Dead Rooms and Live Wires

Harvard, Hollywood, and the Deconstruction of Architectural Acoustics, 1900–1930

*By Emily Thompson**

ABSTRACT

In 1900 Wallace Sabine, a physicist at Harvard University, published a mathematical formula for calculating the reverberation time in a room, a measure of how quickly or slowly sound energy dies away in an enclosed space. In 1930 Carl Eyring, a physicist working in the Sound Motion Picture Studio at Bell Telephone Laboratories, revised Sabine's equation. This essay examines material changes in the practice of architectural acoustics in order to explain how and why Eyring was motivated to reformulate the Sabine equation. Sabine's equation was the product of experimentation in highly reverberant rooms. Eyring worked in a world increasingly constructed of sound-absorbing building materials—a world of acoustically "dead" rooms in which Sabine's original assumptions were no longer valid. Further, Eyring's world was filled with electroacoustic devices that had not existed in 1900. "Live" wires powered new tools for producing, measuring, and controlling sound, and the new electroacoustic technologies additionally provided a new conceptual framework for thinking about the behavior of sound. Eyring's equation is shown to be a direct product of these new material conditions of the science and practice of architectural acoustics.

IN 1900 WALLACE SABINE (see Frontispiece), a physicist at Harvard University, published a mathematical formula for calculating the reverberation time of a room, a measure of how quickly or slowly sound energy dies away in an enclosed space. Thirty years later Carl Eyring (Figure 1), a physicist working in the Sound Motion Picture Studio at Bell Telephone Laboratories, modified Sabine's formula. Eyring's revision was essentially the replacement of a numeric value for the sound-absorbing power of a room, α_a, with a logarithmic function of that value:[1]

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[1] The derivation of each equation will be described a bit more fully in the essay that follows; for now, a simple comparison of form is the object.

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Wallace Clement Sabine in 1898, just a few months before he developed his reverberation equation. (From William Dana Orcutt, Wallace Clement Sabine: A Study in Achievement *[Norwood, Mass.: Plimpton, 1933], facing page 86.)*

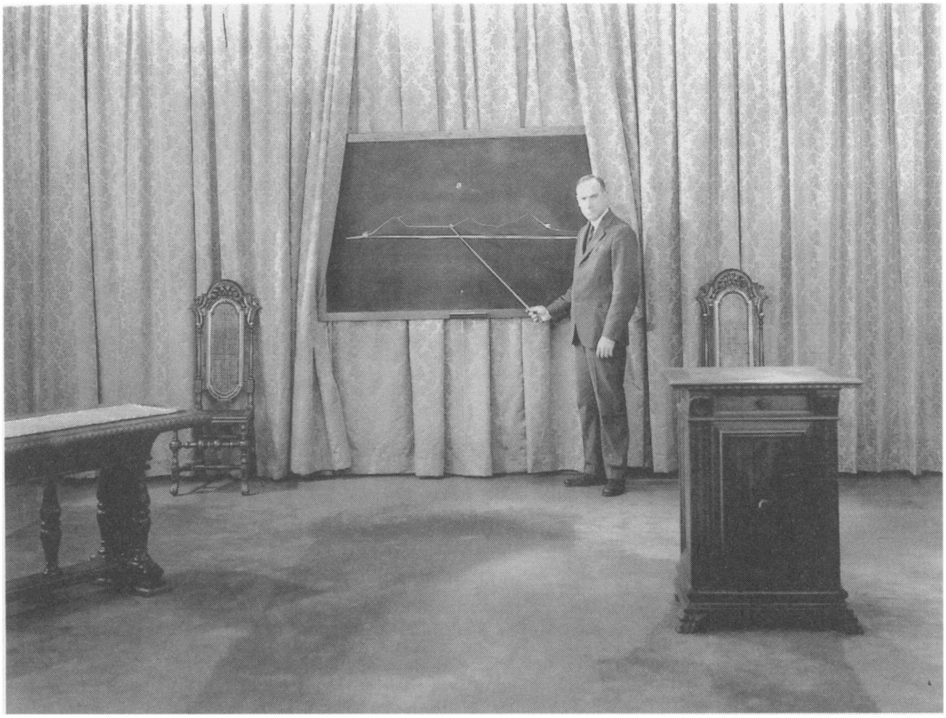

Figure 1. *Carl Eyring in the Sound Motion Picture Studio of Bell Telephone Laboratories in New York, circa 1930, at the time that he revised Sabine's reverberation equation. (Property of AT&T Archives. Reprinted with permission of AT&T.)*

SABINE	EYRING
$T = \frac{.164\ V}{S\alpha_a}$	$T = \frac{.164\ V}{-S \ln (1 - \alpha_a)}.$

Eyring's modification could be described as a logical mathematical development of Sabine's equation, a development that expanded its applicability beyond certain limitations imposed by its initial form. Indeed, Eyring himself presented it as such. One might further point out that Eyring benefited from the use of measuring tools more precise and accurate than those employed by Sabine. These tools measured data that called into question the sufficiency of Sabine's equation and stimulated its reformulation. Such an account would be entirely true, but it would not provide a historically accurate explanation of what really happened. To understand how and why Sabine's equation was transformed into Eyring's equation, one must turn away from the internal logic of the mathematics and look beyond the precision and accuracy of the tools of measurement. In fact, it is best if one not *look* at all but, instead, *listen* to the two men at work.

Carl Eyring's world sounded very different from Wallace Sabine's world. In the thirty years following Sabine's work, architectural spaces were increasingly constructed of new kinds of building materials—sound-absorbing materials with names like Akoustolith, Acousti-Celotex, and Silent-Ceal. These acoustically "dead" rooms possessed reverberation times dramatically lower than those measured in traditional spaces built of stone, wood, glass, and plaster. Additionally, between 1900 and 1930 scientists and engineers increasingly employed electroacoustic devices in their studies of sound. "Live" wires powered vacuum-tube amplifiers, condenser microphones, and dynamic loudspeakers. These tools provided new ways of measuring sound; more significantly, they also provided new means for producing it, controlling it, and even thinking about it. These material changes—the utilization of live wires in increasingly dead rooms—stimulated investigators to generate new ideas about what constituted good sound and how one should obtain it. They also fostered fundamentally new conceptualizations of the behavior of sound in rooms.

Wallace Sabine's understanding of the phenomenon of reverberation was rooted in the material nature of the physical environment in which he worked. He characterized reverberation as the decay of a body of sound energy contained in architectural space; the decay was the result of energy being absorbed by the material surfaces that bounded the space. The physical architecture in his architectural acoustics was very real and ever present.

For Carl Eyring, the physical reality of architectural construction was far less significant. Eyring worked in a world where new material technologies had transformed rooms into acoustical "black boxes," neutral spaces that seemingly left no mark on the sounds produced within them. Electroacoustic devices, not walls or floors, were employed to create an illusory sensation of space. Eyring thus conceived of reverberation not as the result of interactions between sound energy and architectural construction but, instead, as the output of imaginary, unbounded arrays of "image sources" of sound. The physical room became conceptually irrelevant as Eyring deconstructed—in the literal, not the literary sense—the architecture of architectural acoustics to create what we today might call a "virtual" acoustical environment. As will be shown, Eyring's reverberation equation embodies this new way of thinking about reverberation, a way of thinking that—as for Sabine—is the product of the material environment in which he worked.

Carl Eyring's reformulation of Wallace Sabine's reverberation equation can only be understood in light of these material changes in the science and practice of architectural acoustics. Indeed, the material provides the historical explanation. In this way, the following account has been inspired by, and attempts to build upon, other scholars' examinations of the role of materials in the generation of scientific knowledge.[2] Additionally, by focusing

[2] Published scholarship on the role of materials in the generation of scientific knowledge and the execution of scientific work is best developed for the biological sciences. See the special section on "The Right Organism for the Job" in *Journal of the History of Biology,* 1993, *26,* esp. the articles by Robert Kohler ("*Drosophila:* A Life in the Laboratory," pp. 281–310), Frederic L. Holmes ("The Old Martyr of Science: The Frog in Experimental Physiology," pp. 311–328), and Bonnie Tocher Clause ("The Wistar Rat as a Right Choice: Establishing Mammalian Standards and the Ideal of a Standardized Mammal," pp. 329–350) on, respectively, flies, frogs, and rats. See also Kohler, *Lords of the Fly;* Drosophila *Genetics and the Experimental Life* (Chicago: Univ. Chicago Press, 1994); and Adele Clarke and Joan Fujimura; eds., *The Right Tools for the Job: At Work in Twentieth-Century Life Sciences* (Princeton, N.J.: Princeton Univ. Press, 1992). See also papers by participants in the 1993/1994 Princeton University Workshop in the History of Science on "Materials in Science," esp. Angela Creager, "From Transfusion Therapeutics to 'Pure' Molecules: World War II and the Growth of Human Blood Research"; Karen Rader, "Of Mice, Medicine, and Genetics: C. C. Little's Creation and Standardization of the Laboratory Mouse for Research"; and Maria Trumpler, "Of Muscles and Metals: Changing Sites of Galvanic Action, 1791–1810."

For the role of materials in the generation of knowledge about the physical world see Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: Univ. Chicago Press, 1997); and Princeton Workshop papers by Kostas Gavroglu, "From Defiant Youth to Conformist Adulthood: The Sad Story of Liquid Helium"; Bruce Hunt, "Insulation for an Empire: Gutta-Percha and the Development of Electrical Measurement in Victorian Britain"; and David Hounshell, "The Dialectics of Materials."

The electroacoustic "materials" discussed in this article might appropriately be classified as "instruments," and so the rich and extensive literature on the role of instruments in the generation of scientific knowledge is also relevant. Works particularly influential for this study include the articles in Timothy Lenoir and Yehuda on *architectural* materials and science, this essay builds upon the rich and growing body of literature dedicated to the role of space and place in the history of science.

In 1986 Owen Hannaway and Sophie Forgan published groundbreaking articles that initiated many historians of science into the pleasures and rewards of inquiry into the architectural structures in which scientific activity is carried out. Since then, numerous scholars have focused their attention on the spatial location of science, to address the question of how "the conditions of our knowledge vary according to our placement in social and physical space."[3] To date, however, interest in the social aspect of space has outweighed interest in its more physical nature.[4] Walls and doors have been examined, not so much for their structural materiality, but for their capacity to sequester and divide groups of people, to distinguish private space from public space, to define who gets to do science, and to represent a particular image of science to those within and without. In these accounts, architecture is typically dealt with on the level of form—of plan or layout—with little attention to its material constitution.[5]

This essay will complement the existing literature by demonstrating that the *materiality* of architecture is equally significant for understanding scientific thought and practice. It exemplifies an approach that is relatively recent, but already vital, in the literature of the history of science.[6] When architecture is considered as both form and material, a construction both social and physical, our opportunities to learn from it increase immeasurably.

Elkana, eds., *Practice, Context, and the Dialogue between Theory and Experiment, Science in Context,* 1988, *2,* esp. M. Norton Wise, "Mediating Machines," pp. 77–113; Lenoir, "Models and Instruments in the Development of Electrophysiology, 1845–1912," *Historical Studies in the Physical and Biological Sciences,* 1986, *17:*1–54; Galison, *How Experiments End* (Chicago: Univ. Chicago Press, 1987); and the essays in Albert Van Helden and Thomas Hankins, eds., *Instruments, Osiris,* 2nd Ser., 1994, *9,* esp. Lenoir, "Helmholtz and the Materialities of Communication," pp. 185–207. Lenoir's account of how Helmholtz's experience working with telegraphic technologies influenced the development of his theories of vision and sound resonates particularly strongly with my own examination of the role of electroacoustic technologies in the development of Carl Eyring's theory of reverberation.

[3] Owen Hannaway, "Laboratory Design and the Aim of Science: Andreas Libavius versus Tycho Brahe," *Isis,* 1986, *77:*585–610; Sophie Forgan, "Context, Image, and Function: A Preliminary Enquiry into the Architecture of Scientific Societies," *British Journal for the History of Science,* 1986, *19:*89–113; and Adi Ophir and Steven Shapin, "The Place of Knowledge: A Methodological Survey," *Sci. Context,* 1991, *4:*3–21, on p. 9.

[4] See, e.g., Steven Shapin, "The House of Experiment in Seventeenth-Century England," *Isis,* 1988, *79:* 373–404; Sophie Forgan, "The Architecture of Science and the Idea of a University," *Studies in History and Philosophy of Science,* 1989, *20:*405–434; Adi Ophir, Steven Shapin, and Simon Schaffer, eds., *The Place of Knowledge: The Spatial Setting and Its Relation to the Production of Knowledge, Sci. Context,* 1991, *4;* Jole Shackelford, "Tycho Brahe, Laboratory Design, and the Aim of Science: Reading Plans in Context," *Isis,* 1993, *84:*211–230; and Anne Secord, "Science in the Pub: Artisan Botanists in Early Nineteenth-Century Lancashire," *History of Science,* 1994, *32:*269–315.

[5] Exceptions to this generalization are Shackelford's discussion of the windows and light in Tycho Brahe's laboratory in "Tycho Brahe," pp. 213–220; and Michael Lynch, "Laboratory Space and the Technological Complex: An Investigation of Topical Contextures," *Sci. Context,* 1991, *4:*51–78. For an example of an analysis in which the materiality of doors is just as significant as their social function see Jim Johnson (a.k.a. Bruno Latour), "Mixing Humans and Nonhumans Together: The Sociology of a Door-Closer," *Social Problems,* 1988, *35:*298–310.

[6] The collection of essays by scientists, architects, historians of science, and historians of architecture in Peter Galison and Emily Thompson, eds., *The Architecture of Science* (Cambridge, Mass.: MIT Press, forthcoming), emphasizes the material, as well as the social, aspect of architecture. See also John Heilbron, "Science in the Church," *Sci. Context,* 1989, *3:*9–28; and Heilbron, "Churches as Scientific Instruments," *Bulletin of the Scientific Instrument Society,* 1996, *48:*4–9.

WALLACE SABINE AND REVERBERATION CIRCA 1900

Wallace Sabine was a young assistant professor of physics at Harvard University in 1895, when he was asked to solve a difficult problem by the university's president, Charles Eliot.[7] The problem was an excessively reverberant lecture room in Harvard's new Fogg Art Museum. Eliot suggested that Sabine develop some quantitative measure of acoustical quality, compare the faulty lecture room to the university's acoustically superb Sanders Theater, and then modify the lecture room to render it suitable for its intended purpose. Sabine spent the next several years attempting to do that and more, as he sought to discover a fundamental physical law that would explain the behavior of sound in rooms.

The subject of architectural acoustics was notoriously devoid of scientific treatment in 1895. Treatises on the topic had appeared sporadically over the previous century, but these works—written primarily by architects—seldom offered more than random and often conflicting suggestions drawn from the inspection of acoustically successful and unsuccessful structures or from rudimentary geometrical analyses of the propagation of "rays" of sound through space.[8] In 1803, the architect Benjamin Latrobe had sought scientific advice on acoustical design, and he concluded that "science . . . has made very little progress on this subject." Amost a century later, Sabine surveyed the literature and came to the same conclusion.[9]

As a late nineteenth-century physicist who conceptualized the physical world in energetic terms,[10] Sabine defined the phenomenon of interest to be the absorption of sound energy by the materials constituting the room. He developed a technique for measuring

[7] Sabine was born in 1868 in Richwood, Ohio. He graduated from Ohio State University in 1886 and moved to Cambridge with his mother and sister to undertake graduate studies in physics at Harvard. He received his M.A. in 1888 and two years later was appointed instructor in physics at the university. In 1895 he was promoted to assistant professor, even though he never underwent examination for his Ph.D. For more on Sabine's life see William Dana Orcutt, *Wallace Clement Sabine: A Study in Achievement* (Norwood, Mass.: Plimpton, 1933); Emily Thompson, " 'Mysteries of the Acoustic' ": Architectural Acoustics in America, 1800–1932" (Ph.D. diss., Princeton Univ., 1992); and Thompson, *Sound, Space, Technology, Modernity: Architectural Acoustics in America, 1800–1932* (in preparation). See also Edwin H. Hall, "Wallace Clement Ware Sabine, 1868–1919," *Biographical Memoirs of the National Academy of Science,* 1926, *11:*1–19.

[8] See, e.g., Count Francesco Algarotti, *An Essay on the Opera* (London: Davis & Reymers, 1767); Pierre Patte, *Essai sur l'architecture théâtrale* (Paris: Chez Moutard, 1782); George Saunders, *A Treatise on Theatres* (London: Taylor, 1790); Benjamin Dean Wyatt, *Observations on the Principles of a Design for a Theatre* (London: Lowndes & Hobbs, 1811); Théodore Lachèz, *Acoustique et optique des salles de réunions publiques* (Paris: Chez l'Auteur, 1848), and second, expanded ed. (Paris: Chez l'Auteur Éditeur, 1879); T. Roger Smith, *A Rudimentary Treatise on the Acoustics of Public Buildings* (London: John Weale, 1861), and later editions of ca. 1878 and 1895; and Charles Garnier, *Le théâtre* (Paris: Hachette, 1871). While Joseph Henry carried out a useful investigation on the formation of echos in rooms in 1856, Sabine does not appear to have been aware of his work. See Joseph Henry, "On Acoustics Applied to Public Buildings," *Smithsonian Institution Report,* 1856, pp. 221–234. These texts and others are discussed more fully in Thompson, " 'Mysteries of the Acoustic,' " Ch. 1.

[9] Benjamin Latrobe to Thomas Parker, ca. 1803, "Remarks on the Best Form of a Room for Hearing and Speaking," in *The Correspondence and Miscellaneous Papers of Benjamin Henry Latrobe,* ed. John C. Van Horne and Lee W. Formwalt, Vol. 1: *1784–1804* (New Haven, Conn.: Yale Univ. Press, 1984), pp. 400–408, on p. 401. "No one can appreciate the condition of architectural acoustics—the science of sound as applied to buildings—who has not with a pressing case in hand sought through the scattered literature for some safe guidance." Sabine went on to lament the "meagerness and inconsistency of the current suggestions." Wallace Sabine, "Reverberation," in *Collected Papers on Acoustics* (Cambridge, Mass.: Harvard Univ. Press, 1922), pp. 3–68, on p. 3.

[10] As a graduate student, Sabine collaborated with Professor John Trowbridge on studies in the optical properties of metals and in electricity. The focus was always upon transformations of energy in wave phenomena. See, e.g., John Trowbridge and W. C. Sabine, "Selective Absorption of Metals for Ultra Violet Light," *Proceedings of the American Academy of Arts and Sciences,* 1888, *23:*299–300; and Trowbridge and Sabine, "Electrical Oscillations in Air," *ibid.,* 1890, *25:*109–123.

the reverberation times of rooms, and he studied the effect of different materials upon this measure. His technique utilized an organ pipe with a pitch of 512 cycles per second (cps), which was sounded with an electrically controlled tank of compressed air. He sounded the pipe until a steady state was achieved—that is, until the sound in the room ceased to grow louder. He then shut off the air supply to the pipe and listened to the residual sound, or reverberation, until it was no longer audible. At that moment of inaudibility, Sabine pressed an electric switch whose current registered a mark on a chronographic record. The earlier cessation of the source had similarly been marked; thus the interval, or reverberation time, was recorded on the graph and could be read to within one hundredth of a second.

Sabine would take a measure of the reverberation time in a room, then bring into that room a number of sound-absorbing seat cushions borrowed from the Sanders Theater. He would then measure the new reverberation time resulting from the presence of the cushions. Sabine introduced hundreds of cushions, a few at a time, into numerous rooms throughout the university. He then experimented with other materials and determined their sound-absorbing powers, which he expressed in terms of his unit of absorption, the Sanders Theater seat cushion. This method, however, failed to elicit the underlying mathematical relationship that Sabine sought. For over two years Sabine meticulously collected data without knowing just what to do with it. By 1897 President Eliot had run out of patience, and when Sabine asked for several more years of research time he responded: "You have made sufficient progress to be able to prescribe for the Fogg Lecture Room, and you are going to make that prescription."[11] Thus forced, Sabine had panels of sound-absorbing hair-felt attached to certain wall surfaces in the lecture room, which rendered the auditorium finally usable, albeit hardly the acoustical equivalent of the Sanders Theater.

Had Sabine's investigation ended with the improvement of the Fogg lecture room, there would have been no mathematical formula for calculating reverberation time and he would have failed to reach his goal of finding a quantitative law that explained the phenomenon.[12] Fortunately, the investigation was resumed when President Eliot approached Sabine once more, this time to pass along the query of his friend Henry Higginson, a local financier, philanthropist, and owner of the Boston Symphony Orchestra. Higginson was planning to build a new music hall for his orchestra, and he sought scientific advice on acoustical design. As Higginson had explained to his architect, Charles McKim of McKim, Mead, and White, he wanted a hall that would do justice to the full dynamic range of the great Romantic composers, particularly his favorite, Ludwig van Beethoven: "Our present hall gives a piano better than a forte, gives an elegant rather than a forcible return of the instruments—noble but weak—I *want* both." Sabine, knowing the limitations of his research, was initially reluctant to undertake the new assignment. According to his biogra-

[11] Charles Eliot to Wallace Sabine, 3 Nov. 1897, quoted in Orcutt, *Wallace Clement Sabine* (cit. n. 7), p. 125. Sabine carried out most of his experiments in the middle of the night, so that background noise would not interfere with his close and careful listening. He once threw out over three thousand measurements, representing several months' work, after he determined that the clothing worn by the observer (himself) had a small but measurable effect upon the outcome of the experiment. Subsequently, he always wore the same outfit ("blue winter coat and vest, winter trousers, thin underwear, high shoes") when experimenting. See Wallace Sabine, "Architectural Acoustics," *American Architect and Building News,* 26 Nov. 1898, *62:*71–73, on p. 72; and Papers of Wallace Clement Sabine, Research Notebooks, Data on Acoustical Research, 1899–1919, Research Notebook #7, p. 57 [HUG 1761.25], courtesy of the Harvard University Archives, Cambridge, Massachusetts. Sabine emphasized the importance of experimental precision and accuracy in his book *A Student's Manual of a Laboratory Course in Physical Measurement* (Boston: Ginn, 1893).

[12] The qualitative state of Sabine's understanding of reverberation at the time that he finished his work on the Fogg lecture room is evident in Sabine, "Architectural Acoustics." This article constitutes the text of a talk he presented on 2 Nov. 1898 at a meeting of the American Institute of Architects.

pher, however, he went home that evening and "devoted himself feverishly to a perusal of his notes, representing the labors of the preceding three years. Then, suddenly, at a moment when his mother was watching him anxiously, he turned to her, his face lighted with gratified satisfaction, and announced quietly, 'I have found it at last!' "[13]

What Sabine found was that when he plotted the quantity of Sanders Theater seat cushions (x) versus the corresponding reverberation time for a room (y), the resulting graph was a rectangular hyperbola, a standard mathematical curve characterized by the equation $xy = k$, where k is a constant. Sabine realized that his discovery of the hyperbolic relationship was a breakthrough for his understanding of reverberation. Now eager to assume responsibility for the acoustics of Higginson's new music hall, he immediately wrote to Eliot:

> When you spoke to me on Friday in regard to a Music Hall I met the suggestion with a hesitancy the impression of which I now desire to correct. At this time, I was floundering in a confusion of observations and results which last night resolved themselves in the clearest manner. You may be interested to know that the curve, in which the duration of the residual sound is plotted against the absorbing material, is a rectangular hyperbola with displaced origin; that the displacement of the origin is the absorbing power of the walls of the room; and that the parameter of the hyperbola is very nearly a linear function of the volume of the room. This opens up a wide field.[14]

Sabine's development of this "wide field" resulted, by 1900, in a comprehensive and quantitative analysis of reverberation. His inquiry was based upon the assumption that the sound energy in a room can be characterized as a homogeneous field, distributed uniformly throughout space, gradually and uniformly being absorbed by the surfaces to which it is exposed. This assumption was derived from the experience that Sabine had accumulated working in the various rooms whose qualities he studied (see Table 1). In rooms constructed of materials like plaster, glass, and pine paneling, Sabine found that the sound energy was reflected off the various surfaces several hundreds of times as it was gradually absorbed. The long reverberation times of the rooms in which he worked (see Table 2) thus launched the analysis that ultimately led to his hyperbolic formulation.[15]

The highly reverberant nature of Sabine's material environment not only launched his analysis but was also embodied in the mathematical detail and development of that anal-

[13] Henry Lee Higginson to Charles McKim, 27 Nov. 1892, Papers of McKim, Mead, and White, Folder M-10: Boston Music Hall, New-York Historical Society, New York; and Orcutt, *Wallace Clement Sabine* (cit. n. 7), p. 133.

[14] Harvard University, Presidents Office, Records of President Charles W. Eliot, 1849–1926, Wallace Clement Sabine to Eliot [October 30, 1898], in Folder 329: Wallace C. Sabine [UAI5.150], courtesy of Harvard University Archives. Sabine had plotted his data before (see Sabine, "Architectural Acoustics" [cit. n. 11], p. 72), but this time, by extrapolating the curve beyond the points representing data that he had collected, he was able to see his experimentally derived fragment as part of a larger picture, a hyperbola. It seems that, while in the midst of experimentation, Sabine was so preoccupied with the accuracy and precision of each individual data point that he was unable to "see the forest for the trees." Only when Eliot forced him to stop gathering data was he able to perceive its larger pattern.

[15] The full mathematical development of Sabine's hyperbolic formulation is presented in Wallace Sabine, "Reverberation," *Amer. Architect Build. News,* Apr.–June 1900, *68:*3, 19, 35, 43, 59, 75, 83. The article appeared in monthly installments, and the series was additionally carried in the *Engineering Record,* 1900, *1:*349, 376, 400, 426, 450, 477, 503. Hereafter, references to "Reverberation" will use the page numbers of the article as it appeared in Sabine, *Collected Papers on Acoustics* (cit. n. 9). For reference to the hundreds of reflections of sound energy see *ibid.,* p. 39. One room with a notably shorter reverberation time (the dining room in Harvard's Memorial Hall) was investigated, but "there was no opportunity to carry the experiment farther than to observe the fact that the duration was surprisingly short, for the frightened appearance of the women from the sleeping-rooms at the top of the hall put an end to the experiment": *ibid.,* p. 42.

Table 1. Reverberation Times in Rooms

Room and Materials	Reverberation Time at 512 cps
Faculty room, University Hall Plaster on wood lath, wood dado	7.04 sec
Lecture room, Fogg Art Museum Plaster on tile walls, plaster on wire lath ceiling	5.61 sec
Lecture room, Jefferson Physical Laboratory Brick walls, plaster on wood lath ceiling	3.91 sec
Sanders Theater Plaster on wood lath, hardwood sheathing	3.42 sec
Large laboratories, Jefferson Physical Laboratory Brick walls, plaster on wood lath ceiling	3.40 sec
Dean's room, University Hall Plaster on wood lath, wood dado	3.38 sec
Committee room, University Hall Plaster on wood lath, wood dado	2.82 sec
Office, Botanic Gardens Hard pine walls, ceiling, and floor	1.91 sec
Sound stage, Bell Telephone Laboratories	0.32 sec

NOTE.—Reverberation times for rooms at Harvard in which Wallace Sabine experimented and for the sound stage at Bell Telephone Laboratories where Carl Eyring worked.

SOURCES.—Wallace Sabine, "Reverberation," in *Collected Papers on Acoustics* (Cambridge, Mass.: Harvard Univ. Press, 1922), pp. 28–31; and Carl Eyring, "Reverberation Times in 'Dead' Rooms," *Journal of the Acoustical Society of America,* 1930, *1*:217–241, on p. 239 (Figure 13). The Eyring value is the average of two measurements: one of the sound stage with drapes spread out, and one with drapes gathered together.

Table 2. Absorption Coefficients for Wall Surfaces

Surface Material	Absorption Coefficient
Wood sheathing (hard pine)	.061
Plaster on wood lath	.034
Plaster on wire lath	.033
Glass, single thickness	.027
Plaster on tile	.025
Brick set in Portland cement	.025
Sound stage insulating material (@500 cps)	.77

NOTE.—Absorption coefficients of the surfaces with which Wallace Sabine experimented (measured at 512 cps) and of the surface in the sound stage at Bell Telephone Laboratories where Carl Eyring worked. A coefficient of 1.00 represents 100 percent absorption of sound energy.

SOURCES.—Wallace Sabine, "Reverberation," in *Collected Papers on Acoustics* (Cambridge, Mass.: Harvard Univ. Press, 1922), p. 56; and Carl Eyring, "Reverberation Time in 'Dead' Rooms," *Journal of the Acoustical Society of America,* 1930, *1*:217–241, on p. 238 (Table 1).

ysis. For example, he constructed an infinite series to represent the total sound energy in a room, with each element of the series representing the energy of sound emitted from a source that has suffered a certain number of reflections off the surfaces of the room:

$$\text{Energy} = \frac{p\,E}{V}\,[1 + (1 - a/s) + (1 - a/s)^2 + \ldots + (1 - a/s)^n],$$

where

p = mean free path of sound between reflections,

E = rate of emission of energy from the sound source,
a = absorbing power of the room,
s = surface area of the room,
V = volume of the room, and
n = number of reflections suffered.

General rules applying to series of this form allowed Sabine to write the series in the condensed form

$$\text{Energy} = \frac{p\,E}{V}\,\frac{1 - (1 - a/s)^n}{1 - (1 - a/s)}.$$

Sabine next assumed that n was large, that is, that the room was highly reflective and that many reflections would be suffered by the sound before an individual contribution of energy would become negligible. The assumption that n was large allowed him further to simplify the series to

$$\text{Energy} = \frac{p\,E\,s}{V\,a}.$$

Sabine used this quantity to represent the energy as he continued his analysis. In this way, the "liveness" of the room was embedded in his equations.

Sabine's analysis ultimately enabled him to determine numerical values for the sound-absorbing capacities of different materials. He determined these capacities, or "absorption coefficients," for a number of common building materials such as plaster, wood, and glass and also for common objects that might be introduced into a room, such as furniture, curtains, and audience. The coefficients, initially defined in terms of his "Sanders Theater seat cushion" unit of absorption, were ultimately expressed in terms of a unit of energy absorption equivalent to that provided by one square meter of open window. A coefficient of 1.00 represented the total absorption of sound, as if all the energy had escaped through an open window. As Table 2 indicates, for the kinds of surfaces with which Sabine experimented, only a small fraction of sound energy was absorbed at each reflection.

The end result of Sabine's investigation was the equation

$$T = \frac{.164\,V}{S\,\alpha_a},$$

where

T = reverberation time (seconds),
.164 = hyperbolic constant,
V = volume of the room (cubic meters),
S = surface area of the room (square meters), and
α_a = average coefficient of absorption for the room;
$= \sum \frac{S_n \alpha_n}{S}$,

where
S_n = surface area of material n and
α_n = absorption coefficient for material n.

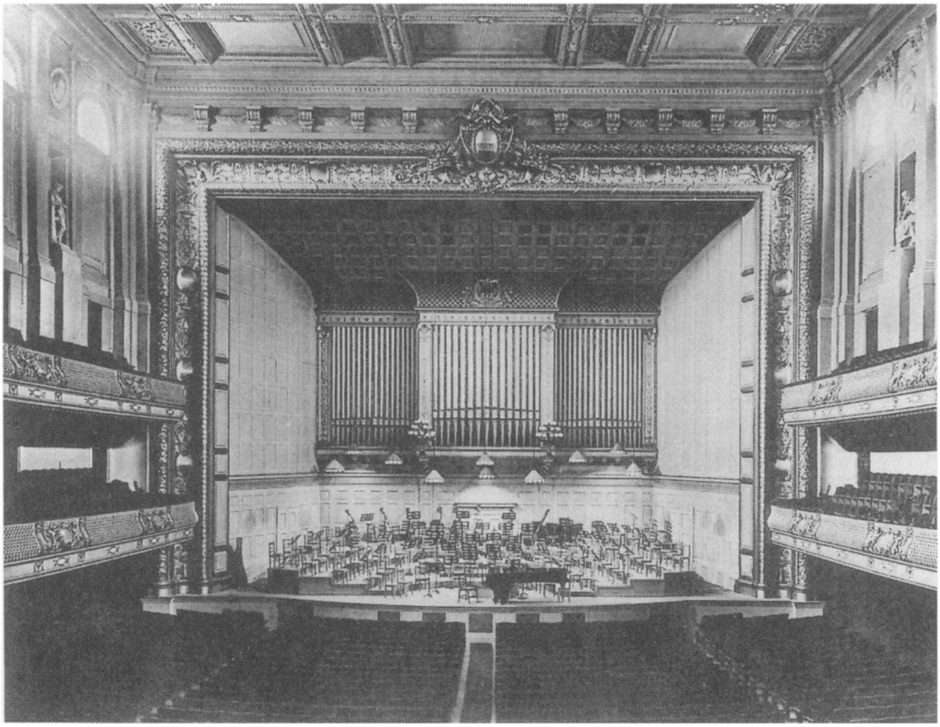

Figure 2. *Symphony Hall, Boston. McKim, Mead, and White, architects; Wallace Sabine, acoustical consultant. The hall opened in 1900, and this photograph was taken around 1915. The shield at the top and center of the proscenium is inscribed "Beethoven." (From* A Monograph of the Work of McKim, Mead & White, 1879–1915 *[New York: Architectural Book Publishing Company, 1915–1920], Plate 141.)*

This equation enabled Sabine to calculate the reverberation time of a room not yet built. Utilizing data taken from an architect's plans (V, S, S_n) and absorption coefficients determined from his experiments (α_n), he could predict the value for T, which is exactly what he did with Charles McKim's design for Higginson's new music hall. When the calculation indicated that the reverberation time of the hall would be considerably greater than was considered optimal, Sabine suggested (and McKim instituted) various design changes that ensured a result in line with Higginson's desires.[16]

Symphony Hall opened in the fall of 1900, and it soon enjoyed a worldwide reputation as an excellent hall in which to hear music.[17] (See Figure 2.) Over the next two decades, Sabine consulted on a wide variety of architectural projects with many of the most promi-

[16] Higginson wanted the reverberation time of his new music hall to duplicate that of the Neues Leipzig Gewandhaus, whose sound he greatly admired. Sabine calculated, from published plans of the Gewandhaus, that its reverberation time was 2.30 sec. When Sabine's equation was applied to McKim's initial design, the formula indicated that its reverberation time would be significantly greater than that of the Gewandhaus. Sabine suggested decreasing the volume of the proposed hall to decrease its reverberation time. McKim did so and, in order to maintain the original seating capacity, added a second balcony. The calculated reverberation time for the revised plan was 2.31 sec. Sabine contributed in numerous other ways to the design of the hall; for more see Thompson, " 'Mysteries of the Acoustic' " (cit. n. 7), Ch. 2.

[17] Some criticism was initially expressed, but within a year or so a consensus had formed around the quality of Symphony Hall's acoustics. For more on the reception of Symphony Hall see *ibid.*

nent architects of the day, and he enjoyed an international reputation as the world's foremost expert on acoustical design.[18] Scientists, too, learned of his work and began to expand upon it. These scientists first tested and confirmed the validity of Sabine's reverberation formula.[19]

With the benefit of hindsight, the historian may choose to test the performance of Sabine's reverberation formula in two extreme cases. First, for the case of a completely reverberant room, with no absorption whatsoever ($\alpha_a = 0$), the equation confirms the intuition that such a room would possess an infinitely long reverberation time; the sound would never die away. The equation fails, however, to confirm the opposite limiting case, that of a completely absorptive room ($\alpha_a = 1$). In this case, the equation does not produce the expected reverberation time of zero; in fact, the reverberation time becomes a function of the shape of the room, as represented by the ratio of volume to surface area.

Neither Sabine nor his early followers ever commented upon this apparent failure of the equation. For them, there simply was no failure to comment upon. No room of acoustical interest circa 1900 came close to being totally absorptive; thus the equation completely and accurately described the material world in which they worked.[20] The simplicity and predictive power of Sabine's reverberation equation, however, subsequently stimulated a transformation of that material world—a transformation that would ultimately, and ironically, assign new limitations to the equation.[21]

1900–1930: ACOUSTICAL MATERIALS AND ARCHITECTURAL ACOUSTICS

Just as important as the formula that he derived was Sabine's pioneering role as a developer of new, special purpose acoustical building materials. In 1911 the architect Ralph Adams Cram introduced Sabine to a ceramic-tile craftsman named Raphael Guastavino. Guastavino's tiles were used extensively in the construction of vaults and domes for large structures such as churches, synagogues, and banks, and Guastavino was eager to offer a new product that would reduce the reverberation of the spaces his tiles enclosed. Sabine was equally eager to develop a sound-absorbing material that, unlike the hair-felt he had em-

[18] In 1916, Sabine traveled to Europe to lecture on architectural acoustics at the Sorbonne in Paris. While abroad, he became deeply involved in the Allied war effort in a variety of civilian capacities. He also suffered a kidney infection from which he never fully recovered. His war work increased—and increasingly taxed his health—throughout 1917, and he died in Cambridge, Massachusetts, on 10 Jan. 1918. For more on Sabine's war experiences see Orcutt, *Wallace Clement Sabine* (cit. n. 7), Chs. 12–15.

[19] An entirely theoretical derivation of the equation was presented in W. S. Franklin, "Derivation of Equation of Decaying Sound in a Room and Definition of Open Window Equivalent of Absorbing Power," *Physical Review,* June 1903, *16:*372–374. G. W. Stewart tested Sabine's experimental technique as well as the validity of his equation in the auditorium at Cornell University, as described in Stewart, "Architectural Acoustics: Some Experiments in the Sibley Auditorium," *Sibley Journal of Engineering,* May 1903, *17:*295–313.

[20] Ann Johnson has pointed out to me that small domestic spaces—for example, the well-upholstered and heavily draped parlors of late Victorian America—constituted a material environment that might have identified a shortcoming in Sabine's formula. This kind of room, however, was seldom if ever the focus of acoustical interest. Sabine (and those who followed) applied his equation almost exclusively to the design or alteration of large public spaces such as auditoriums, churches, and legislative assembly halls.

[21] The ironic turn of the story that follows, in which the reverberation formula brings about the means of its own "destruction," nicely demonstrates David Hounshell's "dialectic" model for the history of materials. In considering the history of natural and synthetic textile fibers, Hounshell writes: "I seek to demonstrate how simply trying to understand the structure and behavior of natural fibers led to the production of new scientific knowledge and how, in a marvelously dialectical manner, the production of new knowledge led to both improved natural fibers and, eventually, synthetic fibers." Hounshell, "Dialectics of Materials" (cit. n. 2), p. 5.

ployed in the Fogg lecture room, was "structural in character."[22] The result of their collaboration, Rumford tile, was a porous ceramic tile that absorbed 26 percent of incident sound energy, far beyond the 5 percent absorption of ordinary Guastavino tiles.[23] Rumford was used in a number of Guastavino projects, including Cram, Goodhue, and Ferguson's St. Thomas's Church in New York. Much more widely employed was Rumford's successor, Akoustolith. An aggregate of pumice particles loosely bonded with cement, Akoustolith tiles provided even greater absorption, as high as 60 percent. In 1933 Guastavino indicated that there were hundreds of installations of Akoustolith, including the National Academy of Sciences building in Washington, D.C., the Princeton and Duke university chapels, and the Nebraska State Capitol.[24]

Rumford and Akoustolith profoundly affected the sound of the spaces that they enclosed. The reverberation times in Akoustolith-lined chapels, for example, were seconds less than those in traditionally constructed structures. Rumford and Akoustolith, moreover, were only the first of an ever-increasing number of new architectural materials specially developed to absorb sound and reduce reverberation.

In 1911 American builders spent $50,000 on acoustical materials; twenty years later just one of the larger producers had sales of over $2 million.[25] By the 1920s, architects could choose from an almost endless variety of acoustical products to constitute interior surfaces. There were felted linings, insulating papers, rigid wallboards, plasters, ceiling tiles, isolating partitions, and floor cushions, all made of everything from seaweed to mineral wool,

[22] Papers of Wallace Clement Sabine, 1899–1919, Correspondence, Sabine to Albert Kahn (June 27, 1911) [HUG 1761.xx], courtesy of Harvard University Archives. The Pusey Library at Harvard holds photocopies of the Sabine correspondence; the originals are located at the Riverbank Acoustical Laboratories, Illinois Institute of Technology Research Institute, Geneva, Illinois.

[23] No explanation of the name "Rumford" has been found, but it is possible that Sabine named the new material in honor of Count Rumford, who, in 1815, had bequeathed to Harvard funds for the promotion of the "Application of Science to the Useful Arts." Although Sabine served as dean of Harvard's Graduate School of Applied Science from its founding in 1906 until its dissolution (in a short-lived merger with MIT) in 1915, he never held the Rumford Chair. In 1914 he was appointed to the Hollis Professorship of Mathematics and Natural Philosophy.

Sabine's ideas about the nature of "pure" science and its application in the larger world, while not developed in this essay, merit attention. Generally speaking, Sabine's views mirror those of Henry Rowland, as elaborated by Ronald Kline in "Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880–1945," *Isis,* 1995, *86:*194–221, on p. 199. Like Rowland, Sabine saw "applied science," including his own practical work in architectural acoustics, as, literally, the application of (pure) science—such as his reverberation equation—to solve practical problems. He also taught, and embodied, Rowland's ideal of the purity of science as something distinct from, and morally superior to, the market. Sabine struggled throughout his career to determine when it was appropriate to accept remuneration, via patents or consulting fees, for his scientific work. Most often he concluded that it was not. For more on Sabine's commercial concerns see Emily Thompson, "A Tale of Two Physicists: Wallace Sabine, Vern Knudsen, and the Origins of Acoustical Consulting," *Sound and Video Contractor,* 20 Mar. 1997, pp. 14–22; and Thompson, *Sound, Space, Technology, Modernity* (cit. n. 7). For more on Sabine's work as dean of the Graduate School of Applied Science see Orcutt, *Wallace Clement Sabine* (cit. n. 7), Ch. 10.

[24] Orcutt, *Wallace Clement Sabine,* p. 209. Akoustolith was not only more absorbent than Rumford; it was also more easily manufactured, as it did not require firing. Documents concerning Rumford and Akoustolith projects are preserved in the Guastavino/Collins Archive, Avery Architectural and Fine Arts Library, Columbia University, New York. More information on Raphael Guastavino and his system of vault construction can be found in George R. Collins, "The Transfer of Thin Masonry Vaulting from Spain to America," *Journal of the Society of Architectural Historians,* Oct. 1968, *27:*176–201. For more on the collaboration between Sabine and Guastavino see Thompson, " 'Mysteries of the Acoustic' " (cit. n. 7), Ch. 4; and Emily Thompson, "Listening to/for Modernity: Architectural Acoustics and the Development of Modern Spaces in America," in *Architecture of Science,* ed. Galison and Thompson (cit. n. 6).

[25] Paul Sabine, "Architectural Acoustics: Its Past and Its Possibilities," *Journal of the Acoustical Society of America,* July 1939, *11:*21–28, on p. 24. According to the acoustician Vern Knudsen, 400,000 square feet of acoustical materials were sold in 1924 and 3 million square feet in 1933: Vern O. Knudsen, "Review of Architectural Acoustics during the Past Twenty-five Years," *ibid.,* Sept. 1954, *26:*646–650, on p. 646.

sugar cane fiber, and asbestos. These materials, sold under brand names like Acousti-Celotex and Silent-Ceal, were used not just for chapels, churches, and state capitols; the new products were also employed in the everyday world of offices, schools, and apartments.

By 1930 "soundproof construction" was identified as a primary feature that prospective tenants were likely to seek. Such construction might consist of Herringbone Rigid Metal Lath, "proven an effective barrier to the most penetrating sound," or Sprayo-Flake acoustical plaster (see Figure 3), "sprayed on with guns" to form a "thick blanket of insulation covering the surface and sealing all cracks and crevices."[26] At the turn of the century, Sabine had been faced with the problems, first, of rendering a university lecture room serviceable; then, of providing an acoustical environment worthy of the musical genius of Higginson's hero, Beethoven. By 1930 the problem behind the desire to control the behavior of sound in rooms was both more pervasive and more pernicious:

> The fact that noise has become a problem necessitating control indicates a fundamental and important change in the life of society. This change relates to the mushroom growth in complexities of existence. It is noticed in pressure and confusion. The stream of business and industrial life swirls daily into new nervous whirlpools; and the demand is growing that more compensatory measures for private life be developed to maintain an equable balance between the various activities of living. The isolation of sound is one such measure.[27]

Concern over harmful levels of noise had been expressed earlier, but in the first decades of the twentieth century a growing collection of middle-class reformers in numerous cities began to redefine and attempt to eliminate "the noise nuisance." Indeed, by 1930, in the city of New York, the nuisance had developed into a full-fledged menace that commanded the attention of a specially appointed Noise Abatement Commission. Doctors, psychologists, lawyers, and acoustical scientists and engineers (some from Bell Laboratories) were brought in to study the sources, amount, and effect of noise in New York and then recommend action to abate it.[28] (See Figure 4.) Other cities followed suit, and corporations, too, discovered that the physical and mental energies of their employees were being sapped by the noise that surrounded them. Industrial psychologists quantified the decrease in worker efficiency that resulted from exposure to noise, and building materials manufac-

[26] J. O. Dahl, "A Check List of Features that Make Apartments Popular," *Architectural Forum,* Sept. 1930, *53:*371–372, on p. 371; *ibid.,* July 1923, *39:*25 (ad section) (Herringbone); and *Sweet's Architectural Trade Catalogue,* 1931, p. B2514 (Sprayo-Flake). Technically speaking, the problem of sound transmission, the passage of sound energy from one room to another, is distinct from the problem of reverberation, the decay of sound energy within a room. Both phenomena contribute to the "noisiness" of a room, however, and the two were not always distinguished in popular literature.

[27] Roger W. Sherman, "Sound Insulation in Apartments," *Architect. Forum,* Sept. 1930, *53:*373–378, on p. 373.

[28] For examples of nineteenth-century inquiries into soundproof building see James Barrett, "Sound through Walls and Floors," *Builder,* 18 Apr. 1857, *15:*222; A. F. Oakey, "Acoustics in Architecture," *Van Nostrand's Engineering Magazine,* Sept. 1881, *25:*228–242; and James Colling, "How to Prevent the Passage of Sound through Floors and Walls," *Amer. Architect Build. News,* 3 June 1882, *11:*260–261. For the New York campaign against noise see Edward F. Brown *et al.,* eds., *City Noise: The Report of the Commission Appointed by Dr. Shirley W. Wynne, Commissioner of Health, to Study Noise in New York City and to Develop Means of Abating It* (New York: Department of Health, 1930). See also Raymond Smilor, "Confronting the Industrial Environment: The Noise Problem in America, 1893–1932" (Ph.D. diss., Univ. Texas at Austin, 1978); Smilor, "Toward an Environmental Perspective: The Anti-Noise Campaign, 1893–1932," in *Pollution and Reform in American Cities, 1870–1930,* ed. Martin Melosi (Austin: Univ. Texas Press, 1980), pp. 135–151; and Thompson, " 'Mysteries of the Acoustic' " (cit. n. 7), Ch. 4. I am currently working on a detailed study of the New York City Noise Abatement Campaign.

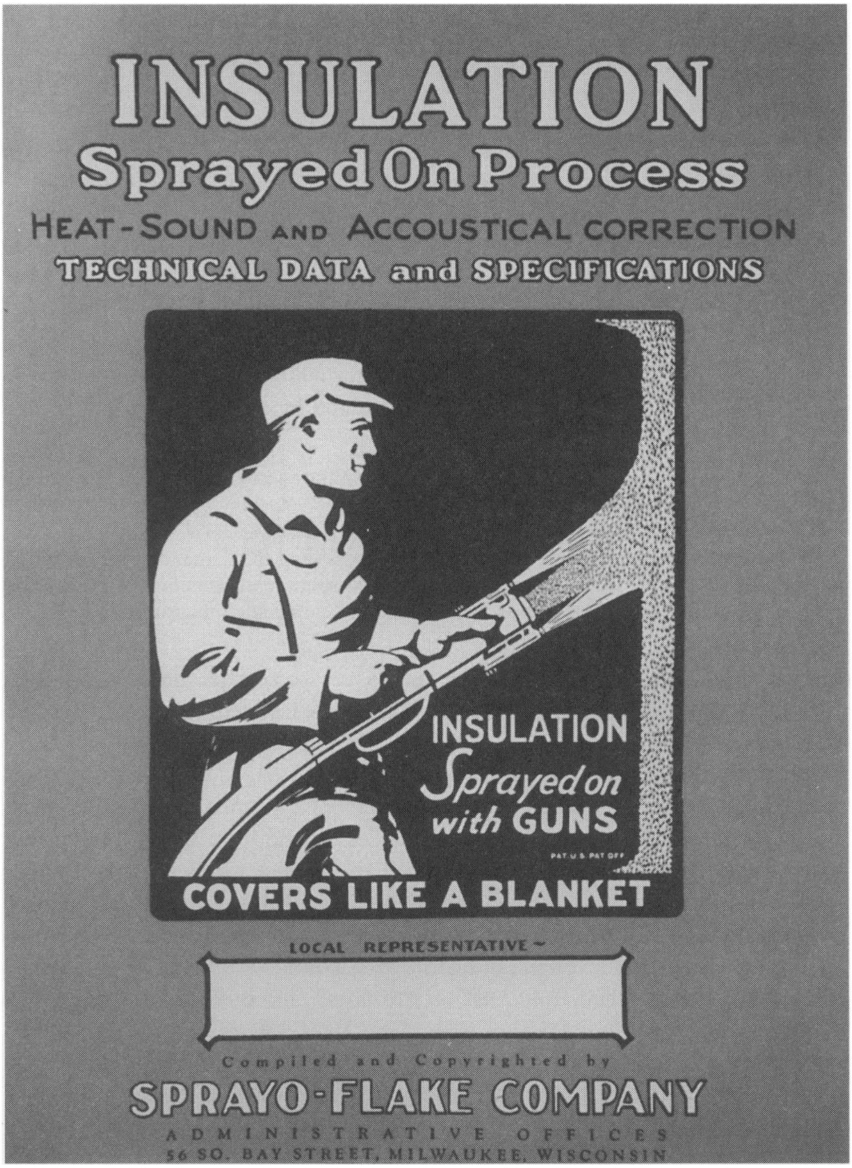

Figure 3. *Advertisement for Sprayo-Flake products, including Sprayo-Flake acoustical plaster. (From* Sweet's Architectural Trade Catalogue, *1931, page B2513.)*

turers began to advertise the cost-effectiveness of installing sound-absorbing materials in the workplace.[29]

[29] See esp. the research of Donald A. Laird, an industrial psychologist at Colgate University, e.g., "The Measurement of the Effects of Noise on Working Efficiency," *Journal of Industrial Hygiene,* Oct. 1927, *9:*431–434. Laird's experimental results were cited directly in advertisements for sound-absorbing building materials, and one investigation was actually sponsored by the Celotex Company, a large manufacturer of acoustical materials. See E. Lawrence Smith and Laird, "The Loudness of Auditory Stimuli which Affect Stomach Contractions in Healthy Human Beings," *J. Acous. Soc. Amer.,* July 1930, *2:*94–98.

Figure 4. *The noise-measuring truck of the Noise Abatement Commission of New York City, circa 1929. The truck was manned by acoustical engineers from Bell Telephone Laboratories and the Johns-Manville Corporation (manufacturers of acoustical building materials) and employees of the New York City Department of Health. It logged over 500 miles on the city's streets, making over 10,000 "observations" at 138 different points in the city. (From Edward F. Brown* et al., *eds.,* City Noise *[New York: Department of Health, 1930], on page 32.)*

Owing to the proliferation of new sound-absorbing materials, their promotion by manufacturers, the interest of a growing body of professional acousticians in studying those materials and supervising their use in various structures,[30] and the perception of a need for those materials by employers and consumers concerned about the problem of noise, many people began to spend increasing amounts of time in increasingly absorptive spaces. Acousticians simultaneously began to promote less reverberant rooms, not just for sleeping and working, but even for listening to music.

Floyd Watson, a physicist at the University of Illinois, published one of the first twentieth-century textbooks on architectural acoustics in 1923. When he reissued his treatise in 1930, he felt compelled to revise the recommendations that he had offered seven years earlier for optimum reverberation times. "Experience indicates," he wrote, "that shorter times of reverberation . . . produce better results." Whereas he had originally recommended

[30] The thirty years between Sabine and Eyring saw the growth and professionalization of the field of architectural acoustics. The Acoustical Society of America was founded, primarily by architectural acousticians, in 1929, and Eyring's equation debuted in the first volume of the society's journal. For more on the professionalization of the field see Thompson, " 'Mysteries of the Acoustic' " (cit. n. 7), Ch. 3.

an average reverberation time of over 3 seconds for a room of 1 million cubic feet, in 1930 Watson lowered that figure to just 2 seconds.[31]

In 1931 the UCLA physicist Vern Knudsen also noted this trend toward "non-reverberant rooms" for music, and he later credited this change to "the enormous increase in the use of absorptive materials in all sorts of rooms, thus conditioning or predisposing people to non-reverberant rooms." Knudsen's own support for nonreverberant rooms originated at least partly in his research on speech intelligibility. His experiments on "percent articulation," a measure of the degree to which a speaker's words were understood by a listener, indicated that intelligibility rose as reverberation decreased. Knudsen concluded that the best environment for listening to speech was the reverberation-free outdoors. He proposed that, in rooms for speech, reverberation should always be kept below 1 second. "Even for music," he claimed, "there seem to be no physical factors which would warrant a time of reverberation much in excess of 1.0 second." When *Science* reported upon Knudsen's work in 1926, the journal asserted that auditorium walls were simply "a necessary nuisance."[32]

Knudsen had the opportunity to build a concert hall free of the "nuisance" of enclosing walls. The Hollywood Bowl was an enormous outdoor amphitheater, located in a sheltered canyon amidst the hills outside Los Angeles. (See Figure 5.) The site was first used for concerts in 1922. In 1929 Knudsen designed a shell that enclosed the performers and projected the sound out to the 22,500 auditors seated on the sloping grounds. The goal was to provide "a pronounced directional flow of sound toward the audience." Upon completion of the shell, the Hollywood Bowl was proclaimed a complete success. "The acoustics of the Bowl," one reviewer wrote in 1929, "are enthusiastically praised by musical critics."[33]

By 1930 numerous indoor theaters effectively provided the same "outdoor" sound that so satisfied listeners at the Hollywood Bowl. A new type of auditorium was being promoted and constructed; long and low, spatulate or fan-shaped, the "Watsonian" auditorium (as one historian has identified it) consisted of an enclosed, reflective stage area and a highly absorbent seating area.[34] Walls surrounding the stage directed the sound generated there out into the auditorium; the sound was sent directly toward the audience, having little opportunity to reflect off the auditorium walls. The effect—directional exposure to a distinct source—was not unlike that enjoyed by listeners at the Hollywood Bowl. One might also compare the acoustics of such an auditorium to the experience of listening to the sound emitted from the electrical loudspeaker of a phonograph or radio, an increasingly

[31] F. R. Watson, *Acoustics of Buildings* (1923; New York: John Wiley, 1930), p. 34. Figures 15 and 16 (pp. 35, 36) in Watson's 1930 edition, showing plots of optimum reverberation time versus room volume, indicate further how his recommended reverberation times decreased from 1923 to 1930.

[32] Vern O. Knudsen, "Acoustics of Music Rooms," *J. Acous. Soc. Amer.,* Apr. 1931, *2:*434–467, on p. 447; Knudsen, "Review of Architectural Acoustics" (cit. n. 25), p. 648; Knudsen, "Interfering Effect of Tones and Noise upon Speech Reception," *Phys. Rev.,* 2nd Ser., July 1925, *26:*133–138; Knudsen, "The Hearing of Speech in Auditoriums," *J. Acous. Soc. Amer.,* Oct. 1929, *1:*56–82, on p. 77; and "Open Air Acoustics," *Science* (Suppl.), 1926, *63:*x. Watson, too, concluded that "the auditorium should be made as dead as outdoors for the benefit of the auditors": Watson, *Acoustics of Buildings* (1930), p. 59.

[33] Vern Knudsen, *Architectural Acoustics* (New York: John Wiley, 1932), p. 505; and Arthur T. North, "The Orchestra Shell of the Hollywood Bowl," *Architect. Forum,* Nov. 1929, *51:*549–552, on p. 551. North mistakenly identified Frank Lloyd Wright as the Hollywood Bowl's designer. Wright's son, Lloyd Wright, had designed two earlier, temporary shells at the site.

[34] Michael Forsyth, *Buildings for Music: The Architect, the Musician, and the Listener from the Seventeenth Century to the Present Day* (Cambridge, Mass.: MIT Press, 1985), p. 262. For a contemporary account of the new kind of auditorium see F. R. Watson, "Ideal Auditorium Acoustics," *Journal of the American Institute of Architects,* July 1928, *16:*259–267.

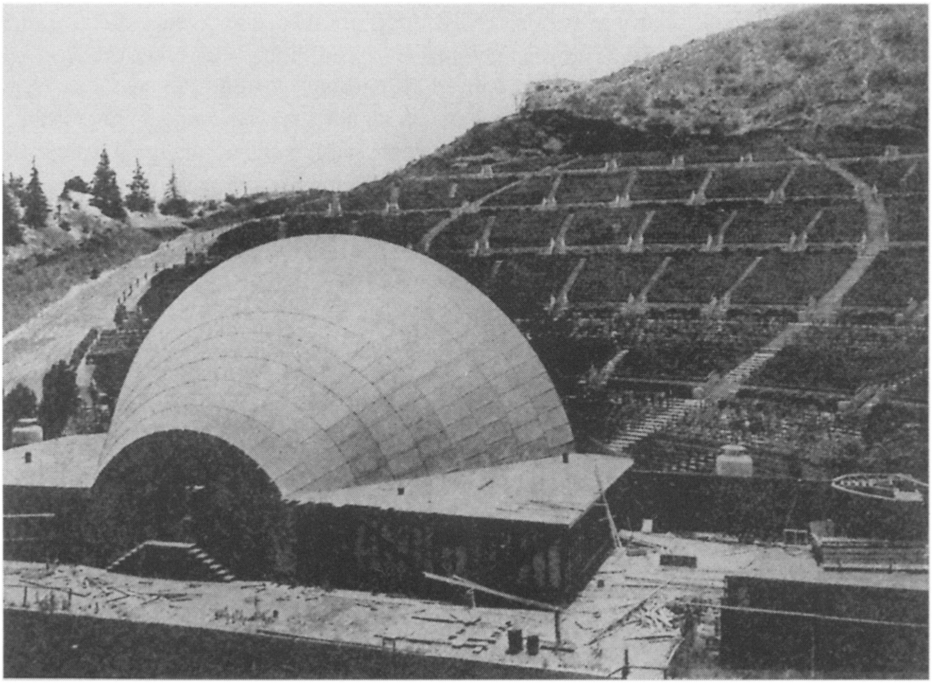

Figure 5. The Hollywood Bowl, circa 1929, showing the new shell still under construction. Vern Knudsen, acoustical consultant. (From Vern Knudsen, Architectural Acoustics *[New York: John Wiley, 1932], on page 504.)*

common experience for auditors in the years between 1925 and 1930. Indeed, by 1930 some auditoriums came equipped with electrical sound-amplification systems.

Not only the development of sound-absorbing materials but also the deployment of electroacoustic technologies contributed to the material transformation of architectural acoustics. The two phenomena occurred simultaneously; each reinforced the other, and the result was that desire for reverberant spaces died away faster than the sound energy in a Watsonian auditorium.

1900–1930: ELECTROACOUSTICS AND ARCHITECTURAL ACOUSTICS

The electrical reproduction of sound was initiated in the 1870s, with the invention of the telephone.[35] In its most popular early twentieth-century form, a carbon transmitter served

[35] Some telegraphic technologies, which predate the telephone, utilized electrical representations of pure tones as carriers of Morse code signals, but my concern here is with the more complex electroacoustic signals associated with speech and music. Even so, this essay can only touch upon the very rich history of the development of telephonic and related electrical technologies in the late nineteenth and early twentieth centuries. For more see Frederick V. Hunt, *Electroacoustics: The Analysis of Transduction, and Its Historical Background* (Cambridge, Mass.: Harvard Univ. Press; New York: John Wiley, 1954); Bruce Hunt, *The Maxwellians* (Ithaca, N.Y.: Cornell Univ. Press, 1991); Ronald Kline, *Steinmetz: Engineer and Socialist* (Baltimore: Johns Hopkins Univ. Press, 1992); Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge: Cambridge Univ. Press, 1985); Michael Eckert and Helmut Schubert, *Crystals, Electrons, Transistors: From Scholar's Study to Industrial Research,* trans. Thomas Hughes (New York: American

as the telephone mouthpiece. Loosely packed carbon granules alter their collective electrical resistance when exposed to mechanical pressure. Variations in air pressure, produced by the sound waves of a speaker's voice, caused the carbon transmitter to create a varying signal in the electrical circuit of the telephone, a signal that represented the speaker's voice. At the receiving end, or earpiece, of the telephone, the electrical signal was passed through a coil of wire surrounding a magnet. The fluctuating current caused the magnetic field surrounding the magnet to vary. This field then pushed and pulled at a steel diaphragm whose motion agitated the air to recreate the speaker's voice in the ear of the listener.

The carbon transducer as utilized in the telephone created an electrical signal that was strong enough to transmit over local telephone lines and resulted in recognizably intelligible speech at the receiving end, but its signal was not considered accurate enough for scientific use,[36] nor was it powerful enough to survive a long-distance trip along telephone lines without becoming lost in electrical noise. As the American Telephone and Telegraph Company (AT&T) worked to set up transcontinental telephone service, electromechanical signal amplifiers, or repeaters, were developed to boost the signal at certain points in its cross-country trek.[37] When coast-to-coast commercial service was established in 1915, such repeaters proved capable, but they were quickly displaced by a new type of purely electrical amplifier that not only achieved long-distance transmission but also became a basic and valuable tool for acoustical science.

The electrical inventor Lee de Forest demonstrated his "audion" to AT&T in 1912, and the telephone engineers immediately realized that this electronic vacuum-tube device could solve the problem of amplification associated with long-distance transmission. AT&T employees, particularly the physicist Harold Arnold, took de Forest's audion and transformed it into a generic audio signal amplifier that was applied to the numerous commercial sound products of the Western Electric Company, AT&T's manufacturing subsidiary.[38]

With the audion available for distortion-free amplification of sound signals, other AT&T

Institute of Physics, 1990); A. Michal McMahon, *The Making of a Profession: A Century of Electrical Engineering in America* (New York: Institute of Electrical and Electronics Engineers, 1984); James Brittain, *Alexanderson: Pioneer in American Electrical Engineering* (Baltimore: Johns Hopkins Univ. Press, 1992); and Bernard Finn, *The History of Electrical Technology: An Annotated Bibliography* (New York: Garland, 1991).

[36] The physicist Harvey Fletcher recalled studying sound with carbon microphones at the Western Electric Research Laboratories of the American Telephone and Telegraph Company circa 1917. When asked whether any of this work was published, Fletcher responded, "There was nothing to publish! No repeatable data!" Quoted in Harry B. Miller, "Acoustical Measurements and Instrumentation," *J. Acous. Soc. Amer.*, Feb. 1977, *61:*274–282, on p. 276.

[37] Hunt, *Electroacoustics* (cit. n. 35), pp. 62–64. See also Sheldon Hochheiser, "AT&T and the Development of Sound Motion-Picture Technology," in *The Dawn of Sound,* ed. Mary Lea Bandy (New York: Museum of Modern Art, 1989), pp. 23–33; and Neil Wasserman, *From Invention to Innovation: Long-Distance Telephone Transmission at the Turn of the Century* (Baltimore: Johns Hopkins Univ. Press, 1985).

[38] For more on the development of the vacuum-tube amplifier and its use in radio as well as telephony see Hugh Aitken, *The Continuous Wave: Technology and American Radio, 1900–1932* (Princeton, N.J.: Princeton Univ. Press, 1985), esp. Ch. 4; Susan J. Douglas, *Inventing American Broadcasting, 1899–1922* (Baltimore: Johns Hopkins Univ. Press, 1987); Tom Lewis, *Empire of the Air: The Men Who Made Radio* (New York: Harper Collins, 1993); and James Hijiya, *Lee de Forest and the Fatherhood of Radio* (Bethlehem, Pa.: Lehigh Univ. Press, 1992). For more general treatments of the rise of industrial research (including research in electronic technologies) at AT&T and at General Electric (its competitor in electroacoustic technologies) see Leonard Reich, "Irving Langmuir and the Pursuit of Science and Technology in the Corporate Environment," *Technology and Culture,* 1983, *24:*199–221; Reich, *Making of American Industrial Research* (cit. n. 35); F. M. Smits, ed., *A History of Engineering and Science in the Bell System: Electronics Technology (1925–1975)* (Indianapolis: AT&T Bell Laboratories, 1985); Eckert and Schubert, *Crystals, Electrons, Transistors,* trans. Hughes (cit. n. 35); and Lillian Hoddeson, "The Emergence of Basic Research in the Bell Telephone System, 1875–1915," *Technol. Cult.,* 1981, *22:*512–544.

researchers worked on developing new, more accurate types of microphones to replace the unreliable carbon models. In 1917 Edward Wente introduced the condenser microphone, a device that utilized the electrical property of capacitance, rather than resistance, to create the sound signal.[39] Receivers were also improved beyond the simple coil-and-magnet earpieces of telephones. By 1920 AT&T had developed "loud-speaking telephones," in which vacuum-tube amplifiers were paired with "projectors" or "loudspeakers" to provide sound for large public gatherings. The presidential conventions of 1920, Warren Harding's subsequent inauguration, and his dedication in 1921 of the Tomb of the Unknown Soldier all saw successful application of the new technology.[40] By 1922 these public address, or P.A., systems were being sold by Western Electric to anyone who required sound amplification, including motion picture directors, theater managers, and radio shop owners.[41]

In 1922 the show business impresario Samuel "Roxy" Rothafel used a Western Electric P.A. system to direct the rehearsals of his famous musical reviews. A few years later, the improved system sounded good enough for the director to consider employing it during the show itself. Roxy proclaimed in 1925: "Acoustics no longer present a problem, since the amplification system, with which we are now experimenting, will carry the voice and will send it perfectly almost any distance within reason, and certainly a distance greater than could be found in any theater."[42] The showman spoke with customary hyperbole, but he articulated a genuine faith in the new technology that would become widespread.

While Roxy used the new P.A. system to amplify live voices and music, the Engineering Department at Western Electric applied the same technology to the recording and reproduction of sound. The phonograph—which, since its invention by Thomas Edison in 1877, had been an entirely mechanical instrument—was redesigned with the aid of electroacoustics, and by 1925 Victor and Columbia, the two largest manufacturers of phonographs and phonograph records, were applying the new technology to their commercial products.[43]

The new technology not only transformed the phonograph industry; it also promised to achieve the long-sought goal of providing synchronized, amplified sound to accompany the projection of motion pictures in theaters. The Western Electric engineers developed a

[39] For a description of the device see Edward C. Wente, "A Condenser Transmitter as a Uniformly Sensitive Instrument for the Absolute Measurement of Sound Intensity," *Phys. Rev.,* 2nd Ser., July 1917, *10:*39–63; and Wente, "The Sensitivity and Precision of the Electrostatic Transmitter for Measuring Sound Intensities," *ibid.,* May 1922, *19:*498–503.

[40] Harding's speech at the Tomb of the Unknown Soldier was transmitted over long-distance telephone lines from Arlington, Virginia, to New York and San Francisco and broadcast to large crowds in both cities; see Hochheiser, "AT&T" (cit. n. 37), p. 24. A detailed description of AT&T public address systems is provided in I. W. Green and J. P. Maxfield, "Public Address Systems," *Journal of the American Institute of Electrical Engineers,* Apr. 1923, *42:*347–358. Evidence of how AT&T intended to integrate these P.A. systems into its network of telephone lines is provided in W. H. Martin and A. B. Clark, "Use of Public Address System with Telephone Lines," *ibid.,* pp. 359–366.

[41] P.A. systems were used by directors to instruct large crowds of extras during the making of epic silent films; see Hochheiser, "AT&T," p. 25. By 1930 radio shop owners had begun to advertise their wares by broadcasting programs at loud volume out into the street, and this noise became a problem for the Noise Abatement Commission of New York; see Brown *et al.,* eds., *City Noise* (cit. n. 28), p. 50.

[42] Samuel L. "Roxy" Rothafel, "What the Public Wants in the Picture Theater," *Architect. Forum,* June 1925, *42:*360–364, on p. 364. See also Ben M. Hall, *The Best Remaining Seats: The Story of the Golden Age of the Movie Palace* (New York: Clarkson N. Potter, 1961), p. 68.

[43] Hochheiser, "AT&T" (cit. n. 37), p. 25. The first commercial products incorporating the new technology, the Victor Orthophonic Phonograph and the Columbia Viva-Tonal Phonograph, were actually mechanical phonographs that played electrically recorded records. The first electric home phonograph was the Brunswick Panatrope. See Oliver Read and Walter L. Welch, *From Tin Foil to Stereo: Evolution of the Phonograph* (Indianapolis: Sams, 1959), p. 268.

synchronized disc-phonograph system to produce sound movies, but the company failed to generate interest in the new product among the major motion picture companies.[44]

A small, ambitious film company run by four brothers named Warner, however, decided to gamble on the new technology and signed on with Western to produce sound movies. The Warner brothers saw sound movies as a way of ensuring uniform, high-quality music and sound effects to accompany their films. Musical "shorts" were produced to replace the live, vaudeville-style performances that usually preceded presentation of a featured film in a theater. The synchronized sound for the first "all sound" feature, John Barrymore's *Don Juan* (1926), consisted only of background music and sound effects; the great lover's voice was never heard. One year later, however, Al Jolson improvised conversation during what was supposed to be a purely musical interlude in the otherwise silent Warner Brothers film *The Jazz Singer.* A new type of motion picture, the "talkie," was born; as Jolson's character presciently exclaimed, "You ain't heard nothin' yet!"

The success of *The Jazz Singer* was such that, by 1928, virtually all the major studios had tooled up for sound production. Within a year, the motion picture industry had invested $50 million in the transformation to sound, and by 1932, 98 percent of the motion picture theaters in America were wired for sound.[45] The rapid transformation of the industry presented enormous technological challenges; among these were new problems of architectural acoustics.

Architectural acousticians were hired to supervise the installation of the new electrical equipment in theaters. As early as 1927, AT&T established a new division, Electrical Research Products Incorporated (ERPI), to handle this aspect of its sound motion picture business. ERPI engineers surveyed silent film theaters, determined the particular sound equipment required to achieve optimal results, supervised installation of the system, and trained theater personnel in its operation. The survey included measurement of reverberation time as well as estimation of power requirements to obtain an appropriate volume level. Surveys indicated whether acoustical correction was required for successful sound reproduction: "correction" consisted primarily of the installation of sound-absorbing materials to reduce reverberation and eliminate echoes.[46]

Acousticians also consulted on sound stage design; the old studios had to be transformed into spaces providing a degree of acoustical control never before attained. (See Figure 6.) Vern Knudsen, fortuitously located in Los Angeles, became the principal consultant for the construction of new sound stages for virtually all the major studios. Knudsen remembered being called into the executive offices of Metro-Goldwyn-Mayer in 1928 to consult upon the design of their first sound stages. " 'We want these two stages, stages A and B,'

[44] The following brief account of the development of sound motion picture technology is based primarily upon Hochheiser, "AT&T"; Richard Koszarski, "On the Record: Seeing and Hearing the Vitaphone," in *Dawn of Sound,* ed. Bandy (cit. n. 37), pp. 15–21; Scott Eyman, *The Speed of Sound: Hollywood and the Talkie Revolution, 1926–1930* (New York: Simon & Schuster, 1997); J. Douglas Gomery, "The Coming of the Talkies: Invention, Innovation, and Diffusion," in *The American Film Industry,* ed. Tino Balio (Madison: Univ. Wisconsin Press, 1976); Gomery, "Warner Bros. Innovates Sound: A Business History," in *The Movies in Our Midst: Documents in the Cultural History of Film in America,* ed. Gerald Mast (Chicago: Univ. Chicago Press, 1982), pp. 267–282; Harry Geduld, *The Birth of the Talkies: From Edison to Jolson* (Bloomington: Indiana Univ. Press, 1975); and Alexander Walker, *The Shattered Silents: How the Talkies Came to Stay* (New York: William Morrow, 1979).

[45] Geduld, *Birth of the Talkies,* p. 253 (investment); and Hochheiser, "AT&T," p. 32 (theaters). Other sound systems, developed by audion inventor Lee de Forest, by RCA (through General Electric), and by the Fox-Case Corporation, appeared and competed with the Western product. These alternatives utilized various methods of creating a photographic record of sound directly on the film. Western Electric soon adapted its projectors to accommodate either disc or film sound, and by 1931 sound on film had become the standard.

[46] Harold B. Franklin, *Sound Motion Pictures: From the Laboratory to Their Presentation* (Garden City, N.Y.: Doubleday, Doran, 1929), pp. 64–75. See also Lewis M. Townsend, "Some Experiences in Adapting Theaters for Sound Reproduction," *Journal of the Society of Motion Picture Engineers,* May 1931, *16:*600–602.

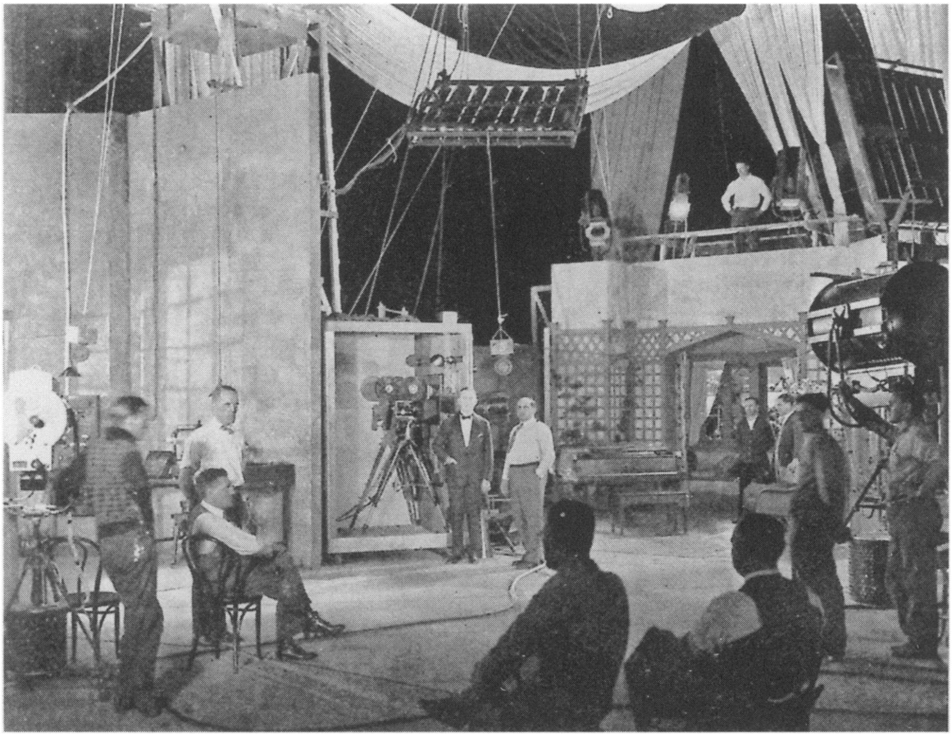

Figure 6. *The first Warner Brothers Vitaphone sound motion picture studio, Brooklyn, New York, circa 1926. The studio had formerly been the site of silent film production for the Vitagraph Company, which Warner Brothers had recently purchased. The soundproof camera booth in the center of this picture would have been entirely closed when filming/recording took place. A microphone hangs above the two men standing next to the camera booth. The megaphone at the men's feet could only have been used to command silence on the set. (From Fitzhugh Green,* The Film Finds Its Tongue *[New York: Putnam's, 1929], facing page 112.)*

Louis B. Mayer explained, 'to be insulated from each other so well that you can have gunfire on one stage and record chamber music on the other stage.' " "Well," Knudsen replied, "This calls for a very costly type of building. He [Mayer] said, 'We don't care. We want that; that's the requirement. That *must* be the requirement.' "[47] A new type of stage was developed that kept out external noise, eliminated the internal noise of hissing lights and rumbling air-conditioning systems, and, through the extensive use of sound-absorbing materials, contributed no particular acoustical qualities of its own to the sound tracks recorded there.

Motion picture technology, or motion picture art, depends for its success upon the superposition of three separate spaces: the studio, the theater, and the fictional space represented on the screen. With the architecture of both studio and theater manipulated to provide acoustically neutral spaces in which to record, then reproduce, the motion picture

[47] James V. Mink and Vern O. Knudsen, *Teacher, Researcher, and Administrator: Vern O. Knudsen* (Los Angeles: UCLA Oral History Program, 1974), p. 652. Department of Special Collections, Oral History Program, University Research Library, UCLA. Courtesy Regents of the University of California.

sound track, all that remained was to create the fictional acoustical space that the image on the screen brought to mind.[48]

Initially, studio practice centered on the employment of stage sets constructed of materials chosen to create certain sounds through the proven techniques of architectural acoustics.[49] As enthusiasm for the new electrical technology grew, however, some engineers proposed creating spatial sound effects by purely electrical means. The very electroacoustic system that made talkies possible—the system that created such interest in, and presented such challenges to, architectural acoustics—quickly became a flexible and powerful tool for manipulating sound as well as for collecting and reproducing it. The result was that architectural acoustics became considerably less architectural.

At a 1928 meeting of the Society of Motion Picture Engineers, the physicist Paul Sabine (a cousin of Wallace Sabine) confidently asserted the ability of architectural acousticians to meet the challenge of sound motion picture production. "The principles governing the behavior of sound within closed spaces are well known," he asserted, "and quantitative data for producing the desired conditions can be had." The discussion that followed his talk, however, focused as much on the electroacoustic as on the architectural control of sound. Edward Kellogg, of General Electric, described how spatial effects could be created in the studio through the judicious placement of microphones: "The liveliness of the room can be compensated for, partly by the position of the microphone. . . . Conclusions about the amount of reverberation time in recording rooms must be tied up with the placing of the microphone used."[50] Kellogg, a sound engineer, associated acoustical control not with the selective employment of architectural materials, but with the use of electrical devices.

Sound engineers, or "mixer men," were now capable of creating spatial effects and acoustical illusions by using electroacoustic devices in conjunction with, or even independently of, architectural space. (See Figure 7.) In addition to the control they achieved through judicious microphone and speaker placement, they could mix the outputs of multiple microphones into a single signal or piece together serially different microphone outputs. They could add special sound effects, filter out noise, adjust sound levels, and alter the quality of a recording in numerous other ways. One engineer asserted that it was best to "shoot" close-up, or direct, sound only and then modify the sound track during rerecording, electronically adding spatial effects where required.[51]

By 1930, at least one studio had begun the practice of miking performers at close range, then reproducing that "dead" signal in a special "reverberant chamber." A second micro-

[48] In fact, the earliest years of sound filmmaking were filled with debate over just how the sound should relate to the image shown on screen. This debate, as well as the more general topic of cooperation and conflict between sound engineers and filmmakers, is the subject of an ongoing investigation by the author.

[49] The Academy of Motion Picture Arts and Sciences, for example, sponsored a study of the acoustical characteristics of commonly used set materials, and the investigation was carried out in Vern Knudsen's lab at UCLA. See J. P. Maxfield and Ralph Townsend, "Acoustic Measurements of Set Materials," *Report No. 4 of the Academy Producers-Technicians Committee* (Hollywood, Calif.: Academy of Motion Picture Arts and Sciences, 1930).

[50] Paul Sabine, "The Acoustics of Sound Recording Rooms," *Transactions of the Society of Motion Picture Engineers,* 1928, *12:*809–822, on p. 809; and Edward Kellogg, discussion following Sabine, "Acoustics of Sound Recording Rooms," *ibid.,* p. 821.

[51] Carl Dreher, "Microphone Concentrators in Picture Production," *J. Soc. Motion Picture Eng.,* Jan. 1931, *16:*23–30, on p. 24. On the techniques of sound engineers see, e.g., Mr. Maxfield, discussion after A. S. Ringel, "Sound-Proofing and Acoustic Treatment of RKO Stages," *ibid.,* Sept. 1930, *15:*352–369, on p. 368; Mr. Coffman, discussion after R. L. Hanson, "One Type of Acoustic Distortion in Sound Picture Sets," *ibid.,* Oct. 1930, *15:*460–472, on p. 471; and John L. Cass, "The Illusion of Sound and Picture," *ibid.,* Mar. 1930, *14:*323–326, on p. 325. See also C. A. Tuthill, "The Art of Monitoring," *Trans. Soc. Motion Picture Eng.,* 1929, *13:*173–177; and Dreher, "Recording, Re-Recording, and Editing of Sound," *J. Soc. Motion Picture Eng.,* June 1931, *16:*756–765.

Figure 7. *Perspective of a sound engineer, or "mixer man," looking down from the monitoring booth onto the sound stage of the Sound Motion Picture Studio of Bell Telephone Laboratories, circa 1930. (From T. E. Shea, "A Modern Laboratory for the Study of Sound Picture Problems,"* Journal of the Society of Motion Picture Engineers, *March 1931, page 280.)*

phone was placed in this otherwise empty chamber to pick up the now-reverberant signal that constituted the final product. In this way "space" was added, in a highly controlled fashion, to a sound signal, itself highly controlled through microphone placement.[52] The sound of space was no longer integral to the architectural location in which the performance was made or heard; it was now a character, a quantity that could be meted out at will and added to any electrical sound signal. Just as the visual techniques of film editing had created a new language of time and space—a language more supple than that of traditional theater—so, too, did sound editing techniques transform the relationship between sound and space. The traditional relationship had been tested and challenged by new architectural

[52] Edward W. Kellogg, "Some New Aspects of Reverberation," *J. Soc. Motion Picture Eng.*, Jan. 1930, *14*:96–107, on p. 105. The studio described by Kellogg was operated by a radio station, not a motion picture company. The powerful new technologies of acoustical control were equally present in both types of studio.

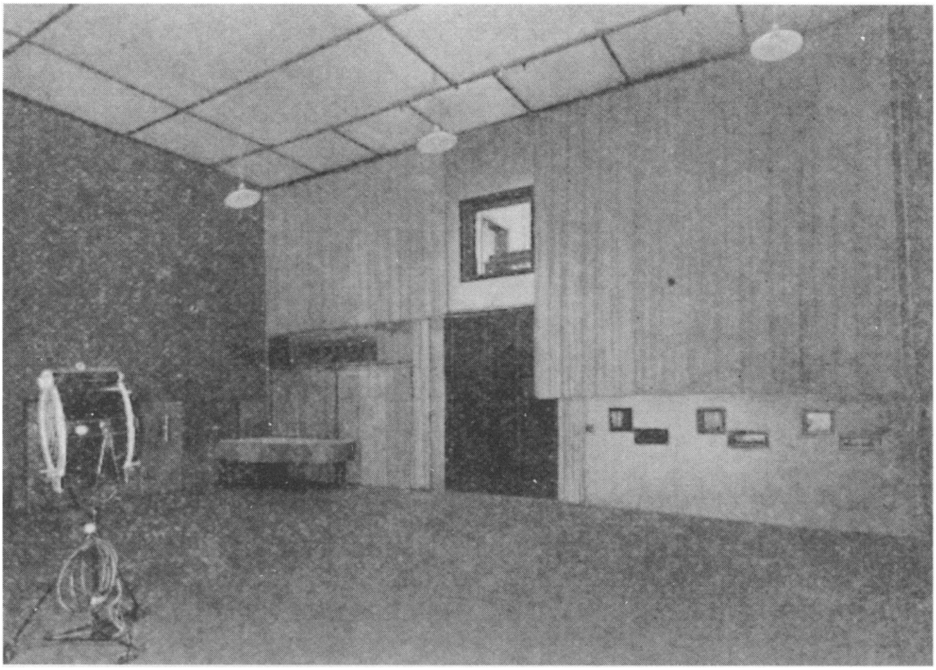

Figure 8. *View of the sound stage of the Sound Motion Picture Studio of Bell Telephone Laboratories, circa 1930. The window of the monitoring booth is clearly visible. (From T. E. Shea, "A Modern Laboratory for the Study of Sound Picture Problems,"* Journal of the Society of Motion Picture Engineers, *March 1931, page 278.)*

materials such as Akoustolith, but now, "with one broad sweep," as Harold Arnold of Bell Laboratories proclaimed, "the barriers of time and space are gone."[53]

Edward Kellogg concluded, "There is practically nothing which auditorium reverberation accomplishes which cannot be secured in a highly damped auditorium by other means." The "other means" to which he referred were the "elements of recording technic." Kellogg elaborated:

> During the past ten years much information has been accumulated, many new and better materials have become available for acoustic treatment, and the principles of good acoustics have been much more widely appreciated, but I believe that the general conclusions reached in the pioneer work of Prof. Wallace Sabine have not been materially altered. Within the past two years, however, a new factor has come strongly into the picture, and I believe that it will call for some radical revisions of our criteria for best acoustics. I refer to the electrical reproduction of sound.[54]

In fact, the revision of criteria predicted by Kellogg in the January 1930 volume of the *Journal of the Society of Motion Picture Engineers* was well under way. Equally significant was the revision of Sabine's "pioneer work" itself, which appeared that same month in the *Journal of the Acoustical Society of America.*

[53] H. D. Arnold, "Introduction," in Harvey Fletcher, *Speech and Hearing* (London: Macmillan, 1929), p. xi. See also Stephen Kern, *The Culture of Time and Space, 1880–1918* (Cambridge, Mass.: Harvard Univ. Press, 1983), pp. 29–30 and *passim.*

[54] Kellogg, "Some New Aspects of Reverberation" (cit. n. 52), pp. 102, 100–101.

CARL EYRING AND REVERBERATION CIRCA 1930

Carl Eyring worked in the Sound Picture Laboratory at the Bell Telephone Laboratories in New York (see Figure 8).[55] The walls and ceiling of the laboratory sound stage were entirely covered with rock-wool sound-absorbing material and adjustable monk's-cloth drapes, and the reverberation time for this large room (47 ft × 70 ft × 25 ft), at 512 cps, was well under half a second (see Tables 1 and 2).[56] To measure reverberation in this room Eyring employed a microphone, vacuum-tube amplifiers, a loudspeaker, and other electroacoustic equipment.[57]

Initial investigation of this extremely "dead" room indicated to Eyring that Sabine's formula for calculating reverberation times would not work here; the equation was valid only for "live" rooms. In the Bell Labs sound stage, sound energy was absorbed so quickly that the initial conditions that Sabine had assumed were never attained. Eyring's working environment constituted the limiting case that Sabine had never encountered or considered; thus Sabine's equation "failed" Eyring in a way that it hadn't failed Sabine thirty years earlier.[58]

Eyring's task was to modify Sabine's equation to fit both "live" and "dead" rooms. He chose to start at the very beginning, to reconceptualize the phenomenon of reverberation in a way that would accommodate rates of absorption that had been inconceivable to Sabine. Eyring's conceptualization, as much as his tools and the physical nature of his workplace, was the product of the material transformation that architectural acoustics had undergone since 1900. Simply put, Eyring presented "an analysis based on the assumption that image sources may replace the walls of a room in calculating the rate of decay of

[55] Carl Eyring was born in Colonia Juarez, Chihuahua, Mexico, in 1889. In 1909 he enrolled at Brigham Young University, where he studied physics with Harvey Fletcher and received his B.A. in 1913. His 1924 Ph.D. was earned under Robert Millikan's supervision at the California Institute of Technology. Eyring was a professor of physics and mathematics at Brigham Young from 1915 until his death in 1951. He served as dean of the College of Arts and Sciences from 1924 onward. Eyring took leave from his university to work at the Bell Telephone Laboratories in New York from 1929 to 1931. In addition to numerous technical papers, he wrote an undergraduate physics textbook and several volumes on Mormon life and thought. See Vern Knudsen, "Carl F. Eyring," *J. Acous. Soc. Amer.*, May 1951, *23:*370–371.

[56] The laboratory is described in T. E. Shea, "A Modern Laboratory for the Study of Sound Picture Problems," *J. Soc. Motion Picture Eng.*, Mar. 1931, *16:*277–285. The reverberation time is cited in Carl Eyring, "Reverberation Time in 'Dead' Rooms," *J. Acous. Soc. Amer.*, Jan. 1930, *1:*217–241, on p. 239, Fig. 13. The sound stages at Radio-Keith-Orpheum also had reverberation times of 1 sec. or less; see Ringel, "Sound-Proofing and Acoustic Treatment of RKO Stages" (cit. n. 51), p. 363, Fig. 6. Radio studios were equally absorbent. Paul Sabine carried out a test in 1926 to determine what studio conditions provided the kind of broadcast sound quality that listeners (at home) preferred. He varied the reverberation in the studio of WLS in Chicago from 0.25 to 0.64 sec. Paul Sabine, "Acoustics of Sound Recording Rooms" (cit. n. 50), p. 814.

[57] For a full description of the reverberation-measuring apparatus that Eyring employed see E. C. Wente and E. H. Bedell, "A Chronographic Method of Measuring Reverberation Time," *J. Acous. Soc. Amer.*, Apr. 1930, *1:*422–427.

[58] Eyring cited the German researchers Schuster and Waetzmann as the first to note that Sabine's formula was implicitly applicable only to "live" rooms. See K. Schuster and E. Waetzmann, "Über den Nachhall in geschlossenen Räumen," *Annalen der Physik*, 5th Ser., 12 Mar. 1929, *1:*671–695. Paul Sabine pointed out, in 1939, that Eyring's treatment was in fact stimulated by a discussion at the May 1929 meeting of the Acoustical Society of America, in which R. F. Norris suggested the modification to Sabine's equation that Eyring subsequently developed. See Sabine, "Architectural Acoustics" (cit. n. 25), p. 26. The revised formula is sometimes referred to as the "Eyring-Norris" equation. Norris's derivation is presented in Knudsen, *Architectural Acoustics* (cit. n. 33), pp. 603–605. For the purposes of this essay, the issue of assigning priority is not relevant. In fact, the "simultaneous discovery" by numerous individuals of the limitations of Sabine's equation only highlights the fact that no such limitation had been identified by the many investigators who employed it in the years between 1900 and 1929.

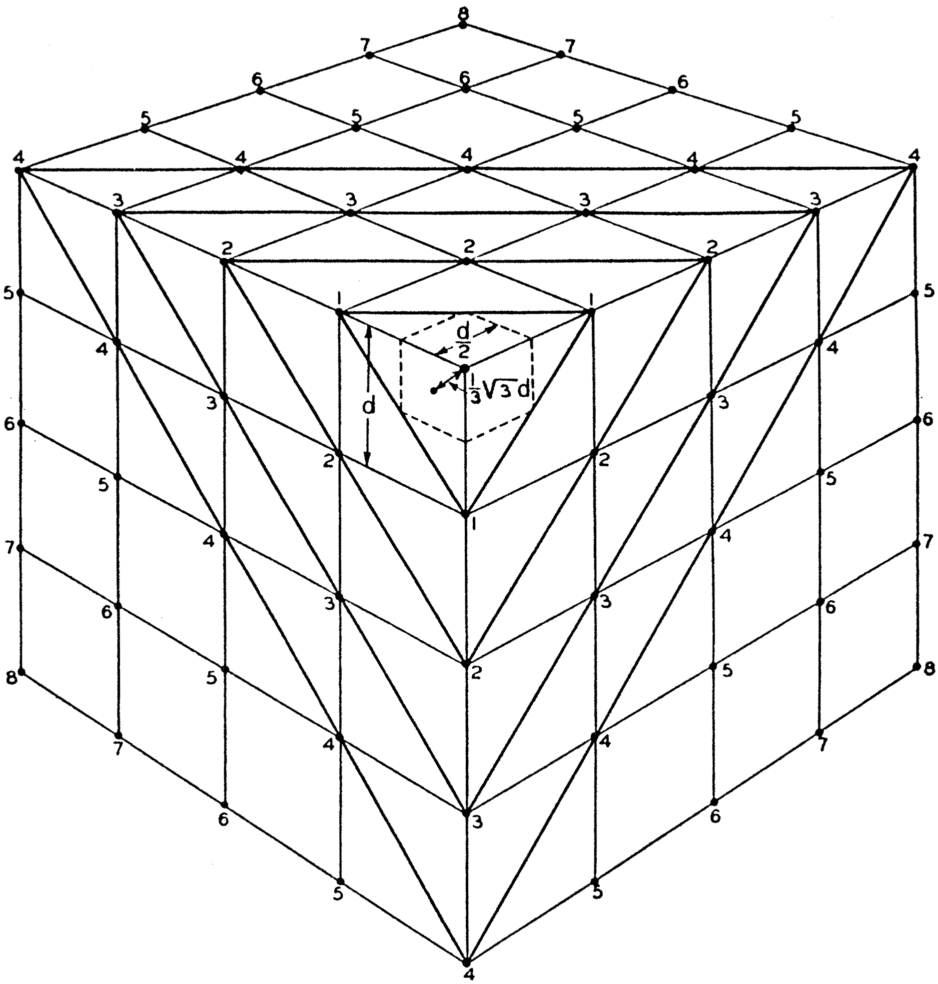

Figure 9. *Carl Eyring's diagram of the array of acoustical image sources that replaced actual reflections of sound off the walls of a room in his analysis of reverberation. The room abstractly represented by this diagram is a cube of length* d, *with a source of sound at its center. This center is located at the top front corner of the array. (From Carl F. Eyring, "Reverberation Time in 'Dead' Rooms,"* Journal of the Acoustical Society of America, *January 1930,* 1:*217–241, on page 223.)*

sound intensity."[59] Instead of imagining sound energy as emitted by a single source and then reflected off architectural surfaces, slowly dying away as energy was absorbed at each rebound, Eyring conceptualized a source in free space, surrounded not by walls but by an infinite number of other sources located at increasing distances from the original, all simultaneously emitting sound back toward the original source. (See Figure 9.)

Eyring was not the first to envision sound reflections as emissions of sound from image sources. Textbooks on physics and sound from the nineteenth and twentieth centuries regularly portrayed and explained reflections of sound by the method of images. Floyd

[59] Eyring, "Reverberation Time in 'Dead' Rooms" (cit. n. 56), p. 217.

Watson, too, had used this approach in 1928. Watson *compared* walls to "acoustical mirrors" creating images of sources of sound. Yet, he interjected, "of course this image is imaginary, and its speech is nothing more than the reflected sound." Eyring, in contrast, *replaced* the walls of the room with "image sources located in evenly spaced discrete zones."[60] No walls at all were depicted in Eyring's article. Instead, he transformed the room into an abstract electroacoustic array existing in unbounded space. The object of study and the tools of study coalesced to become one and the same, as Eyring, like the sound engineer Edward Kellogg, perceived the behavior and control of sound in nonarchitectural terms. This coalescence was made possible not only by the material transformation of the acoustical laboratory through the increasing use of electroacoustic devices, but also because intellectual transformations were occurring simultaneously—intellectual transformations that further blurred the distinction between sound, space, and circuits.

Sound waves in a medium can be mathematically represented by systems of linear differential equations. These equations, and the variables within them, are analogous to the differential equations that are used to represent the behavior of certain classes of electrical circuits. In the field of acoustics in the 1920s, "use of electric-network analogs for deductive analysis sprang up spontaneously in so many places at about the same time that it seems as useless as it would be difficult to establish who did it first." The analogy provided "a language for thinking and talking" that helped "to clear the mind and assist reasoning."[61]

The key to the analogy between electrical circuits and mechanical acoustical systems is the concept of impedance. Electrical impedance is a measure of the opposition to the flow of an alternating current in a circuit, a concept introduced by Oliver Heaviside in the 1880s. In 1912 Arthur Kennelly and George Pierce, of Harvard University, studied the behavior of telephone receivers and linked the electrical impedance of the instruments to their mechanical properties.[62] In 1914 Arthur Webster introduced the concept of acoustical impedance, the ratio of the pressure to the volume displacement in a sound-transmitting medium.[63] This quantity enabled acousticians to apply mathematical equations that represented electrical circuits to mechanical acoustical systems. Established expertise in elec-

[60] Watson, "Ideal Auditorium Acoustics" (cit. n. 34), pp. 260–261; and Eyring, "Reverberation Time in 'Dead' Rooms," p. 225. For earlier examples of the use of acoustical images see, e.g., Adolphe Ganot, *Elementary Treatise on Physics,* trans. Edmund Atkinson from 9th ed. (London, 1863); Augustin Privat-Deschanel, *Elementary Treatise on Natural Philosophy,* trans. and ed. J. D. Everett (London, 1875); and R. A. Millikan and John Mills, *Electricity, Sound, and Light* (Boston, 1908).

[61] Hunt, *Electroacoustics* (cit. n. 35), p. 66; and W. H. Eccles, "The New Acoustics," *Proceedings of the Physical Society* (London), 15 June 1929, *41:*231–239, on p. 233. Hunt lists numerous articles and patents that used the analogy to explain acoustical devices and phenomena. For more on the role of analogies and models in scientific and technical thought see Lenoir, "Models and Instruments" (cit. n. 2); Wise, "Mediating Machines" (cit. n. 2); and Robert Kargon, "Model and Analogy in Victorian Science: Maxwell's Critique of the French Physicists," *Journal of the History of Ideas,* 1969, *30:*423–436.

[62] A. E. Kennelly and G. W. Pierce, "The Impedance of Telephone Receivers as Affected by the Motion of Their Diaphragms," *Proc. Amer. Acad. Arts Sci.,* Sept. 1912, *48:*113–151. For more on Heaviside's work see Paul Nahin, *Oliver Heaviside: Sage in Silence* (New York: Institute of Electrical and Electronic Engineers, 1988); and Ido Yavetz, *From Obscurity to Enigma: The Work of Oliver Heaviside, 1872–1889* (Basel: Birkhäuser, 1995).

[63] Arthur Gordon Webster, "Acoustical Impedance, and the Theory of Horns and of the Phonograph," *Proceedings of the National Academy of Sciences,* July 1919, *5:*275–282. Webster describes this 1919 paper as the delayed publication of a talk that he had given in 1914 at a meeting of the American Physical Society in Philadelphia. That talk, "On Acoustic Impedance, and an Approximate Theory of Conical Horns," is listed (no abstract is provided) in *Phys. Rev.,* 2nd Ser., Feb. 1915, *5:*177.

trical theory was thus drawn upon to explain the behavior of acoustical systems, particularly systems of receivers, horns, and acoustic filters.[64]

In 1925 Bell Laboratories researchers Joseph Maxfield and Henry Harrison took the analogy one step further, using their understanding of circuit behavior to improve the design of the mechanical phonograph.[65] By establishing the electrical analog of the mechanical phonograph, Maxfield and Harrison transformed the highly complex problem of improving the fidelity of a phonograph into the simple, straightforward problem of optimizing the frequency response of an equivalent circuit. They then translated the optimized circuit back into a mechanical system, and the result was a new, improved phonograph. The design technique that the two men employed was just as significant as the product that resulted; to those who studied sound, suddenly, "the whole body of electric communication network theory . . . came within the domain of acoustical engineering."[66]

Carl Eyring's analysis of reverberation did not directly employ analogous electrical circuits, but the increasingly popular technique contributed generally—and significantly—to the material transformations that stimulated and shaped his work. With the distinction between mechanical systems and electrical systems—between sounds and circuits—now far less distinct, Eyring was able to reconceptualize the phenomenon of reverberation in a way that had not been possible for Sabine thirty years earlier. This reconceptualization—the replacement of a room filled with reflections of sound energy by an unbounded array of image sources—was the key to the reformulation of the reverberation equation that resulted.

Eyring's analysis led him to understand the absorption of sound energy in a way that differed considerably from Sabine's characterization. Where Sabine had supposed a smooth, gradual, and continuous decay of energy, Eyring described a discontinuous process, whereby the flow of energy suffered abrupt drops: "This constant energy flow followed by an abrupt drop, rather than a continuous drop to this same level, means a greater absorption during the same interval of time and hence a more rapid decay of sound."[67]

With this new understanding of the decay of sound energy, Eyring ultimately developed a new equation for calculating reverberation time:

$$T = \frac{.164\ V}{-S\ \ln(1 - \alpha_a)},$$

where (as with Sabine's equation)

[64] The technique of equivalent circuits was applied to the solution of other types of mechanical problems well before its usefulness to acousticians became apparent. For example, Charles Steinmetz derived an equivalent circuit for an induction motor in 1897. See Kline, *Steinmetz* (cit. n. 35), pp. 112–113.

[65] The authors explained: "The economic need for the solution of many of the problems connected with electric wave transmission over long distances coupled with the consequent development of accurate electric measuring apparatus has led to a rather complete theoretical and practical knowledge of electrical wave transmission. The advance has been so great that the knowledge of electric systems has surpassed our previous engineering knowledge of mechanical wave transmission systems. The result is, therefore, that mechanical transmission systems can be designed more successfully if they are viewed as analogs of electric circuits." J. P. Maxfield and H. C. Harrison, "Methods of High Quality Recording and Reproducing of Music and Speech Based upon Telephone Research," *Transactions of the American Institute of Electrical Engineers,* Feb. 1926, *45:*334–348. The article also appeared in the *Bell System Technical Journal,* July 1926, *5:*493–523; I have quoted from the latter, p. 502.

[66] Miller, "Acoustical Measurements and Instrumentation" (cit. n. 36), p. 278. Miller characterized the Maxfield and Harrison article as "a textbook which taught both synthesis and analysis of mechanical circuits; and indeed popularized the very concept of the mechanical circuit" (p. 277).

[67] Eyring, "Reverberation Time in 'Dead' Rooms" (cit. n. 56), p. 230.

T = reverberation time (seconds),
.164 = hyperbolic constant,
V = volume of the room (cubic meters),
S = surface area of the room (square meters),
α_a = average coefficient of absorption for the room;

$$= \sum \frac{S_n \alpha_n}{S}$$

where
S_n = surface area of material n and
α_n = absorption coefficient for material n.

The new equation met the new requirement that in a completely absorbent room ($\alpha_a = 1$) the reverberation time would approach zero. It further reduced to Sabine's equation when applied to "live" spaces, rooms with small values of α_a.[68]

Carl Eyring's revision of Wallace Sabine's reverberation equation was immediately put to work by his colleagues, and it simultaneously began to appear in articles and texts on architectural acoustics.[69] In these accounts Eyring's new characterization of the decay of sound was recapitulated, his equation was mathematically derived, and it was shown how his general equation reduced to Sabine's equation under special, "live" conditions. The presentation makes perfect sense—except to the historically inquisitive reader who wonders why it took thirty years for Sabine's special case to be recognized as such. As this essay has attempted to show, it took thirty years because Eyring's equation described a world that hadn't existed in 1900. The "material transformation" wasn't simply the appearance of new, improved tools able to generate "improved" data requiring new explanations; rather, it was more generally located within and a product of the total material environment of architectural acoustics—an environment that incorporated the object of study, the tools with which it was studied, and the space in which the study was contained. As sound-absorbing building materials increasingly muffled interior spaces, as loudspeakers multiplied and poured forth their electroacoustic sounds, as sounds and circuits commingled and coalesced, as acoustical image replaced acoustical reality, as reality itself changed—only then did Sabine's formula become inadequate.

CONCLUSION

When Carl Eyring replaced Wallace Sabine's α_a with $-\ln (1 - \alpha_a)$, he signified in a cryptic mathematical code that the material world, the physical world of rooms filled with sound, had fundamentally changed. We continue to live in Eyring's world today, a world of highly controlled, "virtual" environments in which not just sound but also temperature, light, and air are all manufactured to create spaces that (ideally) enable us to go about doing what we do without being distracted by the constraints that the natural environment

[68] This general form of Eyring's equation is applicable only to cases in which the sound energy in a room is considered to be diffuse (an assumption that Sabine also made). Eyring's article also describes how to manipulate the equation for nondiffuse conditions.

[69] See, e.g., Knudsen, *Architectural Acoustics* (cit. n. 33), pp. 128–130.

often imposes upon its inhabitants.[70] Perhaps because we are so comfortable, we too often take our material surroundings for granted. In life and in scholarship, the workplace is treated as a "black box" whose material constitution is largely irrelevant to the activity that it houses.

This essay has attempted not to "open up" the black box but, instead, to turn the box itself into an object of study, to recognize its own material history and its agency in affecting the actions of those who labor both within and without. By focusing on the science of architectural acoustics, where the box is by definition simultaneously place of study and object of study, the interaction between the two has been explicitly demonstrated. The connection is, I would suggest, equally significant, if perhaps more subtle, in other fields of scientific inquiry.[71]

[70] Techniques of acoustical control have, of course, continued to develop since Eyring's era, but today's state-of-the-art technology only extends Eyring's material environment; it does not present a fundamentally different acoustical paradigm. In June 1994, at a meeting of the Acoustical Society of America that commemorated the centenary of Wallace Sabine's work in architectural acoustics, I experienced a product advertised as a "virtual acoustical environment." The portable chamber (11 ft × 13 ft × 12 ft) was lined with sound-absorbing materials and wired throughout with an array of microphones and loudspeakers that were connected to a small computer located outside the chamber. Sounds generated by occupants of the room were picked up by the microphones, processed through computer programs, then re-emitted by the loudspeakers scattered about the room. The Wenger Acoustic Virtual Environment, or WAVE™, was capable of creating for musicians who performed within it the sound of a large modern concert hall, a medieval cathedral, an intimate baroque music chamber, a cave. The WAVE™ seemed at first to propel me into a strange new world, but upon reflection (intellectual, not acoustical) the technology seemed less and less remarkable, and I came to realize that I only found myself in the midst of Eyring's imaginary array of acoustical sources, a virtual space constructed almost seventy years ago.

[71] Norton Wise, for example, has applied this approach to understand the connections between the material culture of nineteenth-century Prussia and the scientific work of Hermann Helmholtz. For Wise, the material environment is located not just within architectural rooms but also without, in the public and private gardens of Potsdam and other Prussian cities. See M. Norton Wise, "Architectures for Steam," in *Architecture of Science,* ed. Galison and Thompson (cit. n. 6).

Studies of the material environment of more contemporary science, in which computers are present, are equally effective and have belied the commonly held notion that the cyberworld is fundamentally immaterial. See Lynch, "Laboratory Space and the Technological Complex" (cit. n. 5); Caroline Jones and Peter Galison, "Factory, Laboratory, Studio: Dispersing Sites of Production," in *Architecture of Science,* ed. Galison and Thompson; and Galison, *Image and Logic* (cit. n. 2).