The Electrical Imagination: Sound Analogies, Equivalent Circuits, and the Rise of Electroacoustics, 1863–1939
Author(s): Roland Wittje
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The Electrical Imagination:
Sound Analogies, Equivalent Circuits, and the Rise of Electroacoustics, 1863–1939

*by Roland Wittje**

ABSTRACT

The transformation of acoustics into electroacoustics in the early twentieth century was brought about by at least two significant changes in the mechanical world of acoustics. Electrical technologies entered the acoustics laboratory and profoundly changed the research practices therein. At the same time, electrodynamic theory and electric circuit design advanced rapidly to replace mechanical conceptions as the explanatory basis for the physical sciences. Equivalent-circuit diagrams facilitated a reductionist representation as well as the design of real circuits for electric generation and manipulation of sound by translating acoustic problems into electric systems. Consequently, electroacoustics became more than a research technology and evolved from a laboratory practice into a new way of thinking and talking about sound.

INTRODUCTION

The transformation of acoustics into electroacoustics is central to the reshaping of the science of sound in the first half of the twentieth century. In addition to science, electric recording, transmission, manipulation, and amplification of sound have defined a large part of our common aural experience ever since. The history of electroacoustics has thus far been understood predominantly as a history of technologies such as the telephone, microphones, loudspeakers, and electric amplification. These were coproduced with new technologies of mass media, particularly radio broadcasting and sound motion pictures, and then entered the research laboratory.[1] I argue that this transformation of acoustics into electroacoustics reached far beyond electrical technology and led to a conceptual redefining of our understanding of sound. The new electrical understanding of sound was represented by means of equivalent-

* History of Science Unit, University of Regensburg, D-93040 Regensburg, Germany; roland.wittje @psk.uni-regensburg.de.

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[1] See Frederick Vinton Hunt, *Electroacoustics: The Analysis of Transduction, and Its Historical Background* (Cambridge, Mass., 1954); Robert T. Beyer, *Sounds of Our Times: Two Hundred Years of Acoustics* (New York, 1999), 177–86; Emily Thompson, *The Soundscape of Modernity: Architectural Acoustics and the Culture of Listening in America, 1900–1933* (Cambridge, Mass., 2002), 229–93; and Thompson, "Dead Rooms and Live Wires: Harvard, Hollywood, and the Deconstruction of Architectural Acoustics, 1900–1930," *Isis* 88 (1997): 596–626.

circuit diagrams and other types of electrical analogies that became firmly established in the 1930s.

Scientific knowledge and technology are developed locally but within a transnational network of exchange of ideas and practices. That local and national development can only be understood in international context is particularly true with regard to the rapid expansion of acoustic knowledge and technologies of mass media. Acoustic knowledge and technologies became highly relevant for warfare during the Great War, as well as for the national and international markets of the electrical and media industries of the interwar period. Being internationally well informed and able to adapt became a matter of competitiveness, if not survival. Thus, the history of electroacoustics must be understood as a transnational history that had its local and national implementations. My story draws upon examples and developments during the interwar period mainly from Germany and Great Britain, but also from Norway and the United States, where Bell Telephone Laboratories in particular took an international lead in electroacoustics research and development.

Scientists in the nineteenth as well as in the twentieth century have emphasized the specificities of acoustics within the physical sciences. According to Hermann von Helmholtz, "*physical acoustics* is essentially nothing but a section of the theory of the motions of elastic bodies."[2] For Helmholtz and other scientists, it was precisely the human sensation of hearing that made acoustics an interesting chapter in the branch of mechanics. John William Strutt, third Lord Rayleigh, specified that "we shall confine ourselves to those classes of vibrations for which our ears afford a ready made and wonderfully sensitive instrument of investigation. Without ears we should hardly care much more about vibrations than without eyes we should care about light."[3] Comparing the sensation of hearing to the sensation of vision, Helmholtz emphasized that "music stands in a much closer connection with pure sensation than any other [including visual] arts," thereby arguing for a distinctive relationship between the human perception of musical tones and aesthetics.[4]

In the 1920s, the industrial physicist Ferdinand Trendelenburg argued in similar ways; it was the close relationship of acoustics with other branches of knowledge and its importance for general cultural issues that justified a special treatment of acoustics next to the problems of mechanics. Just like Rayleigh, Trendelenburg confined his treatment of acoustics to the physical processes that act upon the human sense of hearing.[5] But acoustics had been transformed in the interwar period. Next to the importance of acoustics for "general cultural issues," Trendelenburg highlighted "recent technical issues" that had significantly reshaped the scientific treatment of acoustics.[6] In the nineteenth century, acoustics was primarily perceived and presented as occupying a domain in between the physical world of mechanics and the cultural world of the music of the educated upper middle class.[7] From this position between mechanics and music as high culture, acoustics was gradually relocated into electrodynamics,

[2] Helmholtz, *On the Sensations of Tone as a Physiological Basis for the Theory of Music* (London, 1875), 4.

[3] Rayleigh, *The Theory of Sound*, 2 vols. (London, 1877–8), 1:vi.

[4] Helmholtz, *On the Sensations of Tone* (cit. n. 2), 3.

[5] Trendelenburg, ed., *Akustik*, vol. 8 of *Handbuch der Physik* (Berlin, 1927), 1.

[6] Ibid. See also Erich Waetzmann, ed., *Technische Akustik*, vol. 1 of *Handbuch der Experimentalphysik* (Leipzig, 1934), v.

[7] See Myles W. Jackson, *Harmonious Triads: Physicists, Musicians, and Instrument Makers in Nineteenth-Century Germany* (Cambridge, Mass., 2006).

electrical technology, and mass media. With the rise of electroacoustics, the way music was produced, consumed, and understood was transformed as well.[8] In order to understand these developments in electroacoustics, we must consider both the development of electrical technologies as well as the changing understanding of electrodynamics, especially electric oscillations and electric circuit design.

The electroanalog field became a new language, a new way of thinking and talking about sound in the twentieth century. Its practices were shaped by the circuit diagram, rather than linguistic or mathematical expressions. Circuit diagrams belonged to an array of abstract visual concepts, such as flowcharts and thermodynamic cycles, developed by scientists and engineers. Within the framework of these visual concepts, technical problems could be formulated, analyzed, and solved.[9] Circuit diagrams, just like Swedish scientist and engineer Christopher Polhem's mechanical alphabet and German mechanical engineer Franz Reuleaux's machine grammar, conveyed their own sign language and grammar. These consisted of standardized symbols for standardized electric components and a network of idealized electric connections.[10] Even though engineers and scientists could easily envision a real electric circuit from the diagram and produce it in the workshop, the relationship between the drawing and the material circuit was not straightforward. Circuit diagrams were not about the materiality of the circuit but about its operation. In contrast to mechanical drawings, circuit diagrams were meant to show not spatial arrangements but functional relations.[11]

This abstract and conceptual nature of circuit diagrams was especially prominent in electroacoustics. Circuit drawings could represent actual electric circuits such as amplifier circuits, microphone and loudspeaker wiring, or electric filters. They could also represent acoustic systems that were partly or entirely nonelectric. This is evinced by an example from research in sound insulation in buildings at Norges Tekniske Høgskole (the Norwegian Institute of Technology) in the 1930s. In figure 1 an equivalent-circuit diagram illustrates the transmission of sound through a double wall. While the upper drawing shows the wall construction with the incoming and

[8] See Joachim Stange, *Die Bedeutung der elektroakustischen Medien für die Musik im 20. Jahrhundert* (Osnabrück, 1988); Peter Donhauser, *Elektrische Klangmaschinen—die Pionierzeit in Deutschland und Österreich* (Vienna, 2007); and Thompson, *Soundscape of Modernity* (cit. n. 1).

[9] Precious little has been written on the history of circuit design. See Edward Jones-Imhotep, "Icons and Electronics," *Historical Studies in the Natural Sciences* 38, no. 3 (2008): 405–50, for debates in the postwar period, and Eugene S. Ferguson, *Engineering and the Mind's Eye* (Cambridge, Mass., 1992), 11, for abstract visual concepts in engineering. Ferguson argues for these concepts being specific to engineers while scientists tend to use mathematical concepts. In the history of electroacoustics, however, it becomes impossible to always separate scientists from engineers, especially in the case of technical and industrial physicists, many of whom crossed the line and felt at home in both communities—science and electrical engineering.

[10] The mechanical alphabet consisted of a collection of seventy-nine wooden mechanical models, used as a pedagogical instrument by Polhem (1661–1751) in the Laboratorium Mechanicum, a school of mechanics that he founded in 1697. Reuleaux (1829–1905) formulated his machine grammar in his 1875 monograph *Theoretische Kinematik: Grundzüge einer Theorie des Maschinenwesens* (published in English as *The Kinematics of Machinery* [1876]). This system uses a kinematic notation to unite pairs of elements into kinematic chains. For more on Polhem and Reuleaux, see Ferguson, *Engineering and the Mind's Eye* (cit. n. 9), 137–47.

[11] Jones-Imhotep, "Icons and Electronics" (cit. n. 9), 416. Engineers, scientists, and technicians could build material circuits from a circuit diagram, thanks in large part to standardized electric components. Radio amateurs in particular built their own equipment using circuit diagrams published in journals such as *Wireless World* and components from radio-supply shops.

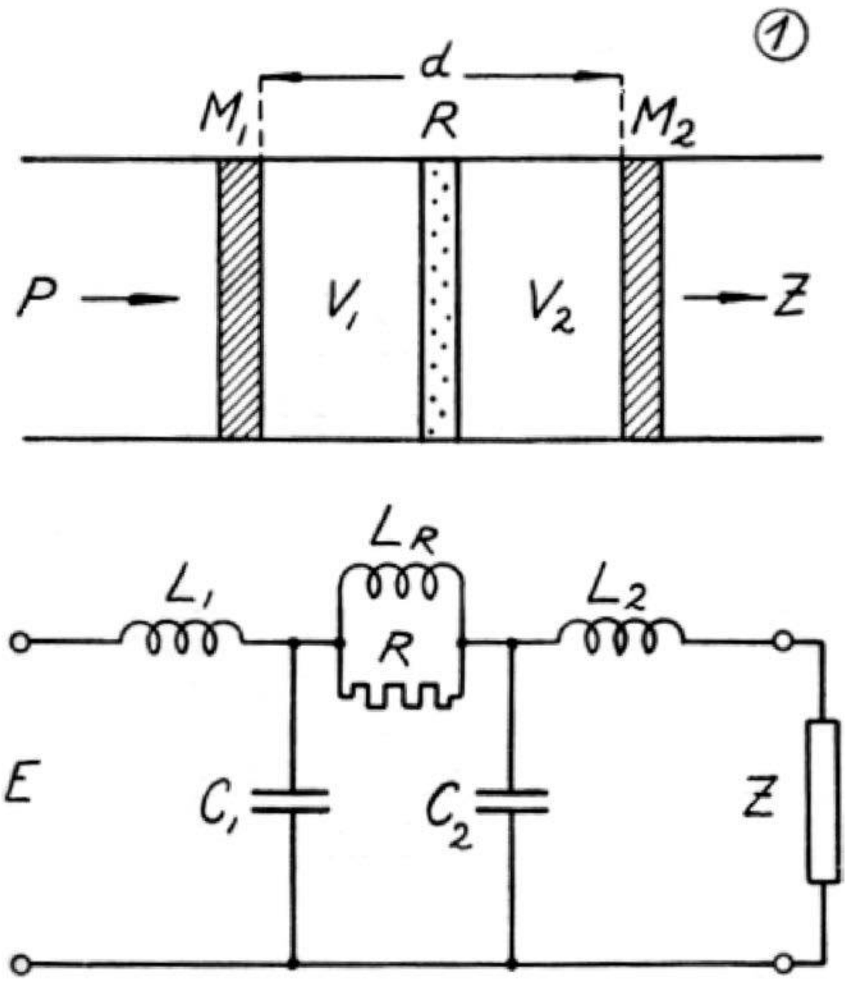


Figure 1. *The electric equivalent-circuit diagram of a double wall as an oscillating system with damping; Berg and Holtsmark, "Schallisolation von Doppelwänden" (cit. n. 12), 75.*

transmitted sound, the lower equivalent-circuit diagram represents the wall as an oscillating system with damping.[12]

What was truly remarkable about the representation of the double wall by an equivalent-circuit diagram was that there was nothing electrical about the wall or the sound traveling through it. By the 1930s electric circuit diagrams, even in the case of representations of nonelectric systems, had become a lingua franca of the new acoustics. Moving from the acoustic to the electric system was an act of transla-

[12] Reno Berg and Johan P. Holtsmark, "Die Schallisolation von Doppelwänden I: Holzwände," *Det Kongelige Norske Videnskabers Selskabs Forhandlinger* 8, no. 23 (1935): 75–8. Holtsmark was professor of physics at the Norwegian Institute of Technology in Trondheim, where he established an acoustic laboratory in 1929. His assistant Berg was an electrical engineer. See Roland Wittje, *Acoustics, Atom Smashing and Amateur Radio: Physics and Instrumentation at the Norwegian Institute of Technology in the Interwar Period* (Trondheim, 2003), 69–142.

tion. Electric oscillations with the same waveforms as acoustic vibrations could be described by the same mathematical equations by substituting the equivalent electric variables for the acoustic variables. Acoustic variables such as force, speed, displacement, mass, and elasticity were replaced by electric variables such as tension, current, charge, self-induction, and capacity. The electric systems then became mathematically identical representations of the acoustic systems.[13]

Acousticians of the interwar period frequently pointed out that acoustics was perceived as a dormant and antiquated discipline from the 1890s until the outbreak of the Great War.[14] On the industrialized battlefields of the Great War, acoustics became an important body of knowledge, and music ceased to be its main frame of reference. But instead of emphasizing discontinuity, the history of acoustics before, during, and after the Great War can also be read as one of continuity. The use of analogies between different physical phenomena was rather common throughout the nineteenth century. Analogies served didactic purposes and linked apparently separate phenomena in order to achieve the ultimate goal of a unified physical science. Analogies between electrical and acoustic phenomena were frequently used, but so were analogies with light, heat, and other phenomena.

The use of the term *electroacoustics* itself can be traced back to around 1900, when it appeared first in the German literature.[15] The timing coincided with the rise of an electromagnetic worldview, which sought to replace mechanical conceptions with electromagnetic ones as the foundation of the physical sciences. The electromagnetic regime eventually failed as a worldview, but it brought the development of electromagnetic representations and electrical technology to the forefront of the physical sciences and engineering. Scientists studied the electric arc as an oscillating system for wireless telephony. They also invented the amplifier tube for long-distance telephony. Both were regarded as research in electricity rather than acoustics. Precisely this work in electricity in the decade prior to the Great War made the rapid development and application of artillery ranging, submarine detection, wireless telephony, and other electroacoustic technologies for warfare possible. At the same time, the tradition of nineteenth-century acoustics, which was deeply rooted in the study of classical music and musical instruments, seems to have stagnated.

As the first industrial war, the Great War was an important turning point for acoustics research through the introduction of new themes and technologies to sound studies, an experience that scientists on both sides of the Atlantic shared. In the immediate interwar period, actors in the electrical and media industry became the main driving forces in the production and consumption of the new electroacoustic knowledge.[16]

[13] See, e.g., Bjørn Trumpy, *Akustikk—utvalgte forelesninger for elektroavdelingens, 4. årskurs (linje for svakstrøm)* [Acoustics—selected lectures for the Department of Electrical Engineering, fourth year (Program of Low-Current Engineering)] (Trondheim, 1930), pt. 1, 13–4, 52–3.

[14] Waetzmann, *Technische Akustik* (cit. n. 6), v; Erwin Meyer and Waetzmann, "Die Bedeutung der Akustik im Rahmen der gesamten Physik und Technik," *Zeitschrift für technische Physik* 17, no. 12 (1936): 508–12, on 508; Bruce Lindsay, preface, in John William Strutt, Baron Rayleigh, *The Theory of Sound*, vol. 1, 2nd ed. (1894; repr., New York, 1945), xxviii; Beyer, *Sounds of Our Times*, 177; Thompson, *Soundscape of Modernity*, 59 (Both cit. n. 1).

[15] Robert Hartmann-Kempf, *Über den Einfluß der Amplitude auf Tonhöhe und Decrement von Stimmgabeln und zungenförmigen Stahlfedern: Elektroakustische Untersuchungen* (Frankfurt am Main, 1903).

[16] William H. Eccles, "The New Acoustics," *Proceedings of the Physical Society* 41 (1929): 231–9.

Frederick Vinton Hunt began his extensive historical introduction to electroacoustics with the proclamation that the field was as old as thunder and lightning, which was, for the scientist, a natural electroacoustic phenomenon.[17] For our aims, however, it will be sufficient to trace the history of the entanglement of acoustics with electrical technology and electrodynamic theory back to the middle of the nineteenth century and its two most influential works, those by Helmholtz and Rayleigh.

THE ACOUSTICS OF HELMHOLTZ AND RAYLEIGH: THE *SENSATIONS OF TONE* AND THE *THEORY OF SOUND*

> The first and principal difference between various sounds experienced by our ear, is that between *noises* and *musical tones*. . . . We can easily compound noises out of musical tones. . . . This shews us that musical tones are the simpler and more regular elements of the sensations of hearing, and that we have consequently first to study the laws and peculiarities of this class of sensations.[18]

> Before proceeding further we must consider a distinction, which is of great importance, though not free from difficulty. Sounds may be classified as musical and unmusical; the former for convenience may be called *notes* and the latter *noises*. . . . We are thus led to give our attention, in the first instance, mainly to musical sounds.[19]

The two most influential works in acoustics in the nineteenth century were Helmholtz's *Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (On the sensations of tone as a physiological basis for the theory of music) of 1863 and Rayleigh's *Theory of Sound*, which was in two volumes, published in 1877 and 1878, then revised and enlarged in the 1894 and 1896 second editions. Helmholtz's *Sensations of Tone* and Rayleigh's *Theory of Sound* were both very similar as well as remarkably different in their scientific aims, their representations of sound phenomena, and their targeted readership.

Helmholtz's involvement with acoustics, like most of his work during the period when he was professor of physiology at the University of Heidelberg (1858–71), was informed by his approach to physiology: to reduce all phenomena to the simple laws of mechanics. Helmholtz's acoustics must also be viewed in the context of his investigations in physiological optics, carried out during the same period. While both treated issues of sensation and perception, Helmholtz's acoustics went further than his optics in its aim to place the aesthetic perception of music on scientific grounds. In addition to physicists and physiologists, Helmholtz sought out musicologists and aestheticians as the main readership of his *Sensations of Tone*.[20] Rayleigh targeted a very different readership of mathematically trained scientists. He aimed at laying "before the reader a connected exposition of the theory of sound, which should include the more important of the advances made in modern times by Mathematicians and Physicists."[21] Helmholtz limited the use of higher mathematics, especially differential calculus, in order to make his volume accessible to readers from musicol-

[17] Hunt, *Electroacoustics* (cit. n. 1), 1.
[18] Helmholtz, *On the Sensations of Tone* (cit. n. 2), 11–2, "Noise and Musical Tone."
[19] Rayleigh, *Theory of Sound* (cit. n. 3), 1:4.
[20] Hermann von Helmholtz, *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (Brunswick, 1863), 1.
[21] Rayleigh, *Theory of Sound* (cit. n. 3), 1:v.

ogy or physiology, who did not necessarily undergo special training in mathematics or physics. Rayleigh's book, in contrast, was filled with differential calculus; it was intended as a handbook to provide the trained reader with comprehensive tools for mathematical treatment of all kinds of acoustic phenomena. While Helmholtz used many of the visual representations of sound, including inscriptions from tuning forks, Chladni figures, and Lissajous figures, such representations are remarkably absent in Rayleigh's books.[22]

We should not, however, lose sight of the similarities between Helmholtz's and Rayleigh's approaches to acoustics. Both treated sound fundamentally as a mechanical phenomenon, which was explained by oscillations in solids, liquids, and gases. Both used musical sounds as a main reference for their investigations. The very fact that acoustic oscillations were understood as audible frequencies was the main argument, for Helmholtz as well as Rayleigh, for keeping acoustics as a field of inquiry separate from mechanical vibrations. The ear remained the most sensitive sound detector for both, despite visual representations and Rayleigh's measurements of sound intensities by a disc suspended on a torsion thread (later known as the Rayleigh disc). Rayleigh's *Theory of Sound*, though conceptualized as a mathematical and physical treatise, contained a section on audition and discussed Helmholtz's theory of combination tones in the second edition of its volume 2 in 1896. By discussing anatomical and physiological issues that were outside the scope of his original work, Rayleigh paid tribute to Helmholtz and the subsequent debate over his theory of combination tones.[23]

THE ELECTRIFICATION OF SOUND: ELECTRODYNAMIC THEORY, CIRCUIT DESIGN, AND ELECTRICAL INSTRUMENTATION

Both Helmholtz and Rayleigh drew upon emerging electrical technologies and electrical analogies in their work on acoustics. Helmholtz used telegraph technology in his acoustic investigations, employing electromagnets and interrupters to drive the tuning forks for his tuning-fork resonator and his vibration microscope. Helmholtz also employed telegraph wires as an analogy, explaining that the nerves conveyed sensation as wires conveyed telegraph pulses. Helmholtz's representations of sound were, however, visual, not electrical or electroanalog. He did not draw upon an analogy between electric oscillations and acoustic vibrations; the analogy between perceptions of sound and perceptions of light was nevertheless important. This mirrors the understanding of electric oscillation as well as communication technology at the time. Telegraph signals were understood as pulses, or electric shocks, which could drive Helmholtz's tuning forks, and not as electric waves, which could be translated into equivalent acoustic waves by means of transducers.

Physicists' understanding of electric oscillations rapidly changed with the advance

[22] Among the few exceptions are the Lissajous figures in vol. 1; ibid., 29.

[23] This debate was a major dispute arising from Helmholtz's *Sensations of Tone*. See David Pantalony, "Rudolph Koenig's Workshop of Sound: Instruments, Theories, and the Debate over Combination Tones," *Annals of Science* 62, no. 1 (2005): 57–82, on 80–1, and Julia Kursell, "Wohlklang im Körper: Kombinationstöne in der experimentellen Hörphysiologie von Hermann v. Helmholtz," in *Resonanz: Potentiale einer akustischen Figur*, ed. Karsten Lichau, Viktoria Tkaczyk, and Rebecca Wolf (Paderborn, 2009), 55–74, on 73–4. See also Erich Waetzmann, *Die Resonanztheorie des Hörens* (Brunswick, 1912).

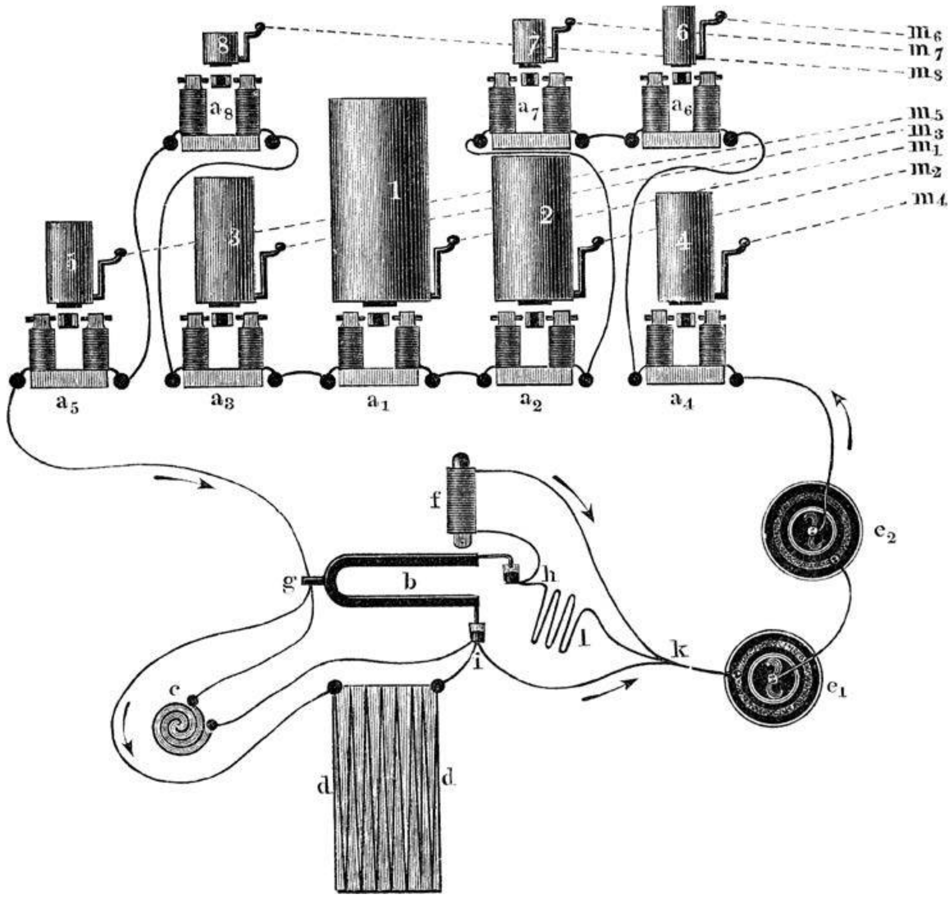


Figure 2. *Helmholtz's wiring diagram for his electromagnetically driven tuning-fork synthesizer; Helmholtz,* Lehre von den Tonempfindungen *(cit. n. 20), 584. The diagram follows very different conventions than twentieth-century circuit diagrams. Components* a_1 *to* a_5 *represent the electromagnets driving the tuning fork;* b *is the interrupting fork driven by the coil* f; e_1 *and* e_2 *represent two Grove cells;* c *is a condenser; and* d *is a "very great" resistance.*

of electrodynamic theory, the design of electric circuits, and the development of the telephone as the first reversible electric sound transducer. These were all developments in which Helmholtz himself played an important role. Like his work in acoustics, Helmholtz's interest in electricity was initially informed by his work in physiology. In the 1850s he conducted a number of experiments on nervous excitation that led him to the first quantitative treatment of self-induction and the extension of Ohm's law to variable currents.[24] He was an early proponent of what is today known as the voltage-source equivalent, a foundation for the equivalent-circuit concept, which he established while working on the measurement of voltages and currents in

[24] Olivier Darrigol, *Electrodynamics from Ampère to Einstein* (Oxford, 2000), 220.

muscle tissue.[25] Helmholtz was mainly interested in open circuits and oscillatory discharge. In the 1870s he published a series of papers on the theory of electrodynamics, in which he compared the assumptions and theories of Wilhelm Weber and Franz Neumann with those of Michael Faraday and James Clerk Maxwell.[26] The industrialist Werner Siemens presented his work on the electromagnetic telegraph to the Berlin Physical Society around 1850, the same time period in which Helmholtz presented his work on nerve transmission. Helmholtz's adaptation and use of telegraph technology and analogy in his physiological investigations comes as no big surprise given that he and Siemens were close acquaintances.[27]

It was, however, not Prussia but Great Britain that was the undisputed leader in establishing a worldwide network of cable telegraphy, which became the "nervous system" of the British Empire, in the second half of the nineteenth century.[28] Enlarging and improving the telegraph system created a large demand for electrical knowledge. William Thomson, professor of natural philosophy at the University of Glasgow, became chief adviser to the first transatlantic telegraph cable project in 1857 and developed electrical measurement instruments for the telegraph industry. The testing laboratories of the cable industry, rather than university laboratories, were the most sophisticated and best-equipped electrical laboratories of the time. The requirements of cable telegraphy led to the development of standard electric units, precision measurement instruments, electric circuit design, and electrodynamic theory.[29]

In his *Treatise on Electricity and Magnetism* (1873), Maxwell acknowledged the importance of telegraphy to the understanding of electrodynamics.[30] In his electromagnetic theory, Maxwell applied analogies not between electric oscillations and acoustics, but between the propagation of electric and magnetic forces in the ether and the propagation of light. This was to support his theory that the electromagnetic ether and the light ether were the same medium, and that light was an electromagnetic disturbance in this medium. The theory of hydromechanics nevertheless established a link between the imponderable ether and the ponderable media where sound propagated. Maxwell made use of mechanical models as vivid representations of electrical phenomena, declaring that illustrative mechanical models provided the best way to translate complex mechanical relationships into a concrete and readily grasped form without a loss of rigor.[31] Among the Maxwellians, a group of physicists who interpreted and developed Maxwell's theory after his death in 1879, George Francis FitzGerald and Oliver Lodge were the ones who adopted the use of mechanical models to explain the mode of operation of electromagnetic phenomena within the ether. According to FitzGerald these models embodied only analogies, or likenesses, and not a true representation of how the ether was supposed to be imagined.[32]

[25] Hermann Helmholtz, "Ueber einige Gesetze der Vertheilung elektrischer Ströme in körperlichen Leitern mit Anwendung auf die thierisch-elektrischen Versuche," *Annalen der Physik und Chemie* 89, no. 6 (1853): 211–33; Don H. Johnson, "Origins of the Equivalent Circuit Concept: The Voltage-Source Equivalent," *Proceedings of the IEEE* 91 (2003): 636–40.

[26] Darrigol, *Electrodynamics* (cit. n. 24), 223–33.

[27] Timothy Lenoir, "Helmholtz and the Materialities of Communication," *Osiris*, 2nd ser., 9 (1994): 184–207, on 187–8. See also Christoph Hoffmann, "Helmholtz' Apparatuses: Telegraphy as Working Model of Nerve Physiology," *Philosophia Scientiae* 7, no. 1 (2003): 129–49.

[28] Bruce J. Hunt, *The Maxwellians* (Ithaca, N.Y., 1991), 54.

[29] Ibid., 55.

[30] Ibid., 55–6.

[31] Ibid., 75.

[32] Ibid., 83.

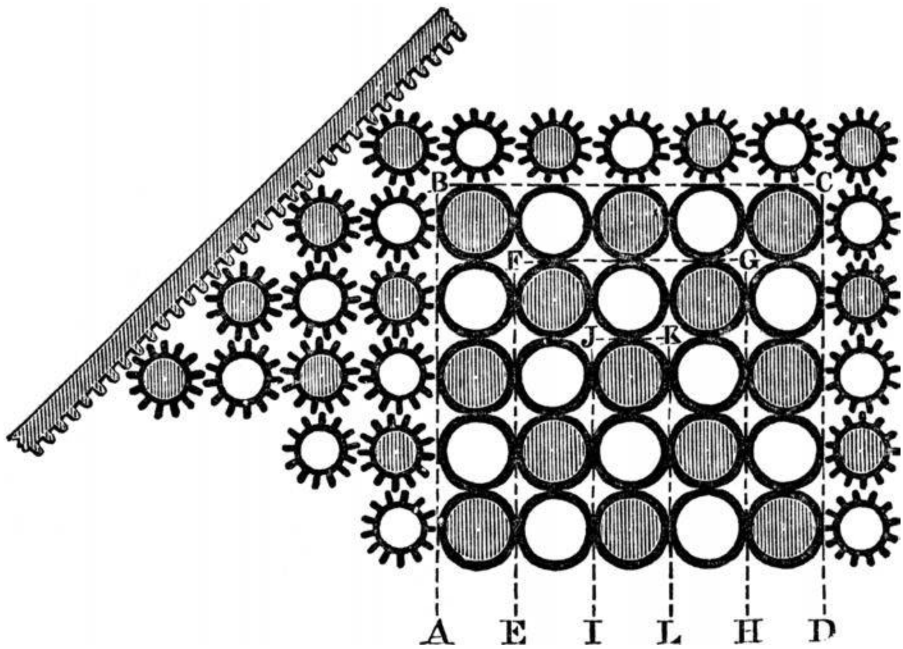


Figure 3. *Model illustrating a current induced in metal by an increasing magnetic field; Oliver Lodge,* Modern Views of Electricity *(London, 1889), 194. Some models of electricity and magnetism, such as Lodge's hydrostatic model of the Leyden jar, were actually built as lecture demonstration devices; see Max Kohl,* Physical Apparatus *(cit. n. 45), 836, fig. 60638.*

The analogy between sound waves and electromagnetic waves became important when the Maxwellians discussed the electromagnetic production of light. By 1880, FitzGerald had come to the conclusion that the electromagnetic production of light was impossible. But then, after carefully studying Rayleigh's *Theory of Sound*, he had to reconsider this viewpoint. Rayleigh's solution of the equation that FitzGerald dealt with, which took the same form for acoustics and electromagnetism, suggested that "a simply periodic current would originate wave disturbances such as light."[33] It was not the British Maxwellians but Helmholtz's former student Heinrich Hertz who was the first to produce electric waves that propagated in free space and to establish their affinity to light waves in 1887 and 1888. Hertz used the analogy between his electric oscillations and acoustics in order to describe the nature of the oscillations that he produced.[34] However, it was once again the analogy with light waves, not acoustic waves, that Hertz had to establish in order to identify his electric waves as light of very long wavelengths.

Hertz's experiments gave a boost to the understanding and further study of electrodynamic theory. Equally important for the development of the electroacoustic agenda was telephony. Oliver Heaviside, a telegraph operator who quit his job in 1874 to pursue private research, became a member of the inner circle of the Maxwellians and

[33] Ibid., 38–42, on 39.
[34] Hertz, *Electric Waves* (London, 1893), 49, 135–6.

one of the leaders in further developing Maxwell's theory. Between 1885 and 1887, Heaviside applied Maxwell's theory to an examination of how electric signals traveled along wires and how their distortion could be reduced or eliminated. Heaviside thereby conceived electric signals in a fundamentally new way, not as pulses in wires, but as trains of electromagnetic waves on wires. Heaviside's discovery of inductive loading in 1887 would be extremely valuable for long-distance telephony.[35]

Rayleigh had used analogies between acoustic phenomena and electric currents in his first edition of 1877–8 to introduce the concept of acoustic conductivity.[36] When the second edition of volume 1 of his *Theory of Sound* appeared in 1894, electrodynamic theory and telephone technology had advanced to such a degree that he found it necessary to add a chapter on electric vibrations (chap. XB). It was rather disconnected from the other chapters, and Rayleigh did not use the term *electroacoustics*. He nevertheless clearly realized the growing importance of electrodynamic theory, instruments, and practice for the future development of acoustics.

Equally as important as electrodynamic theory was the rise and emancipation of electrical engineering for the advance of electroanalog thinking and the development of standardized circuit diagrams as a language to represent physical phenomena. In the 1880s electrical engineering was institutionalized as a new discipline at the German Technische Hochschulen (Institutes of Technology). Its main drivers were the rapid advance of electrification and the heavy-power electrical industry; telegraphy and telephony played virtually no role. Electrical engineering emerged as an amalgam of physics and mechanical engineering, oriented toward practice in the industry.[37] As important as Maxwell's electrodynamic theory was for the understanding of electric oscillations and their propagation both on wires and in free space, it was too abstract to be taught to engineers and impractical for designing heavy-current machinery. Electrical engineers needed more visual and less mathematical tools to design calculations of electric devices.[38]

One of the pioneers in developing these new tools for designing calculations of heavy-current machinery was Carl Proteus Steinmetz. He was one of the leading figures in the theory of heavy-current electrical engineering and a forceful promoter of alternating current.[39] Steinmetz introduced graphical methods and complex numbers into heavy-current engineering and made ample use of analogies between electricity and mechanics. In his textbook on alternating-current phenomena of 1897, Steinmetz applied equivalent-circuit diagrams in explaining alternating-current transformers.[40]

[35] Hunt, *Maxwellians* (cit. n. 28), 129–51. Heaviside's work led to the "British electrical debate," a conflict between the Maxwellians on one side, who proposed loading the telephone lines with additional self-induction, and William Henry Preece of the Post Office Telegraph Department and other practitioners on the other side, who opposed such loading.

[36] Rayleigh, *Theory of Sound* (cit. n. 3), 2:159.

[37] Wolfgang König, *Technikwissenschaften: Die Entstehung der Elektrotechnik aus Industrie und Wissenschaft zwischen 1880 und 1914* (Chur, 1995).

[38] See Ronald Kline, *Steinmetz: Engineer and Socialist* (Baltimore, 1992), 108–12.

[39] Ibid. Steinmetz had studied mathematics, physics, and electrical engineering in Breslau (now Wrocław) and Zurich before he emigrated to the United States in 1889 and started working in the expanding electrical industry.

[40] Steinmetz and Ernst J. Berg, *Theory and Calculation of Alternating Current Phenomena* (New York, 1897), 183–5. For a history of the origins of the equivalent-circuit concept, see also Johnson, "Voltage-Source Equivalent" (cit. n. 25), and Johnson, "Origins of the Equivalent Circuit Concept: The Current-Source Equivalent," *Proceedings of the IEEE* 91 (2003): 817–21.

These representations of alternating-current transformers in equivalent-circuit diagrams later inspired equivalent-circuit representations in electroacoustics.

ELECTROACOUSTICS AS MODERN PHYSICS: THE ELECTRIC ARC AS AN EXPERIMENTAL SYSTEM FOR *SCHWINGUNGSFORSCHUNG*

With the rise of electromagnetic theory, electric machinery, and the identification of cathode rays as electrons around 1900, an electromagnetic worldview swiftly supplanted mechanical conceptions, replacing the fundamental laws of mechanics to which all physical phenomena should be reduced with fundamental laws of electromagnetism.[41] As Bruce Hunt has put it, "Physicists ceased to feel a need to look for a mechanism behind the electromagnetic laws or to believe that their understanding would be improved by one."[42] The understanding of oscillations as the basis of a principle that transcended and interlinked all subdisciplines of the physical sciences would become equally important in the formation of such new research fields as quantum theory.[43] With the rise of the electromagnetic worldview and electrical technology, electric oscillations increasingly replaced mechanical models for oscillation theory.

Around the same time, the notion of electroacoustics made its appearance. In 1903, Robert Hartmann-Kempf added the subtitle *Elektroakustische Untersuchungen* (Electroacoustic investigations) to his dissertation, which he had worked on under Wilhelm Wien at the University of Würzburg.[44] In his dissertation, Hartmann-Kempf investigated the effect of amplitude on the resonance frequency and damping of tuning forks and steel springs driven by electric oscillations. Despite the new term, Hartmann-Kempf's experimental regime remained related to the one laid out for acoustics by Helmholtz forty years earlier. Around 1900, the telephone was classified and understood as an electrical, not an acoustic, instrument. Electrically driven tuning forks were generally classified as acoustic instruments.[45] Investigations in acoustics were still mainly related to music and musical instruments and dominated by the debate about Helmholtz's theory of combination tones. The collection on technical acoustics at the Deutsches Museum in Munich, which opened in 1906, comprised only musical instruments.[46]

But a "new acoustics" emerged in this electric age. Amplifier tubes were developed to solve the problem of long-distance telephone transmission. For the scien-

[41] The electromagnetic worldview reached its zenith around 1905 and lost its appeal around 1914 due to the rise of quantum theory and relativity. See Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century* (Princeton, N.J., 1999), 103–19.

[42] Hunt, *Maxwellians* (cit. n. 28), 104.

[43] Wave formalism allowed for the transfer of formalism from acoustic wave theory to quantum mechanics, as Johan Holtsmark and Hilding Faxén, for example, transferred Rayleigh wave scattering to electron scattering in 1927; see Faxén and Holtsmark, "Beitrag zur Theorie des Durchgangs langsamer Elektronen durch Gase," *Zeitschrift für Physik* 45 (1927): 307–24, and Wittje, *Acoustics, Atom Smashing and Amateur Radio* (cit. n. 12), 145–6.

[44] See Hartmann-Kempf, *Über den Einfluß der Amplitude* (cit. n. 15). Hartmann-Kempf was the son of Wilhelm Eugen Hartmann, one of the founders of the electrical instrument company Hartmann & Braun. Hartmann-Kempf used Hartmann & Braun instruments in the investigations for his dissertation, and later joined the company.

[45] See Max Kohl, *Physical Apparatus, Price List No. 50*, vols. 2 and 3 (Chemnitz, n.d. [1911]). Electrically driven tuning forks also served other purposes than to produce sounds; see, e.g., the tuning-fork chronograph.

[46] Franz Fuchs, *Der Aufbau der technischen Akustik im Deutschen Museum* (Munich, 1963), 1.

tists and engineers working with electrical communication technologies, the acoustic problems of sound propagation were intrinsically tied to the electrical problems of signal propagation. A similar relation was established in the sound laboratory by the rapid dominance of electrical measurement instrumentation.[47] As a transducer, the telephone connected the otherwise still separate electrical and acoustic worlds. The telephone was employed as an instrument in investigating the origin and nature of combination tones.[48]

In contrast to the telephone, the speaking or singing electric arc, an apparatus whose components are nowadays known as the plasma loudspeaker and plasma microphone, has nearly fallen into oblivion as an electroacoustic communication technology. Around 1900, however, the electric arc was a widespread technology with a promising future for electric lighting, for binding nitrogen from the air for fertilizers and explosives, and for transmitting wireless telegraphy and telephony. As an oscillating system it could broadcast both electromagnetic waves and the human voice in free space without using a membrane like the telephone. The arc could also detect electromagnetic waves as well as sound. What could be a more ideal experimental system for acoustics in the electric age?

William du Bois Duddell in Britain and Hermann Theodor Simon (known as Theodor) in Germany both developed and investigated the singing or speaking arc.[49] Their device was a carbon arc lamp in which a variable resistor or a microphone was used to alternate the sound produced by the arc (figs. 4 and 5). The speaking arc became a popular demonstration device in physics classes that could be used with a microphone or as an "electric piano," playing a simple melody (see fig. 5). In the instrument catalogs as well as in textbooks and teaching collections of the pre–World War I period, the speaking arc was classified as an electrical instrument, in the section of electric oscillations and wireless telegraphy along with other electroacoustic instruments like the telephone and magnetic sound-recording devices.

From 1901 Simon was professor of applied electricity (*angewandte Elektrizität*) at the University of Göttingen. The creation of the professorship was part of mathematics professor Felix Klein's efforts to establish applied sciences in the university.[50] Simon and his students systematically analyzed the electrical and acoustic properties of the arc as an oscillating system in the years before the Great War. They conducted both theoretical as well as experimental investigations that covered all different aspects of the arc's discharge. Several of Simon's students would become

[47] Thompson, "Dead Rooms and Live Wires," 596–626; Thompson, *Soundscape of Modernity*, 229–93 (Both cit. n. 1).

[48] See Karl L. Schaefer, "Über die Erzeugung physikalischer Kombinationstöne mittels des Stentortelephons," *Annalen der Physik* 322 (1905): 572–83, and Waetzmann, *Resonanztheorie des Hörens* (cit. n. 23), 120–3.

[49] Duddell, "On Rapid Variations in the Current through the Direct-Current Arc," *Journal of the Institution of Electrical Engineers* 30 (1900): 232–67; Simon, "Akustische Erscheinungen am electrischen Flammenbogen," *Ann. Physik* 300, no. 2 (1898): 233–9; Simon, "Zur Theorie des selbsttönenden Lichtbogens," *Physikalische Zeitschrift* 7, no. 13 (1906): 433–45; Simon, *Der elektrische Lichtbogen—Experimentalvortrag* (Leipzig, 1911).

[50] Hermann Th. Simon, "Das Institut für angewandte Elektrizität der Universität Göttingen," *Physikalische Zeitschrift* 7, no. 12 (1906): 401–12; Adelheid Wein, *Heinrich Barkhausen und die Anfänge der wissenschaftlichen Schwachstromtechnik* (master's thesis, Philosophy Faculty I, Univ. of Regensburg, 2011); about Simon, see Theodor des Coudres, "Hermann Th. Simon †," *Physikalische Zeitschrift* 14 (1919): 313–20.

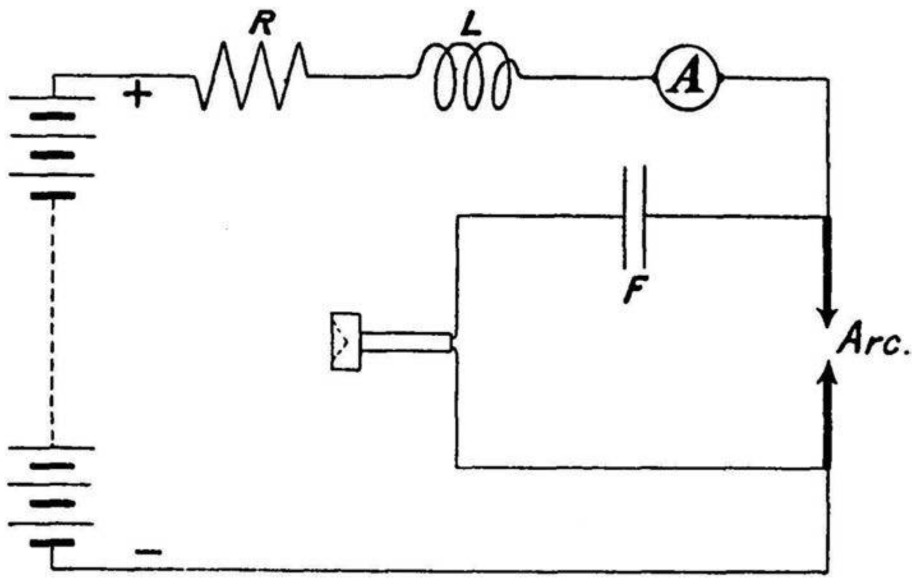


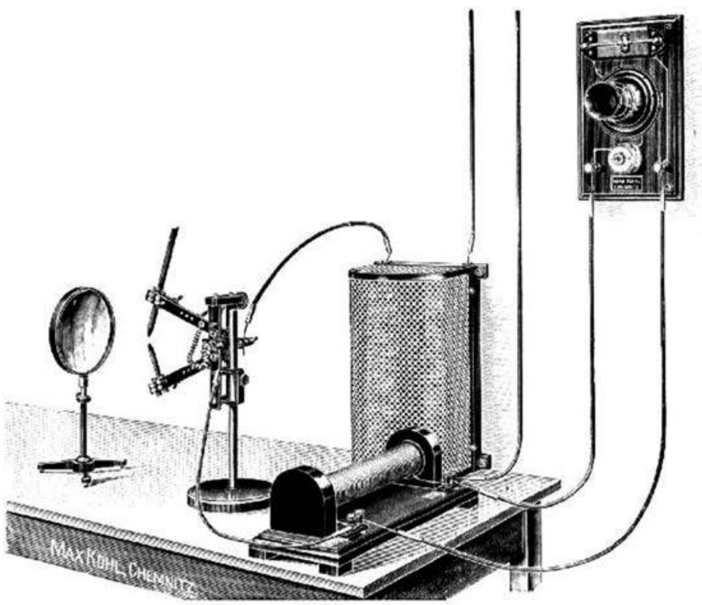
Figure 4. Circuit diagram of the speaking arc as a telephone transmitter; Duddell, "On Rapid Variations" (cit. n. 49), 242.

important figures in the formation of the electroacoustics research agenda in the interwar period. Karl Willy Wagner would be the founder and first director of the Heinrich Hertz Institut für Schwingungsforschung (Heinrich Hertz Institute of Oscillation Research). Hugo Lichte, who studied the sound produced by the electric arc, became head of the acoustics division of the Allgemeine Elektricitäts-Gesellschaft Forschungsinstitut (AEG Research Institute).[51] Heinrich Barkhausen became professor of *Schwachstromtechnik* (electrical communication engineering) at the Technische Hochschule Dresden. Barkhausen had compiled a comparative study on the generation of oscillations in electric and mechanical systems with a special emphasis on rapid electric oscillations generated by the arc.[52] His thesis, *Das Problem der Schwingungserzeugung*, was a point of origin of the program of *Schwingungsforschung* (oscillation and vibration research), which both Barkhausen in Dresden and Wagner at the Heinrich Hertz Institut followed in the interwar period.

In 1911 Simon summarized the different properties and potential capabilities of the arc as an electric system, including its heat- and light-producing powers, its capacity

[51] The AEG Forschungsinstitut was founded in 1928 with Carl Ramsauer as its first director. Lichte and the acoustics department worked mainly on a German system for sound motion pictures. For the AEG Forschungsinstitut, see Ernst Brüche, *Zehn Jahre Forschungsinstitut der AEG* (Berlin-Reinickendorf, 1938). For Lichte, see *Neue Deutsche Biographie*, vol. 14 (Berlin, 1985), s.v. "Lichte, Hugo," by Helmut Mielert; for his research on sound produced by the electric arc, see Lichte, "Über die Schallintensität des tönenden Lichtbogens," *Ann. Physik* 347, no. 14 (1913): 843–70. For Wagner, see Ernst Lübke, "Karl Willy Wagners Beiträge zur akustischen Forschung," *Akustische Zeitschrift* 8 (1943): 78–80, and Marianne Peilstöcker, "Professor Dr. Karl Willy Wagner [1883–1953]," *Jahrbuch Hochtaunuskreis 2003* (2002): 96–103.

[52] Barkhausen, *Das Problem der Schwingungserzeugung mit besonderer Berücksichtigung schneller elektrischer Schwingungen* (Leipzig, 1907).



63 395, 50 892, 63 386, 63 388, 63 389. 1 : 8.

Max Kohl A. G. Chemnitz, Germany.

	£ s. d.
Complete Apparatus for Experiments with the Speaking Arc Lamp after Weinhold (W. D., Fig. 601), consisting of:	
Arc Light Hand Regulator and Resistance: see Nos. 50,892, 63,386 and 63,387, p. 1057.	
63,390. **Induction Coil,** Figure	3. 4. 0
63,391. **Microphone with Switch and Regulating Resistance, and 1 Fuse with simple current indicator for same**	3. 0. 0
Additional Apparatus for above so as to be able to demonstrate the automatically singing (whistling) arc lamp also, consisting of:	
63,392. **Small Induction Coil** (W. D., Fig. 604), with aluminium ring for Thomson's Experiment	0. 16. 0
61,122. **Switch**	0. 3. 6
63,393. **Paper Condenser** in simple wood box, approx. 8 mfd.	2. 0. 0
63,394. **Staged Paper Condenser,** with four steps, for use instead of No. 63,393; this permits of obtaining a simple melody with the arc (electric piano) since the pitch varies with the capacity cut in	6. 0. 0

Figure 5. *Apparatuses for singing- and speaking-arc experiments from the Max Kohl catalog, around 1911; Max Kohl,* Physical Apparatus *(cit. n. 45), 1058. In the same section of the catalog, entitled "Telephony and Microphony," Max Kohl advertised sets for photophonic apparatuses (used in wireless light telephony), employing acetylene light and selenium cells.*

to produce and consume sound, and finally its capacity to produce and detect rapid electric oscillations in free space.[53] Its capacity to produce rapid electric oscillations combined with its function as a reversible transducer made the carbon arc a perfect candidate for wireless telephony based on electric waves, especially after the problem of producing a constant arc had been solved by Duddell. Simon did not stop with sketching the fascinating technical prospects of the electric arc as a simple yet al-

[53] Simon, *Elektrische Lichtbogen* (cit. n. 49).

mighty wireless electroacoustic communication system. Emphasizing his theoretical and scientific interest, Simon placed the arc firmly in the electromagnetic worldview comprising electrons, atoms, and the all-penetrating world ether.[54] Through their research program on the electric arc as an oscillating system, Simon and his students placed acoustics, perhaps for the first time, in an electrical frame rather than a mechanical one.

ACOUSTICS IN THE CHEMISTS' WAR

Simon's investigations into the electric arc came to a halt with the outbreak of the Great War in 1914, when he and his students started to work on underwater acoustics related to submarine warfare for the German Imperial Navy in Kiel. The underwater world was an important battlefield but by no means the only one for acousticians. The Great War is sometimes called the War of the Chemists, emphasizing the importance of the chemical military-industrial-scientific complex in producing substitutes for scarce raw materials and, of course, in chemical warfare. But the notion belies the role of physicists and mathematicians in the mobilization and self-mobilization of scientists.[55] The Great War was the first large-scale industrial war where weapon systems like the submarine, the airplane, and the tank were used, and where large numbers of scientists were deployed in warfare research and development.[56] The field of acoustics became important for telephony, but even more so for artillery ranging, aircraft ranging, submarine detection, and the detection of tunnels under trenches.[57] In 1936 Erwin Meyer and Erich Waetzmann identified the Great War as the main driving force in the revival of acoustics research in the early twentieth century.[58] Meyer, born in 1899, was drafted as a soldier in 1917 before he started his studies with Waetzmann, professor of physics at Breslau. Waetzmann based his report on his own participation in scientific warfare. He had been a central actor in the German development of sound ranging of artillery and aircraft.[59]

Collaboration between scientists and the military in wireless telegraphy predated the Great War. Simon had initiated the Radioelektrische Versuchsanstalt für Marine und Heer (Radioelectric Testing Laboratory for the German Navy and Army) in Göttingen in 1908. His assistant Max Reich, who had been director of the Versuchsanstalt, became in 1915 head of a group at the Inspektion des Torpedowesens (German Command for Technical Inspection of the Torpedo Sector) in Kiel to develop

[54] Ibid., 32–5.

[55] Arne Schirrmacher, "Von der Geschossbahn zum Atomorbital? Möglichkeiten der Mobilisierung von Kriegs- und Grundlagenforschung füreinander," in *Mit Feder und Schwert: Militär und Wissenschaft—Wissenschaftler und Krieg*, ed. Matthias Berg, Jens Thiel, and Peter Th. Walther (Stuttgart, 2009), 155–75, on 153.

[56] Helmuth Trischler, "Die neue Räumlichkeit des Krieges: Wissenschaft und Technik im 1. Weltkrieg," *Berichte zur Wissenschaftsgeschichte* 19 (1996): 95–103; Guy Hartcup, *The War of Invention: Science in the Great War, 1914–18* (London, 1988).

[57] Hartcup, *War of Invention* (cit. n. 56), 68–80, 129–35, 164; Willem D. Hackmann, *Seek and Strike: Sonar, Anti-submarine Warfare, and the Royal Navy, 1914–54* (London, 1984); Schirrmacher, "Von der Geschossbahn zum Atomorbital?" (cit. n. 55).

[58] Meyer and Waetzmann, "Bedeutung der Akustik" (cit. n. 14), 508; see also Beyer, *Sounds of Our Times* (cit. n. 1), 197.

[59] Meyer, "Erich Waetzmann zum Gedächtnis," *Akustische Zeitschrift* 3 (1938): 241–4; Lothar Cremer, "Erwin Meyer, 21. Juli 1899 – 6. März 1972," *Jahrbuch der Akademie der Wissenschaften in Göttingen* 1972, 179–85.

and investigate a system for sound ranging of submarines, while Simon carried out complementary experiments at the University of Göttingen. Other students of Simon who were drafted for the Inspektion des Torpedowesens in 1915 to work on underwater acoustics were Barkhausen and Lichte. The group of physicists who worked on problems of underwater acoustics in Kiel during the Great War included Hans Riegger, who worked for Siemens & Halske, and Alard du Bois-Reymond (son of Emil du Bois-Reymond), Karl Heinrich Hecht, and Walter Hahnemann, who worked for the Signal Gesellschaft, a subsidiary of Hanseatische Apparatebaugesellschaft Neufeldt & Kuhnke.[60]

During the Great War it became clear to scientists and engineers that it was not the electric arc but the triode vacuum tube that held the potential to become the dominant, overarching component for generating, amplifying, modifying, and broadcasting electric oscillations. Electromechanically, electromagnetically, or electrostatically driven loudspeakers became the norm. The sound-producing and sound-consuming properties of the electric arc, as fascinating as they were, remained only a curiosity.

After the Great War, scientists who were involved in sound ranging and sound signaling published their war research, including Lichte, Barkhausen, and Du Bois-Reymond.[61] Hahnemann and Hecht of the Signal Gesellschaft in Kiel published a series of papers about theoretical properties of sound transmitters and sound receivers, which were structured as a generalized theory of electroacoustic transmitters.[62] In order to conceptualize the theory of the electromechanical transformer, Hahnemann and Hecht fell back on the well-understood theory of the alternating-current transformer, which Steinmetz had explained in 1897 using equivalent-circuit diagrams.[63] Hahnemann and Hecht's approach was to replace the mechanical movement of the coil driving the membrane of a sound transmitter with a secondary circuit that was equivalent to the mechanical system. Instead of driving a coil and membrane, the primary circuit would induce an equivalent oscillation in the secondary circuit (see fig. 6). Hahnemann and Hecht thereby replaced a coupled system, which contained both electric and mechanical components, with a purely electrical representation of the system. The electrical representation of coupled systems became the backbone of the theory of electroacoustic transducers and the use of equivalent-circuit diagrams,

[60] For Riegger, see Hans Gerdien, "Hans Riegger †," *Zeitschrift für technische Physik* 7 (1926): 321–4; for Hecht, see Hugo Lichte, "Dr. Heinrich Hecht zum 60. Geburtstag," *Zeitschrift für technische Physik* 21, no. 2 (1940): 25–7, and *Neue Deutsche Biographie*, vol. 8 (Berlin, 1969), s.v. "Hecht, Karl Heinrich," by Erhard Ahrens; for Hahnemann, see Jonathan Zenneck, "W. Hahnemann," *Hochfrequenztechnik und Elektroakustik* 53, no. 6 (1939): 214.

[61] Heinrich Barkhausen and Hugo Lichte, "Quantitative Unterwasserschallversuche," *Ann. Physik* 367 (1920): 485–516; Alard du Bois-Reymond, "Englische U-Boot-Abwehr," *Zeitschrift für technische Physik* 2, no. 9 (1921): 234–8.

[62] Walter Hahnemann and Heinrich Hecht, "Schallgeber und Schallempfänger I" and "Schallgeber und Schallempfänger II," *Physikalische Zeitschrift* 20 (1919): 104–14 and 245–51; Hahnemann and Hecht, "Der mechanisch-akustische Aufbau eines Telephons," *Ann. Physik* 365 (1919): 454–80. Hecht later published two monographs, on equivalent circuits and differential equations of mechanical and electrical oscillating systems in 1939, and on the theory of electroacoustic transducers in 1941: Hecht, *Schaltschemata und Differentialgleichungen elektrischer und mechanischer Schwingungsgebilde* (Leipzig, 1939); Hecht, *Die elektroakustischen Wandler* (Leipzig, 1941).

[63] Steinmetz and Berg, *Theory and Calculation of Alternating Current Phenomena* (cit. n. 40), 184–5; Hahnemann and Hecht, "Schallgeber und Schallempfänger I" (cit. n. 62). Hahnemann and Hecht did not make any reference to Steinmetz, but to Gisbert Kapp's 1907 textbook on transformers; see "Schallgeber und Schallempfänger I," 107, and Kapp, *Transformatoren für Wechselstrom und Drehstrom* (Berlin, 1907), 140, 227, 232. It is noteworthy that Kapp used a hydraulic analogy to explain magnetic scattering in his textbook (4).

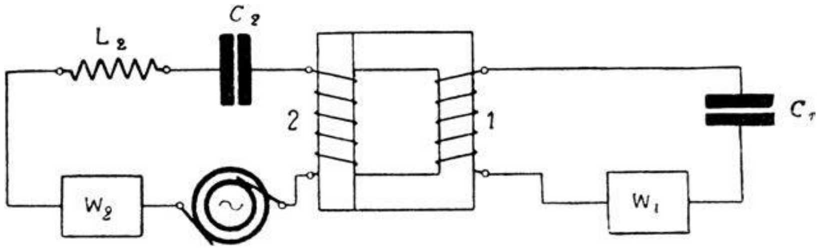


Figure 6. Electric-circuit diagram of an electromagnetic transducer as a sound receiver. The circuit of the transducer was equivalent to that of an electromagnetic transformer. The circuit 2 *represented the mechanical movement of the speaker, with* L_2 *and* C_2 *being equivalent to the elasticity of the membrane, the mass of the oscillating parts, and the mechanical and acoustic radiation resistance; Hahnemann and Hecht, "Schallgeber und Schallempfänger II" (cit. n. 62), 245.*

as presented in Frederick Vinton Hunt's monograph in 1954. But the equivalent-circuit regime could achieve even more. In the course of the interwar years, the equivalent-circuit diagram came to be mobilized to represent acoustic systems that did not have an electric component, such as walls in a house, automobile sound silencers, and even the human voice.

THE ADVANCE OF THE EQUIVALENT CIRCUIT: TRANSLATING SOUND INTO ELECTRICAL NETWORKS

On 22 March 1929, the physicist William Henry Eccles, who had made important contributions to circuit design, gave a presidential address to the Physical Society of London, bringing to the attention of British physicists the novelty and importance of the "new acoustics" that had arisen in the previous decade.[64] In addition to the prominence that electroacoustic measurement technology had gained in acoustics research and the rise of electroacoustic media technology, Eccles paid special attention to the conceptual aspects that had transformed electroacoustics into a new language of sound:

> Besides these tangible adjuncts to the technique of experimental acoustics, electrical science has brought subtle assistance to the more theoretical aspects of the subject. This comes about because vibration phenomena of all kinds approximately satisfy the same linear differential equations. Inasmuch as the study of electrical vibrations in well-defined electrical circuits is easier and has been more cultivated (for practical purposes) than that of air vibrations, acoustic science profits from electrical by a free exchange of ideas about vibrations. Many acoustical problems can be translated into problems concerning electrical networks, and as there exists a great body of knowledge of such networks, the problem is often solved in the act of translation. Further, by adopting the phraseology of the electrician into acoustics, so that translation of the acoustic problem into the electrical problem becomes automatic, a language for thinking and talking becomes available and is found to clear the mind and assist reasoning.[65]

[64] Eccles, "New Acoustics" (cit. n. 16). For Eccles, see John Ashworth Ratcliffe, "William Henry Eccles, 1875–1966," *Biographical Memoirs of Fellows of the Royal Society* 17 (1971): 195–214. In 1918, Eccles and Frank Wilfred Jordan had patented a trigger circuit based on vacuum tubes, which later became known as the first flip-flop circuit.
[65] Eccles, "New Acoustics" (cit. n. 16), 233.

Furthermore, Eccles observed that, despite the prominence given to the study of acoustics by Rayleigh, the new electroacoustics was not studied as eagerly in Britain as it was in the United States and Germany.[66]

Eccles was not the only one to identify a gap between his home nation's academic efforts in the new electrical communication sciences and those of the United States. In Germany, which Eccles saw as one of the leaders in the new acoustics research, Karl Willy Wagner, as president of the Telegraphentechnisches Reichsamt (Telegraph Technology Office), expressed similar concerns. Wagner left the Reichsamt in 1927 in order to initiate and direct the Heinrich Hertz Institut. The foundation of the institute was an explicit attempt by Wagner and others in the German research community to catch up and compete with American research, especially with the Bell Telephone Laboratories, which AT&T and Western Electric had formed in 1925 as a consolidated research laboratory.

Wagner did not attempt to copy the structures and practices of private American research laboratories. The patrons of the Heinrich Hertz Institut were the Studiengesellschaft für Schwingungsforschung (Association for the Study of Oscillation Research) and the Heinrich-Hertz-Gesellschaft zur Förderung des Funkwesens (Heinrich Hertz Association for the Advancement of Radio Communications), which was composed of representatives from the Reichspost (the Imperial Post, which administered the state monopoly of telephony, telegraphy, and radio broadcasting), the electrical industry, and the Technische Hochschule Berlin-Charlottenburg. While universities used to be the main arena for acoustics research before the Great War, the electrical industry, public research and testing laboratories, and Technische Hochschulen now took the lead in the new acoustics research in the interwar period. The Heinrich Hertz Institut brought all three actors together, forming an institution that was unique in the international context.

Just as its institutional composition was unique, so too was its research program.[67] The strong links among acoustics, communication technologies such as telegraphy and telephony, electric sound generation and amplification, and radio broadcasting led to the emergence of the research field of Schwingungsforschung, which brought together scientific and engineering disciplines.[68] The research program of Schwingungsforschung was not Wagner's invention, as we have already discussed, but grew out of Barkhausen's dissertation during their time at Göttingen. Wagner as the president of the Heinrich-Hertz-Gesellschaft acknowledged Barkhausen's contributions in the formation of the field of Schwingungsforschung by awarding him the first gold Heinrich Hertz Medal in 1928.[69]

In addition to Barkhausen and Wagner, there were others who formulated a research program for Schwingungsforschung in Germany. In an article in the *Zeitschrift für technische Physik* in 1922, Walter Hahnemann proposed problems arising from

[66] Ibid., 239.
[67] Friedrich-Wilhelm Hagemeyer, *Die Entstehung von Informationskonzepten in der Nachrichtentechnik: Eine Fallstudie zur Theoriebildung in der Technik in Industrie- und Kriegsforschung* (Berlin, 1979), 139–40, 267.
[68] Ibid., 326; Karl Willy Wagner, "Das Heinrich-Hertz Institut für Schwingungsforschung," *Elektrische Nachrichtentechnik* 7 (1930): 174–91; Wittje, *Acoustics, Atom Smashing and Amateur Radio* (cit. n. 12), 78.
[69] Wein, *Heinrich Barkhausen* (cit. n. 50), 1–2.

oscillation as the main frame for the new technical acoustics research.[70] The notion of electroacoustics gained momentum around the same time. The industrial physicist Walter Schottky, who spent most of his career at the Siemens Laboratories, wrote the chapter on electroacoustics in *Die wissenschaftlichen Grundlagen des Rundfunkempfangs* (The scientific basis of radio), a volume edited by Wagner in 1927 following a lecture series organized by the Heinrich-Hertz-Gesellschaft. In 1931, the *Zeitschrift für Hochfrequenztechnik,* a journal for electrical communication engineering, changed its name to *Zeitschrift für Hochfrequenztechnik und Elektroakustik,* reflecting the growing importance of electroacoustics within physics and electrical engineering.

Schottky, who worked on loudspeakers and microphones in the 1920s, is better known for his theoretical work on radio tubes and solid-state physics.[71] It was Ferdinand Trendelenburg who became the main acoustician at the Forschungslaboratorium (research laboratory) of Siemens & Halske and the Siemens-Schuckertwerke. Trendelenburg had obtained his doctorate at the University of Göttingen in 1922 with Max Reich, who had become Theodor Simon's successor as chair of applied electricity.[72] In 1932, Trendelenburg assembled a monograph on recent proceedings in acoustics, which he extended in a second edition in 1934.[73] In the section on hearing and speech, which was Trendelenburg's own research interest, he discussed a schematic representation of speech, which used an electric circuit of a self-exciting radio transmitter as an equivalent representation of the human voice (fig. 7). Trendelenburg referred to two scientists from the Bell Laboratories, Irving Crandall and Raymond Lester Wegel, the latter of whom had discussed representing the vibration of the vocal cords by an electric equivalent circuit.[74] John Q. Stewart, a research engineer in the Development and Research Department of AT&T, had already published a circuit diagram for producing simple speech sounds in 1922.[75]

Developing equivalent circuits for the human voice was certainly useful if one intended to build an analog electric human-speech synthesizer, an endeavor in which Bell Laboratories became a central actor. The electric-circuit analysis, however, could be applied to a whole range of acoustic systems that would never be built as real electric machines like the voder, the name under which the human-speech synthesizer came to be known. Noise abatement had become one of the most active

[70] Hahnemann, "Schwingungstechnische Probleme als Grundlage der technischen Akustik," *Zeitschrift für technische Physik* 3, no. 2 (1922): 44–6.

[71] Reinhard W. Serchinger, *Walter Schottky—Atomtheoretiker und Elektrotechniker* (Diepholz, 2008).

[72] Trendelenburg can thus be seen in the Göttingen tradition of electroacoustics research, established by Simon. In his thesis, Trendelenburg had worked on the thermophone as a sound transducer. For Trendelenburg, see Ernst Lübke, "Ferdinand Trendelenburg 60 Jahre," *Physikalische Blätter* 12 (1956): 270.

[73] Trendelenburg, *Die Fortschritte der physikalischen und technischen Akustik* (Leipzig, 1932); 2nd enlarged ed., 1934.

[74] Trendelenburg, *Fortschritte der physikalischen und technischen Akustik* 1934 (cit. n. 73), 77; see Hunt, *Electroacoustics* (cit. n. 1, on 66) for Wegel. Crandall introduced a range of electrical analogies in his *Theory of Vibrating Systems and Sound* (New York, 1926).

[75] Stewart, "An Electrical Analogue of the Vocal Organs," *Nature* 110 (1922): 311–2. Stewart, an astrophysicist, is better known for his engagement with social physics. During the Great War he served as chief instructor in sound ranging at the Army Engineering School, after which he worked for AT&T until 1921. See David H. DeVorkin, *Henry Norris Russell: Dean of American Astronomers* (Princeton, N.J., 2000), 208.

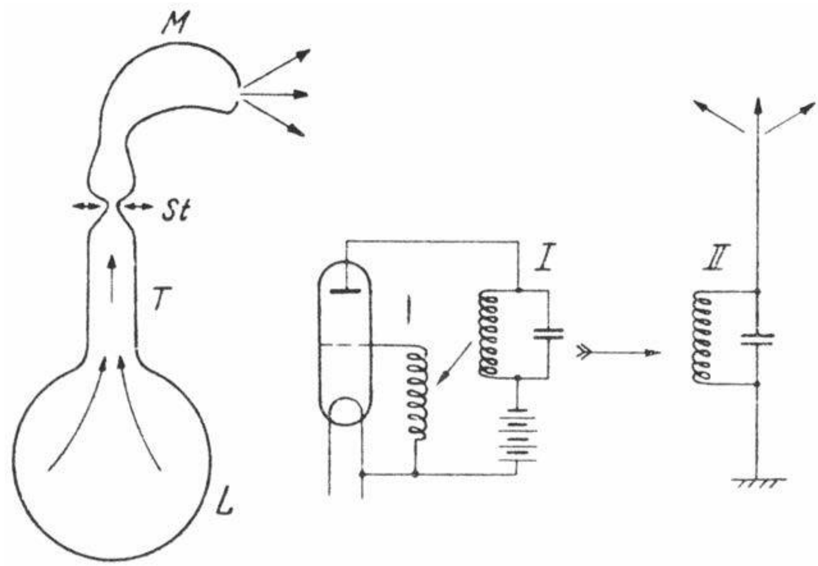


Figure 7. *The self-exciting radio-tube transmitter as an equivalent circuit for the human voice; Trendelenburg,* Fortschritte der physikalischen und technischen Akustik *1934 (cit. n. 73), 76.*

fields of acoustics research and development in the interwar period, owing its prominence partly to the battlefields of the Great War, partly to the pathogenic (though less deadly) sound levels of modern industrial and urban life.[76] Trendelenburg added a separate section on noise abatement in the second enlarged edition of his monograph in 1934.

The development of sound silencers was another field where equivalent-circuit diagrams became useful. Demand for sound silencers came, for example, from the growing automobile industry in Europe and North America, which needed to silence the noise produced by combustion engines of both cars and motorbikes. Most of the sound silencers were built on the principle of acoustic filters.[77] The theory of electric filters had advanced quite far. George W. Stewart, a physicist at Iowa State University, had designed an aircraft sound locator for the US National Research Council during the Great War.[78] In the early 1920s he worked on acoustic wave filters based on analogies with well-understood electric wave filters. Stewart sold some of his patent rights to Bell Laboratories but did not envision the sound silencer as an application.[79] This was done by Martin Kluge, a former student of Heinrich Barkhausen in Dresden. His habilitation thesis was on the silencing of the noise produced by

[76] Thompson, *Soundscape of Modernity* (cit. n. 1), 115–68.

[77] Trendelenburg, *Fortschritte der physikalischen und technischen Akustik* 1934 (cit. n. 73), 168.

[78] Stewart, "Location of Aircraft by Sound," *Physical Review* 14, no. 2 (1919): 166–7.

[79] Stewart, "An Acoustic Wave Filter," *Physical Review* 17, no. 3 (1921): 382–4; Stewart, "Acoustic Wave Filters," *Physical Review* 20, no. 6 (1922): 528–51; Harvey Fletcher, "George W. Stewart, 1876–1956," *Biographical Memoirs of the National Academy of Sciences* 32 (1958): 378–98. Stewart referred to George W. Pierce, professor of physics at Harvard University, who worked on wireless and electric circuits, with regard to electric filters. Karl Willy Wagner developed a theory of electric filters during the Great War as well.

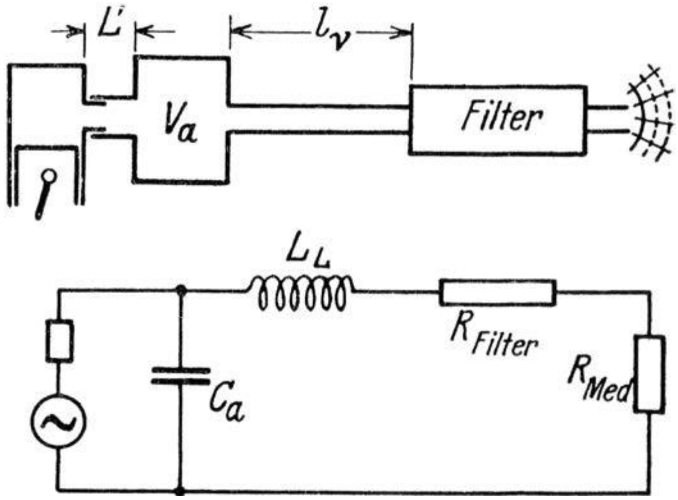


Figure 8. *Design and electric equivalent-circuit diagram of an automobile exhaust silencer with accumulation chamber by Martin Kluge; Trendelenburg,* Fortschritte der physikalischen und technischen Akustik *1934 (cit. n. 73), 169.*

combustion engines. As an electrical engineer, Kluge used electric equivalent-circuit diagrams in his design of an acoustic filter (fig. 8).

Architectural acoustics and the sound insulation of buildings were other prominent areas for the representation of acoustic systems by equivalent-circuit diagrams, as we have seen in figure 1. Not only Reno Berg and Johan Holtsmark in Trondheim, but also Erwin Meyer, the head of the Department of Acoustics at the Heinrich Hertz Institut in Berlin, used equivalent-circuit diagrams in studying how sound traveled through a wall.[80] In the 1930s Meyer had become Germany's most recognized acoustician and gave lectures in the United States, the Soviet Union, and Great Britain. The five lectures that Meyer gave at the Institution of Electrical Engineers in London in autumn 1937 were subsequently published in 1939 under the title *Electro-acoustics*, one among several monographs on electroacoustics at the time.[81]

By 1939 acoustics in Germany had experienced several years of remilitarization of its research agenda. The Berlin Institut für Schwingungsforschung was stripped of its eponym *Heinrich Hertz*, as Hertz, having been of partly Jewish ancestry, was unacceptable to the new National Socialist rulers. Within a few years Germany was at war with Britain, the Soviet Union, and the United States. Meyer headed research in underwater acoustics for submarine warfare. Under the auspices of Project Alberich he worked to make German submarines invisible to sonar. On the other side of the Atlantic, Harvard University's Frederick Vinton Hunt developed efficient sonar systems, which were supposed to detect and ultimately sink these very submarines. We must believe that the application of electrical analogies and equivalent circuits aided both Meyer and Hunt in their endeavors.[82]

[80] Meyer, *Electro-acoustics* (London, 1939), 112.

[81] Ibid. See also Philippe Le Corbeiller, *Electro-acoustique* (Paris, 1934); Agostino Gemelli and Giuseppina Pastori, *L'analisi elettroacustica del linguaggio* (Milan, 1934).

[82] Hunt made explicit reference to the advances that electroacoustics made in the United States during the Second World War; Hunt, *Electroacoustics* (cit. n. 1), vi.

CONCLUSION

In the interwar period, the electroanalog understanding of acoustics and its technologies and methods, especially the use of equivalent-circuit diagrams, unfolded into a new language of sound. Equivalent-circuit diagrams started out as a method to describe and analyze purely electric systems, such as transformers, and were then extended to coupled systems that contained both electric and mechanical components, such as loudspeakers and microphones. Interestingly, many of the acoustic systems represented by equivalent-circuit diagrams in the 1930s did not contain any electric components in their material composition, as we have seen in the examples of sound traveling through a wall in a building, the human voice, and automobile sound silencers.

The widespread use and importance of analogies in science can be traced throughout history.[83] The heuristic functions of analogies are various and multilayered. Analogies can propagate a certain worldview by relating elements. They can also serve more practical and pragmatic goals, such as to conceptualize, analyze, and solve scientific and technical problems. Analogies can allow the transfer of thought patterns, language, and mathematical formalism, and can be used to build models and machinery. They can point toward the likenesses of phenomena and supply arguments for identifying two apparently different phenomena as being physically identical. This was the case in Maxwell's and Hertz's identification of light as an electromagnetic phenomenon. But instead of claiming physical identity, analogies can also point toward structural identity and aid the visual and functional understanding of systems and processes by transferring from the well understood to the novel and unknown.[84]

How, then, did the electrical representation of sound in the 1930s differ from the Maxwellian representation of electromagnetic phenomena through the mechanics of the ether in the late nineteenth century? Victorian physicists like Maxwell, FitzGerald, and Lodge imagined electromagnetic phenomena as mechanical machinery in order to understand and explain their mode of operation. Even though the mechanical models were not thought of as true representations of the ether, the ether was believed to be of a truly mechanical nature. To conceive of a mechanical model meant to have understood the phenomenon. Despite the efforts of Polhem and Reuleaux, there was no mechanical alphabet or grammar available similar to the equivalent-circuit diagram. Some of these models were built as functional devices for lecture demonstration. These demonstration devices were not only meant to show the fundamentally mechanical nature of electromagnetism; through their analogy with well-understood mechanics, they also taught abstract and unfamiliar electromagnetic phenomena to scientists and engineers. Then, with the decline of a mechanical worldview and the increasing familiarity of scientists and engineers with electrical technology, the need to explain the mechanism of electromagnetic phenomena decreased.

The use of electrical analogies and equivalent-circuit diagrams in acoustics in the twentieth century was, in contrast, driven not by worldviews but by more pragmatic and technical considerations. With the rapid decline of the electromagnetic world-

[83] See Klaus Hentschel, ed., *Analogien in Naturwissenschaften, Medizin und Technik* (Stuttgart, 2010).
[84] Ibid., 32–3.

view no one claimed physical identity or argued for a fundamentally electrical nature of sound. Physical acoustics continued to be understood essentially as a section of the motions of elastic bodies within the field of mechanics as introduced by Helmholtz and Rayleigh. Why did these electrical representations of acoustic systems still become so powerful and widespread in the interwar period?

The answer to this question can be given by three arguments. First, measurement technology in acoustics research had become increasingly electrical. Before the electrification of acoustic measurement, a trained ear and an understanding of the system of European classical music were required. After electrification, the acoustician was not supposed to trust his own ear but had to develop an understanding of the design, behavior, and manipulation of electric circuits and transducers. Even if the acoustic system that was analyzed was purely mechanical, like a wall construction or a sound silencer, electrical technology and electrical thinking were already present. Electrical engineers and scientists proficient in electrical measurement technology therefore dominated acoustics research even in fields like civil engineering and automobile mechanics.

Second, electric oscillations were well understood and structurally analogous to acoustic vibrations. Acoustic systems could therefore be translated into electric systems. With the concepts of the voltage-source equivalent and the current-source equivalent, circuit diagrams had become a powerful tool to conceptualize, analyze, and solve all kinds of complex oscillation problems, whether they were electrical, electromechanical, or purely mechanical. The language of equivalent-circuit diagrams was a language of signs and relations that offered a reduced representation in which extraneous information was eliminated. Dealing with electric systems had become common practice for a large community of scientists and engineers who shared the language of the circuit diagram.

Third, equivalent-circuit diagrams were useful for designing, analyzing, and improving technology. This could be electroacoustic technology; for example, a loudspeaker, a microphone, or an audio amplifier. But purely mechanical technology like a wall construction or an automobile sound silencer could also be successfully analyzed and improved with the help of equivalent-circuit diagrams. As a structuralist language they created a direct link between sound and the industrial design and production of technology.

The electroanalog understanding of sound persists today as one of the foundations of acoustics in textbooks and manuals, and as an inherent component of the conceptual toolbox of the acoustician. Of course, since the 1960s a new digital concept of sound has emerged with the arrival of compact discs, computer music, and MP3 players, which has taken over the analog sound we had gotten so used to from radio, vinyl discs, and cassette tapes. Another translation has taken place from the analog to the digital, where electric signals are converted into bits and stored in binary form. Through digitization, our way to conceptualize, manipulate, and experience sound has again changed significantly. Together with computer algorithms, the concept of *information* has entered our aural world as a novel but fundamental entity. Again, a new phraseology of acoustics has become automatic "and is found to clear the mind and assist reasoning."[85] What has persisted into the twenty-first century is the essentially cultural as well as technological nature of our approach to sound.

[85] Eccles, "New Acoustics" (cit. n. 16), 233.