* he presented a clock synchronization system of his own invention, in which he "employed the same principles [of his electricity meter], albeit to a different

40. Aron, "Elektrische Uhr," German patent, DE 32026, filed 16 Dec 1884, issued 1885, to which Aron filed supplements in July and October 1885 (DE34215 and DE34998), Weinstein, "Bericht über Telegraph-Konferenz" (ref. 39), 455–56.

41. Hermann Aron, "Ueber eine neue elektrische Uhrenregulirung," *ETZ* 7 (1886): 353–60, on their use in his earlier work on 355. On electric clocks Michel Viredaz, "Electric Clocks," http://homepage.bluewin.ch/electric-clocks/ (last accessed on 20 Aug 2009) and Roger Stevenson, "Mechanical and Electrical Clocks," in *Greenwich Time and the Discovery of the Longitude*, ed. Derek Howse (Oxford: Oxford University Press, 1980), 205–19, on 213–19.

aim."[42] His patent for the dry mercury cell, like his meter, reveals Aron's taste for expensive devices that satisfy high demands.[43] Apparently, economy was not his central concern. Indeed, it seems that Aron did not have clear business plans to exploit his inventions. For want of better historical evidence, this also seems true for the most promising of them—the electricity meter. On the technical side, Aron improved his models and continued selling them from late 1885. However, he probably did not raise capital to construct a production facility or to prepare an inventory of meters. His expenses were modest: the rent of one industrial room "no bigger than the private office of an average manager [in a British electricity company]" and a small staff for manual production, probably recruited only after the first orders. Small loans, if needed at all, were offered for such purposes by German banks.[44] According to later recollections of his acquaintances, only in 1887 did Aron raise capital to build a production line. This followed an increase in the demand for his meters, among others, with one large order of five hundred instruments by the British General Electric Company (GEC). As demand increased, friends convinced Aron to accept their financial investment in his company. Indeed for the next five years his interest in any technical question not specifically related to the meters lessened. So, according to later recollections at least, Aron was pushed into the role of entrepreneur.[45] Although unlike an Edison quick to seek capital to

42. Aron, "Uhrenregulirung" (ref. 41), 358. Aron's system was based on advancing or retarding an out-of-phase pendulum of "slave" (secondary) clocks by the changed vibration period caused by an electromagnetic coil. Small levers in the slave and master clocks moved in the phase of the pendulum and closed the electric circuits in the slave clocks in such a way that only a current in the direction needed to correct the error passed through each coil. Aron examined the system in his laboratory from January to August 1886, before presenting it (Aron, "Uhrenregulirung" [ref. 41]) However, it seems that this system did not become commercial. From the mid-1890s, Aron's company commercially constructed a different system of clock synchronization. Unsigned booklet, *Fünfundzwanzig Jahre Elektrizitäts-Zähler-Fabrikation: Den Freunden unseres Unternehmens aus Anlass des 25 jährigen Bestehens unseren Firma* (Charlottenburg: H. Aron Elektricitätszähler-Fabrik G.M.B.H., 1909).

43. Hermann Aron, "Galvanisches Element," German patent DE38220, filed 30 Jun 1886, issued 1886.

44. German banks were a central source of investments in German industry. Gustav Stolper, continued by Karl Hser and Kunt Borchardt, *The German Economy 1870 to the Present*, trans. Toni Stolper (London: Weidenfeld and Nicolson, 1967), 25–27.

45. Annonymous, "Professor Aron and the G.E.C," *Magnet Magazine* 2 (1913): 216–27, (recollections by Hirst) quotations on 218, 219–20; Eugen Goldstein, "Aus vergangenen Tagen der Berliner Physikalischen Gesellschaft," *Naturwissenschaften* 13 (1925): 39–45. Despite some discrepancies between Hirst's recollections and other sources and some personal bias, the historian does not have good grounds to reject the main claims, especially where the two sources agree.

TABLE 2. Number of Electricity Meters Sold by Aron's Company

Year	*1885*	*1886*	*1887*	*1888*	*1889*	*1890*	*Jan–Jul 1891*
No. of Meters Sold	100	325	853	1570	2194	4236	3770

	Total Number Sold	
until Jul 1891	until 1895	until 1897
13,048	35,000	65,000

Source: Aron, "Elektricitätszähler für Centralstationen" (ref. 39), 25, and *ETZ* from 1895 and 1897.

enable commercial exploitation of his inventions, Aron nevertheless successfully fulfilled the role of inventor-entrepreneur and company manager. From 1887 his sales and business grew quickly and impressively. (Table 2)

Aron's electricity meter won first prizes in international contests and exhibitions. Positive technical reports led central stations in Europe, and especially in Germany, to adopt it. By 1893 it was the most widespread meter in Germany, and very common in other European countries, though probably not across the Atlantic.[46] Aron's company relied not only on the quality of its product and its improvements, but also on business moves such as the foundation of sister companies and factories in Paris (1890), London (1893), and Vienna-Budapest (1897). Aron asked his brother Maurice, two years his senior, to manage his English firm. This move resembles the strategy of Werner Siemens, who nominated his brother Wilhelm (later William) to direct the British branch of their company.[47] Also, Aron did not simply hold to his original technological ideas. When the cheaper motor electric meter became precise enough for small consumers, his company began to produce motor meters of Aron's design, while marketing its pendulum meters to users for whom precision was more important. While the pendulum electric meter was the basis of growth for the company, it also produced meters for other ends (e.g., taxis, gas) and systems of synchronized electric clocks. By 1909 Aron directed an impressive cluster of

46. *25 Jahre Fabrikation* (ref. 42) mentions central prizes. For contemporary views and reports of use see E. Hospitalier, "Concours de compteurs d'énergie électrique," *La nature* 19 (1891): 21–25; Felix Auerbach, "Beziehungen des Magnetismus zu anderen Erscheinungen," in *Handbuch der Physik*, ed. Adolph Winkelmann (Breslau: Eduard Trewendt, 1895), 233–96, 249; Anonymous, "Aron's Electric Meter," *Science* 14 (1889): 123.

47. Maurice immigrated to Australia in 1864 and to England in 1891 (Michael Aron, Maurice's great grandson, personal e-mail communication, Aug 2007).

companies with more than one thousand employees and an authorized capital of five million marks.[48]

Aron's technological achievements—the meter and, to a lesser extent, the clocks—shaped the structure of his company, which virtually specialized in one and later two products. This kind of specialization was not very common in the early electrical industry, which attracted various kinds of entrepreneurs. Rather, it characterized companies based on specific technological expertise. In other cases, entrepreneurs in small and medium-sized companies (like Aron's) were tempted to spread their risks and chances among more than simply a few products. Take for example the Jakob Einstein & Co. Elektrotechnische Fabrik, which has received much attention thanks to the later fame of Albert, whose uncle was Jakob, the technical head of the firm. In 1891 Einstein's company was important enough to appear in the Frankfurt electrical exhibition along with twenty other companies, among them Aron's Elektrizitätzähler Fabrik. At the exhibition Einstein presented a dynamo of the company's design (by Jakob in collaboration with other inventors), several arc lamps, and an electricity meter. Contrary to Lewis Pyenson's claim, Einstein's meter (invented with Sebastian Kornprobst) was not based on comparing clocks. The company supplied electricity to several public buildings with their own devices. They attempted to sell these various devices and to construct central electric stations, which they eventually did in two Italian cities. In the nonspecialized field of electric power, giants like AEG and Siemens had obvious advantages. Many companies, like Einstein's, did not survive.[49]

Aron, on the other hand, found a niche in which his device was superior to others. He was successful because the electricity meter was not embedded within

48. *25 Jahre Fabrikation* (ref. 42); Aron, "Rede" (ref. 7), 6. This was a small firm compared to giants like AEG, with capital of 104 million marks in 1910, or Schuckert (the third largest in Germany) with 60 million in 1900. Yet the fifth-largest company in 1907 had just 14 million, Werner E. Mosse, *Jews in the German Economy: the German-Jewish Economic Elite 1820–1935* (Oxford: Clarendon Press, 1987), 248). Moreover, only four French electric firms (including utility companies) had more capital than Aron's company, Fox and Guagnini, *Laboratories, Workshops, and Sites* (ref. 19), 178, 181.

49. Lewis Pyenson, "Audacious Enterprise: The Einsteins and Electrotechnology in Late Nineteenth-Century Munich," in *The Young Einstein: The Advent of Relativity* (Bristol: Adam Hilger Ltd, 1985), 35–57, on 40; Sebastian Kornprobst and Firma J.Einstein & Co., "Neuerung an Elektrischen Mess- Und Anzeigevorrichtungen," German patent DED53846, filed 21 Nov 1889, issued 1890. In the first decade of the twentieth century Jakob Einstein was the manager (*Direktor* or *Geschäftsführer*) of Aron's Viennese company, Nicolaus Hettler, "Die elektronische Firma J. Einstein u. Cie in München, 1876–1894" (PhD dissertation, University of Stuttgart, 1996), 181.

a full system. It could work with many different systems of electric distribution, and with relatively simple modifications could be made compatible with different networks (different voltages, distribution systems, kinds of current, and their frequencies). Patent laws protected Aron's devices and thus helped him maintain his superior technological position. Indeed AEG and others tried to have Aron's patents rescinded in order to break his dominant position in the market.[50] Patent protection was not obvious at the time, however, for "before July 1877, when the new patent law came into force, there was no effective patent protection in Germany." While in many cases patent laws served big corporations, in others (like this one) they enabled the development of new firms with modest capital.[51] Indeed, the electricity meter did not require a long, expensive development phase, a fact that was considerably important given Aron's lack of an initial business plan and capital. In this regard the meter differed from the storage batteries. The latter was also a niche technology, which required the full attention of companies in order to succeed. However, it also required capital for development and cooperation with either central electric stations or traction companies that would implement the batteries within their systems, as these were its only significant potential uses.[52] That Aron found a niche especially suitable to the growth of a firm based on knowledge, rather than capital and connections (not that he could do totally without them), was to a considerable degree a fortunate coincidence.[53]

To maintain the technological superiority of his meters, Aron made many improvements to the device (e.g., better agreement between the two pendulums) and modifications according to developments in methods of electricity distribution (e.g., 3- and 5-wire systems, alternating current). These and the management of the company required much time and effort. With the success of the company from around 1888 on, the work on improving the device and

50. "Rede" (ref. 7), 5.

51. Henk van den Belt and Arie Rip, "The Nelson-Winter-Dosi Model and Synthetic Dye Chemistry," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch (Cambridge, MA: MIT Press, 1987), 135–58, on 150. On the importance of the patent law in creating research laboratories in the German dyestuff industry see Ernst Homburg, "The Emergence of Research Laboratories in the Dyestuffs Industry, 1870–1900," *British Journal for the History of Science* 25 (1992): 91–111.

52. Schallenberg, *Bottled Energy* (ref. 24), 61 and elsewhere.

53. It was not completely a coincidence since the need to invest much time and money in small gradual improvements in the storage batteries was probably a factor in turning Aron's attention to other issues.

directing the company explain why Aron directed most of his attention to his factory. Aron's move to industry at that point, without a real position at the university, seems an obvious choice.

Gradually and incompletely, Aron left the academic world. He last published in a physics journal in 1883. He continued to publish in electrotechnical journals, but from 1885 only about his own devices. For a few years his teaching was not affected by his new interests. Until 1890 he kept about the same course load and taught the same kind of courses at the university. Then he reduced his lectures to one hour weekly, eventually leaving the institution in 1895.[54] He continued teaching physics at the artillery and engineering school until his retirement in 1910. Apparently the connection with physics was important to him (clearly he did not need the extra salary), yet he turned his creative power to technological research. This included meters of various kinds (not only of electricity), electric clocks, and in his last years, metal filaments for incandescent lamps.

NEEDS AND SCIENTIFIC KNOWLEDGE IN ARON'S DEVELOPMENT OF THE ELECTRICITY METER

The success of the electricity meter and the need to keep improving it explain why Aron devoted most of his time and efforts to industry. But what led him to the electricity meter? Aron encountered an immediate need for an electricity meter in his research on the storage battery. To estimate the batteries' efficiency he had to measure the electric charge they produced. Since the voltage and thus the current from a battery often changed during discharge, the readings of a galvanometer, which gives the instantaneous current, were problematic. In 1882 Aron employed an electrolytic electricity meter of the type suggested by Edison. Then he gained firsthand experience with the cumbersome process of reading it. The need to weigh its plate for each measurement was tiresome even in the laboratory, when many measurements were needed (fourteen in one of Aron's experiments).[55] Moreover, these meters were imprecise, especially for the small amounts of electric charge often needed in the laboratory (although not in the particular experiments by Aron). Other contemporary

54. The information on Aron's courses is taken from *Verzeichnis der Vorlesungen der Berlin Universität* for the relevant years. His courses from summer 1890 were given without payment, the last four of which were either on electric machines or electric measurements.

55. Aron, "Theorie der Akkumulatoren" (ref. 23), 105–06. On Edison's and other meters see Brown, "Charging for Electricity" (ref. 36).

electricity meters fared no better. So Aron felt the need for a precise, easy-to-use meter. Scientists often invented laboratory instruments—measurement instruments central among them—and usually produced them as well, working much like engineers.[56] In this context Aron's attempt to construct a reliable electricity meter was not extraordinary, but the design of a commercial device was less common. At an early stage he probably recognized that the device had real potential for the future consumers of central electric stations. He designed the meter for a general rather than a scientific use, although he mentioned that it could be used for the latter purpose as well.[57]

Aron probably found the inspiration for the electricity pendulum meter in an exercise common in physics laboratories and classrooms. The pendulum, and the forces and the variables that affect its period, were well known in the physics world. In the Neumann school, to which Aron belonged, it became the central pedagogic example. As Neumann explained:

> Next to the balance, the pendulum is the most important physical instrument. It offers the means to measure forces, to express intervals of length and time and to study these. It serves as well to measure gravity and to study its properties. . . . Not only gravity, but also magnetic, electrical, torsional, and frictional forces are measured with the pendulum.

The pendulum served to teach physical theories and, more importantly, theoretical and experimental techniques, which the students would need in later original research of their own. In particular, the students were taught how to achieve precision in the laboratory: through methods of error reduction by the experimental protocol and mathematical analysis. Comprehensive mathematical accounts of all known and accidental sources of errors were considered to be the best means to experimental precision and thereby to a valid assessment of theoretical claims. Aron surely knew the example from his studies and plausibly from his teaching. Indeed, in presenting his invention he described the high exactitude of the pendulum reached through the careful reduction of errors, a

56. Among the scientists who invented and improved electrical measuring instruments were Jacques and Pierre Curie, Gustav Fechner, Jean Gaugain, Gustav Hankel, Hermann von Helmholtz, Gabriel Lippmann, William Thomson, Wilhelm Weber, and Gustav Wiedemann.

57. The currents and voltages for which he designed and tested his meters are those of the commercial users of electricity for lighting. A differential mechanism is quite dispensable for a laboratory, where one can easily compare the meter with a regular clock. On the high precision that allows its scientific use see Aron, "Elektrizitätszähler" (ref. 28), 486.

precision which served to measure the slight differences in the earth's gravitational force.[58]

In the original exercise, forces other than gravitation were regarded as interference, sources of error, which should be eliminated by changes in design or by calculating their effect. In the new context, the magnetic force became the effect to be measured, and its mathematical expression the way to know its magnitude. The aim was different, but the mathematical theory was the same and the manual experimental knowledge required was similar.[59] Moreover, the meticulous effort to gain precision by detailed examination of the apparatus on all its material and theoretical sides, which was a lesson of the scientific exercise, was central to Aron's development of a precise and reliable instrument. As was common in the Neumann school, mathematical analysis led Aron's effort to reach precision, i.e., the mathematical calculation of the potential error preceded its measurement.

This effort was probably the central factor that made Aron's meter practical, while William Ayrton and John Perry's similar suggestion of an electricity meter based on modified clocks was not.[60] The two English professors filed a patent in 1882. However, they left no record of either an experimental examination similar to Aron's, or a mathematical analysis beyond the first approximation. Apparently they invested more resources in the development of a motor electricity meter, which they introduced in the same patent application. Unlike Aron's, their meter was based on a clock, which could be a spring clock *or* a pendulum. Accordingly, they did not provide a thorough discussion of the forces that affect it. The descriptions of the instrument did not clarify the details of its mechanism and left room to suggest that it was prone to errors. Although in 1883 Perry mentioned experience with their clock meter, it does not seem that it was fully practicable, and it clearly did not go beyond the experimental stage.[61] Like Aron,

58. Ibid., 483–84. On precision in the Neumann school and the use of the pendulum following Bessel's seconds pendulum, see Olesko, *Physics as a Calling* (ref. 8), esp. 146–49, Neumann's quote on 146. Kirchhoff discussed pendulums, including a physical pendulum, in his 1876 textbook of mechanics, which Aron surely knew well as the writer's student and as a teacher of physics. Plausibly, Aron may have studied the example in Kirchhoff's experimental seminar. Gustav Kirchhoff, *Vorlesungen über mathematische Physik, Mechanik*, 2nd ed. (Leipzig: Teubner, 1877), 78–84.

59. Even Aron's method of calculation and comparison of his meter with an ordinary clock was similar to Neumann's methods. Both based comparisons on the number of vibrations. Olesko, *Physics as a Calling* (ref. 8), 148; Aron, "Elektrizitätszähler" (ref. 28), 484–86.

60. In the published version of his lecture on the meter, Aron claimed that he was informed about Ayrton and Perry's meter only after his lecture. Years later, he told his son the same thing. There is no grounds to doubt his claim. Aron, "Elektrizitätszähler" (ref. 28), 488.

61. In selling his meters in England, Aron reached an agreement with Ayrton and Perry (an advertisement from 1899 reproduced in Hirst, "History" [ref. 37], 149). This, combined with the

Ayrton and Perry had a thorough scientific background. Yet they differed in their approaches. Ayrton is famous for his later advocacy of simple laboratory exercises for engineers, which focused on acquaintance with the instruments and the physical concepts but not on the implementation of methods of careful error analysis and correction like those advocated in the Neumann school.[62] Thoroughness in the examination of precision helped Aron to construct a more reliable instrument. Nevertheless, like Aron, the English professors tried to exploit scientific principles for technological ends. In both designs, one can see a preference to use one simple theoretical principle rather than a combination of a few effects, even though Aron realized the need for a correction to the principal effect. This preference characterizes design based on scientific laws.

The engineer-physicists Ayrton and Perry were, respectively, the professors for physics (later termed electrical engineering) and mechanical engineering at Finsbury Technical College in London. They collaborated on many scientific research projects, studies of technology (telegraphy), and patents. Electrical measuring devices were central among the latter. In their research on science and electrical technology, Ayrton and Perry resemble Aron. Yet unlike him, they continued to work in both realms. This was probably connected to the different environments in which they worked, the British probably more supportive of combining science and technology than the German. However, their specific position in a technical school, rather than at a university, seems more important. In his later professorship in London from 1885, Ayrton was prohibited from commercial consulting, and developed mainly instruments for the physical laboratory.[63] As mentioned, Aron continued teaching at the military school until his retirement.

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failure of an effort by German companies to rescind Aron's patent rights by using the Englishmen's patent, supports the conclusion that their meter did not work in practice. William Eduard Ayrton and John Perry, "Registering the Amount of Work Given Electrically to Any Part of an Electric Circuit in a Given Time," GB patent 2642 (application number) 5 Jun 1882; James N. Shoolbred, "On the Measurement of Electricity for Commercial Purposes," *Journal of the Society of Telegraph-Engineers and Electricians* 12 (1883): 84–123, on 101–03, 109–13 (Perry's comments); Brown, "Charging for Electricity" (ref. 36), 516. On the legal procedure in Germany, Aron, "Rede" (ref. 7), 5; on the error due to accidental deviations see Aron, "Elektrizitätszähler" (ref. 28), 488.

62. Ayrton's claim that his students determined the mechanical equivalent of heat using direct readings on electric instruments aroused fierce controversy and resistance in England. His opponents, like the members of the Neumann School, required their students to know the theory behind the instruments. Graeme Gooday, "The Morals of Energy Metering: Constructing and Deconstructing the Precision of the Victorian Electrical Engineer's Ammeter and Voltmeter," in *The Values of Precision*, ed. M. Norton Wise (Princeton, NJ: Princeton University Press, 1995), 239–82.

63. Graeme J. N. Gooday, "Ayrton, William Edward (1847–1908)" and "Perry, John (1850–1920)" in *Oxford Dictionary of National Biography* (Oxford: Oxford University Press, 2004), at http://www.oxforddnb.com/view/article/30509, accessed 17 Nov 2006.

While Aron's experience in science inspired his invention of the electricity meter, scientific knowledge instructed his important 1891 patent for measuring electricity in a three-phase system of electric distribution. As Aron noticed, the use of three electricity meters, one in each branch of the phase system, would not give the total consumption. Through an elegant algebraic deduction based on the laws of electric power in a three-phase system and Kirchhoff's current and voltage laws, Aron showed that to calculate the total energy consumption, one could measure the electric current and voltage in two branches of a circuit especially designed for this purpose. Moreover, with a proper modification of the electricity meter, the measurement could be performed using a single instrument. Aron showed how to modify his own pendulum meter and two other kinds of meters. The patent claim was independent of the kind of meter in use. So companies that used three-phase current had to either buy Aron's meter, pay royalties, or use an inferior system as AEG and Schuckert did.[64] Aron's priority in this case originated beyond his technical competence from the reputation that he had already gained in the field. The promoters of the first large three-phase system constructed for Frankfurt's international exhibition asked Aron to design the required meter. This was somewhat in variance with the ideal type of inventor-entrepreneur, who identifies and defines technological problems himself.[65] The Frankfurt exhibition was a triumph for the three-phase system and set a standard for its equipment.[66] Aron's three-phase meter was a minor, albeit important ingredient in the success of the system, but a major factor in the expansion of Aron's company.

Aron's patent was the subject of a priority dispute with Hans Behn-Eschenburg, who claimed to have proposed the same circuit for measuring energy consumption independently. Behn-Eschenburg was an assistant to Heinrich F. Weber at the ETH in Zurich, when Weber was asked to develop measurement technology for the Frankfurt electric exhibition, simultaneously with Aron. The choice of Weber was not accidental. Weber was an expert not only in precise measurements, but also in their use in the electric industry. He promoted the application of scientific knowledge for technology by publishing technical reports (by 1888 he essentially ceased publishing scientific papers) and more importantly by the foundation and management of a physical institute, which

64. The alternative methods were considerably less exact. F. Wallmüller, *Der Elektrizitätszähler in Theorie und Praxis* (Berlin: Norden, 1935), 417.

65. J. W. Fr. Hofmann, "Geh. Reg.-Rat Prof. Dr. Hermann Aron," *Elektrotechnik und Maschinenbau* (1913): 797–800, on 799. On inventor-entrepreneur see Hughes, *Network* (ref. 38), 19.

66. On the exhibition, Hughes, *Network* (ref. 38), 131–35.

was equally devoted to electro-technology.[67] Still, Weber rarely developed technology, and apparently, his assistant took up the challenge of measuring three-phase electricity. Like Aron, Behn-Eschenburg had a thorough knowledge of physics and mathematics, which he studied at the universities of Berlin and Zurich, where he submitted a dissertation on an electric dynamometer in 1889.[68] Aron was the first to implement the ideas in practice. Yet, both inventors employed their scientific proficiency for the sake of a specific technological goal.[69] Although by 1891 Kirchhoff's laws were common knowledge among electrical engineers, the laws of alternating currents were less familiar (they were based on partial differential equations, a more difficult mathematical subject). Additionally, Kirchhoff formulated his laws in a scientific study of electricity based on physical assumptions and mathematical methods. When the laws were introduced in 1845, they were regarded as a nontrivial consequence of Ohm's law and assumptions.[70]

Scientific knowledge was crucial for Aron's two most important patents (the pendulum meter and the three-phase circuit) and therefore to the success of his firm. The key role of these two patents in the development of Aron-Elektrizitätszähler-Fabrik casts doubt on the significance of König's finding that university graduates were only a small minority among the leading technical personnel in the electric industry of the time. Even if Aron had been the only university graduate in his firm, the company was based on knowledge and expertise that originated in scientific research and education. In this sense it was a science-based industry. Whether that was true for other factories in the electrical industry at the time should be examined. Yet in any event, the small number of university graduates does not show that they were insignificant in transferring scientific knowledge to industry. On the contrary, Aron's case suggests that scientific education was instructive to electrical technological innovation.

67. David Cahan, "The Young Einstein's Physics Education: H. F. Weber, Hermann von Helmholtz, and the Zurich Polytechnic Physics Institute," in *Einstein: The Formative Years, 1879–1909*, ed. Don Howard and John Stachel (Boston: Birkhäuser, 2000), 43–82.

68. A. Traber, "In Memoriam: Hans Behn-Eschenburg," *Bulletin des Schweizerischen Elektrotechnischen Vereins* 29 (1938): 420–21.

69. Aron thought that Behn-Eschenburg had reached his solution by reverse-engineering a three-phase electricity meter made by Aron, to which he had access before he made his claim. Yet Behn-Eschenburg's background and the fact that the technological problem that occupied both minds does not have many good solutions make the assumption of simultaneous discovery more plausible. Aron, "Rede" (ref. 7), 5–6; Hofmann, "Aron" (ref. 65), 799.

70. Kirchhoff formulated the laws as a student in Neumann's seminar. L. Rosenfeld, "Kirchhoff, Gustav Robert," in *Dictionary of Scientific Biography*, vol. 7, ed. Charles C. Gillispie (New York: Charles Scribner's Sons, 1970), 379–82, on 380; Gustav Kirchhoff, "Ueber den Durchgang eines elektrischen Stromes durch eine Ebene, insbesondere durch eine kreisförmige," *AP 64* (1845): 497–514.

Thus, Aron's pendulum meter originated from his research on storage batteries and was inspired by his thorough knowledge of the pendulum. Once the advantage of the pendulum meter became clear, so was the potential of the new instrument. The market for electricity meters in the fast-growing systems of electric distribution suggested three attractions for Aron. The first was the possible financial gain. The second was the power to contribute to the promising field of electrical technology and thus to the well-being of society. This was linked, third, to a pride in one's design and the possible recognition associated with its success. Still, this does not explain why a physics lecturer who had to secure his name in science, like Aron, invested most of his time and effort in developing a commercial device like the storage battery.

KEY REASONS FOR ARON'S TRANSITION TO TECHNOLOGY

One possible factor that pushed Aron from academic physics toward technology was the unlikely prospect of receiving a university professorship. He had good reason to view his Jewishness as a serious obstacle to obtaining a position. This might have reduced his motivation to publish articles in the field. In any case, his modest list of publications could not provide much help.[71] Although evidently Aron had a chance at a secondary position in physics, it is possible that in the early 1880s he saw better opportunities in the novel discipline of electrical engineering, whose early teachers came from physics. In 1885 Siemens suggested Aron among a few candidates for such a professorship.[72] Such prospects might have encouraged Aron to carry out research on electrical technology.

More important than the negative factor that pushed Aron out of physics were a few positive factors that drew him to the study and development of technology. The prevalent interest among physicists in the novel technology of electric power, which Aron shared, was one of them. His choice of electrical technology and his timing were not accidental. In the late 1870s, scientists and all other kinds of electricians displayed a general interest in the novel electric-power technology. Innovations in instruments such as dynamos and incandescent lamps raised high expectations from these technologies, both for the

71. That Aron published little probably relates to his rapid changes of interests, as described by Goldstein, "Aus vergangenen Tagen" (ref. 45).

72. Werner Siemens to Professor Bach, 9 Feb 1885, in the Siemens archive 2/Li 546. I thank the archive for providing me a copy of the letter.

benefit of future users and for possible financial gains. Scientists were especially curious about these developments.[73] Their engagement with electricity preceded that of engineers. Electromagnetism was a central field of physics in the nineteenth century; aspects of it also interested chemists. Discoveries in the physics laboratory enabled the technological utilization of an electric current from the invention of the battery to that of the dynamo. Additionally, scientists, and not only scientists, understood the working principles of practical devices from the laws of physics. They therefore regarded their training as helpful in understanding and judging the new technologies, in consulting companies that developed them, and (less commonly) in developing the technology themselves. As mentioned in the case of the telephone, scientists also studied practical instruments to examine the validity of theories about nature. In addition, they showed sheer curiosity about the mechanisms of these technologies, which they were in a better position to understand than laymen. Aron's participation in the foundation of the *Elektrotechnischer Verein* shows that he, like other physicists, was well aware of and curious about the developments.

Curiosity about novel techniques and devices was only one, albeit important, component. Enthusiasm for the technology and its prospects for society, for the individuals who developed it, and often for both was another important component. The interest in technology was intensified in Berlin, where the newly established *Elektrotechnischer Verein* symbolized the nexus of science, technology, and industry. Information, questions, and problems flowed among the various participants in this nexus. In his activities in the association and in his teaching positions, Aron was at a few of these junctions. Personal meetings and visits, scientific and technical lectures at Berlin's scientific academy, the physical society, the *Elektrotechnischer Verein* and other venues, and of course the technical and scientific literature, all provided knowledge and opportunities to encounter new questions and paths of research. In a later phase, the acquaintance with industrialists and their staff facilitated Aron's move not only to inventions but to industry. The establishment of a commercial company was more respectable in this milieu than it might have been in a German university town. When an industrialist like Werner Siemens was respected not only for his fortune but also for his contribution to technology and even science, the research and development of commercial technology by a *Privatdozent* was culturally acceptable. In addition, the connections between science and technology in Berlin enabled Aron to move gradually. This gradualness was important because

73. Fox and Guagnini, *Laboratories, Workshops, and Sites* (ref. 19).

of the lower risk that it entailed and the psychological connection that Aron maintained with the scientific establishment.

The example of Ayrton and Perry might suggest that the move of scientists to entrepreneurship and technological development was easier in Britain than in Germany, and that in the former it did not entail the abandonment of an academic career. However, like the German case, the British case is more complex than it seems at first glance. For lack of a synthetic study about scientist-entrepreneurs, one can only observe that the conditions in London or in Glasgow were different from those in Cambridge. William Thomson, who both preached and practiced "the harmony between theory and practice," was a unique figure in the British scene as well.[74] His own involvement with technology developed during his career due to influences of different kinds, among them the topics of his scientific studies, offers from commercial companies, partnerships, and his passion for sailing. It is not accidental that Ayrton and Perry were both disciples of Thomson, who, however, had few followers among British physicists. Moreover, the London professors had enjoyed practical experience in the earlier part of their careers, and both taught engineering at some point. Yet the barrier between the academy and industry was lower for engineering in Germany, too. In Britain one finds resistance to commercial work by academics, as shown by the later prohibition of Ayrton's work as a consultant.[75]

Probably the most important factor in Aron's turn to technology was the relevant experience that he gathered in his study, research, and teaching of physics. Scientific practice provided him not only with articulated rules about nature (which he employed in technological research and development) but with specific techniques, attitudes, know-how, and experience with laboratory and practical devices, all of them crucial to his early study of practical instruments.[76] The electrochemistry of solutions and methods of their study were central in his first extensive technological research on the storage battery. The pedagogical exercise with the pendulum and its period inspired his successful electricity meters. In addition, his scientific expertise probably led Aron to believe that it put him in an advantageous position for the development of related technologies.

74. Smith and Wise, *Energy and Empire* (ref. 2), e.g., 653.

75. Gooday, "Ayrton" and "Perry" (ref. 63), Hans L. Dienel, "Professoren als Gutachter für die Kälteindustrie 1870–1930: Ein Beitrag zum Verhältnis von Hochschule und Industrie in Deutschland," *Berichte zur Wissenschaftsgeschichte* 16 (1993): 165–82.

76. The division between a laboratory and practical device is not so clear. For example, the storage battery had both roles.

Aron's background in the mercantile culture of the Jewish lower middle class (and the disposition toward entrepreneurship among Jews of higher means) might suggest that he was more inclined to entrepreneurship than his colleagues, who usually came from the idealistic culture of the German high-bourgeoisie. Although such a hypothesis is seductive, the evidence does not support it. There is no evidence that Aron had connections with businessmen or manufacturers beyond those that he gathered through his scientific career. At an early stage Aron seemed to adopt the idealistic values of the higher-educated German (or Jewish-German) bourgeoisie.[77] Still, Aron's personality probably played a role in his transition to technology. Following Isaiah Berlin's distinction, Aron was "a fox," interested in many subjects and questions, moving rapidly from one issue to the other, and "pursu[ing] many ends." Eugen Goldstein recalled, with some exaggeration, that Aron had changed his research subject every two weeks.[78] His foxlike personality facilitated Aron's transition in two central ways: first, he had broad knowledge, which includes the interesting questions in various subjects; second, and more important, he was open to different kinds of questions—scientific, but also technological (and according to a few stories, even literary)—without being consumed with any one major project.[79]

CONCLUSIONS

The technological devices that Aron developed, successful or not, depended crucially on his scientific expertise. The knowledge and experience that he had acquired in the physical laboratory and in its theoretical analysis were necessary (albeit insufficient) for his secondary battery and the electricity meter. Beyond his application of scientific theories and rules, in these inventions Aron drew on experimental and theoretical know-how from his scientific research. In other words, his experience as an experimental and theoretical researcher and as a teacher provided him with examples, methods, and intimate knowledge of phenomena and artifacts, on which his technological breakthroughs relied. Science

77. For more details see Katzir, "Academic Physics" (ref. 5).

78. Isaiah Berlin, *The Hedgehog and the Fox* (New York: Simon & Schuster, 1953), 1; Goldstein, "Aus vergangenen Tagen" (ref. 45), 40.

79. Theilhaber reports on a lecture by Aron on Hamlet while he was a student in Heidelberg, a story which he attributes to the memories of Aron's friend from that period. I could not corroborate the story beyond confirming Aron's interest in Shakespeare. Felix Theilhaber, "Der Messer der magischen Kraft: Hermann Aron," in *Schicksal und Leistung: Juden in der deutschen Forschung und Leistung* (Berlin: Welt-Verlag, 1931), 157–67, on 159–60.

is more than well-elaborated theories and a list of empirical findings. The practice of science and its ethos of precision played a more important role in Aron's devices. These, more than the theories which Aron employed, made his electricity meters industry science–based in a very concrete sense.[80]

That Aron could employ results and techniques from his scientific study in the design of practical devices is not obvious. Rather, it points to a deep connection between the objects and subjects of inquiry of science and technology at the time. This connection is not a mere coincidence. Late nineteenth-century electric technology was based on effects and laws discovered in scientific research on electricity and magnetism (usually with technological development lagging a few decades beyond the scientific findings). Likewise, technology provided questions and useful devices for scientific study. At least since the seventeenth century, artificial devices and processes had been considered subjects of scientific understanding. For example, the interest in the electrochemistry of solutions was connected with their use in batteries. On a deeper and more practical level, technological and scientific research shared methods and means of experiment and theory alike. Indeed, Aron's successful application of scientific methods and the similarity between his and other works on storage batteries and electricity meters suggest that contemporary advanced technology drew much on the practice of science.

The deep connection between science and technology did not mean that all important differences disappeared. On the contrary, Aron's career shows that science and technology were distinguished intellectually and institutionally. Knowledge was its own aim in Aron's research until 1880; his education and teaching were designed to train students to conduct open-ended research aimed at knowledge rather than at a particular result. A nice illustration of the difference between technological and scientific research is provided by Aron's theory of the microphone. This theory was directed at examining the validity of Helmholtz's explanation of hearing rather than at rules to improve microphones. Solving technological problems and improving design became goals only later during Aron's transition from academia to industry. At that stage Aron used earlier results, methods, and objects. Yet the aim of design (in a general sense of the term) molded his research, which was no longer directed at

80. This contradicts (at least for this case) König's claim that the electric industry at the time did not benefit from contemporary scientific knowledge. König, "Science-Based Industry" (ref. 1). Of course, in a more general and indirect manner the entire electrical industry relied on the findings of electrostatics, electrochemistry, and electromagnetism in eighteenth- and early nineteenth-century natural philosophy.

open questions, but at possible solutions to technological problems. On the institutional level, Aron communicated about technology in journals devoted to that subject (in addition to his work on devices and patents), and at the same time published on physical theory in physics journals and taught it in his university courses. While the institutional settings of physical research at the universities or other institutions of learning were much different from those of technological development in industry (and the engineering professorship provided yet another setting), one could cross the lines between them. In the late nineteenth century, when engineers, inventors, and industrialists recognized the technological potential of scientific research and physicists showed an interest in electric technology, the cultural gap between scientists and engineers was not wide and could be bridged even in Germany with its purist *Bildung* tradition.

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