One-Hundred Years of English-Language Acoustics Textbooks

Steven L. Garrett

> "A computer can provide the wrong answer with 7-digit precision a thousand times each second." (Garrett, 2020)

It is always worthwhile to reflect on the journey that has brought us to the current stage in our careers utilizing acoustical science and technologies. For many of us, the journey started with a friend, family member, teacher, or summer internship. What is rarely heard is the claim that the journey was started with a textbook. Yet, the textbook used in the introductory course(s) in vibration and sound usually created the vocabulary and provided the analytical techniques that we exploited when we entered training for various specialization, whether in ocean acoustics, bioacoustics, architectural acoustics, noise control, psychoacoustics, biomedical acoustics, speech, audiology, engineering, or physical acoustics. The choice of textbook topics and their coverage is neither unique nor universal. All of those choices reflect the prejudices of their authors.

The purpose of this article is to consider the "evolution" of English-language acoustics textbooks. Although this seems like a rather specialized topic, it is likely that each reader, no matter the field, has encountered one or a few textbooks that have influenced their education and careers. Thus, even if a reader did not use the textbooks discussed here, a fine outcome of reading this article might be to motivate readers to think about the most important textbooks they used, about the textbooks from which they are currently teaching or studying, and whether these textbooks have had influence in their respective fields.

Historical Context

For the past eighty-five years, two versions of one textbook have dominated the education of acoustics students throughout the United States and in many other English-speaking countries. It can be argued at a macroscopic level that these textbooks, Morse's *Vibration and Sound* (1948) and Kinsler and Frey's *Fundamentals of Acoustics* (1962), have done a good job of introducing aspiring acousticians to the field since there has clearly been progress during that time.

Given the progress that has taken place, it seems worthwhile to review the antecedents that led to those two textbooks as well as to examine the assumptions and prejudices those textbooks perpetuate. Over the past century, there have been gargantuan changes in the way that acoustics is practiced and the computational tools that have become available for calculation of the behavior of acoustical systems, whereas the content of acoustics textbooks has remained relatively stagnant with their focus on theoretical analyses to the exclusion of an experimentalist's perspective.

In acoustics, I like to mark the start of this transformative century in measurement with the invention of the condenser microphone by Wente in 1917. This was followed by the development of vacuum tube electronics that made it possible to produce instrumentation with a high-input electrical impedance that was also capable of providing substantial gain.

The corresponding explosion in computing power took place about a half-century later as digital electronics first exerted widespread influence within the acoustics community. For acoustics students, this change was heralded by the availability of handheld scientific calculators that replaced the slide rule as the preferred tool for the evaluation of mathematical expressions. The HP-35 was the first "scientific calculator" (see en.wikipedia.org/wiki/HP-35). It was introduced in 1972 for $395, equivalent to nearly $2,500 today.

By the 1980s, most scientists possessed desktop personal computers and software that could plot data and use

https://doi.org/10.1121/AT.2021.17.3.22

established statistical methods (Beers, 1957) to fit functions to deal with datasets that previously were far too cumbersome for casual application. Also in the 1980s, protocols were developed to connect personal computers to the digital instrumentation used in acoustics laboratories and for field experiments (e.g., multimeters, spectrum analyzers, function generators, thermocouple readers, sound level meters). Hunt (1978) cautioned that it would have been wrong "to ignore the profound changes in the scope of acoustics that have occurred [since 1950]."

With such important changes in the substance and practice of acoustics, it may be valuable to reflect on how little of the content and methods taught in the fundamental textbooks have changed over the last century. By the dawn of the twenty-first century, it was possible to generate numerical solutions to the complex coupled nonlinear differential equations that describe the thermokinetic behavior of vibroacoustical systems (Penelet and Garrett, 2019) and produce solutions to acoustical boundary-value problems for objects that did not have a shape that could be expressed in any of the 11 coordinate systems in which the wave equation was separable (Eisenhart, 1934).

The Dominance of the "Morse/Kinsler and Frey" Approach

The Source

The nineteenth century closed with the publication of the second edition of a monumental two-volume summary of the entire field of acoustics as it was understood at that time. It was written by the Nobel Prize-winning physicist John W. Strutt (also known as Lord Rayleigh). The first volume of *The Theory of Sound* (published in 1877) was written on a houseboat on the Nile while the author was recovering from rheumatic fever, so it contained few references. It focused on general theorems governing vibrating systems and the mathematics required for their description. Volume I addressed the dynamics of simple-harmonic oscillators and vibrating strings and the vibrations of thin bars, stretched membranes, plates, and curved shells.

The second volume was dedicated mostly to sound in fluids, with particular attention given to fluids contained within resonators. That volume contains many references, particularly for published experimental results. The first edition of both volumes was followed by a "revised and enlarged" second edition (Strutt, 1894). Rayleigh's choice of topics and his sequence of presentation, starting with simple vibrators, progressing from one-dimensional continua (i.e., strings and thin solid bars) to two-dimensional continua (i.e., membranes and plates) before addressing waves in fluids, is still how acoustics is organized for presentation to students of science and engineering in their introductory coursework, usually taken by upper-division undergraduates or first-year graduate students.

The part of Rayleigh's perspective that was not perpetuated in subsequent textbooks was his dedication to the experimentalist's perspective. In 1868, Rayleigh purchased laboratory apparatus that he set up in his baronial mansion, Terling Place, in Essex, UK (see bit.ly/3xm4VjR). This was because at that time there were no university laboratories. Indeed, little of the historic experimental work in the United Kingdom before Rayleigh's, by the likes of Young, Davy, and Faraday, was performed in a university. It was not until 1871 that Cambridge University established the Cavendish Professorship in Experimental Physics. When Rayleigh succeeded Maxwell as the second Cavendish Professor, in 1879, a substantial part of his effort and £1,500 of university funds (then equivalent to $7,280 and now worth about $3M) were dedicated to creating laboratory courses for large classes in heat, electricity and magnetism, elasticity, optics, and acoustics.

Rayleigh's 1904 Nobel Prize in Physics was awarded for his discovery of argon. He noticed that the mass of nitrogen gas prepared by a chemical reaction differed from the nitrogen extracted from the atmosphere by an amount that was small but larger than his estimated experimental uncertainty. The balance he achieved between theory and experiment was (unfortunately) not reflected in the textbooks that followed. Both Lamb (1925) and Morse (1948) focused on theory and ignored considerations related to experimental techniques and data analysis

The First Textbook

The first acoustics textbook of the post-Rayleigh era was written by Horace Lamb. Lamb made the same contribution as Rayleigh but to the field of fluid dynamics, with the publication of his book, *A Treatise on the Mathematical Theory of the Motion of Fluids*, published in 1879. Later editions were entitled *Hydrodynamics* (Lamb, 1932). Lamb's acoustics textbook, *The Dynamical Theory of*

Sound (1925), followed Rayleigh's sequence of topics. In his preface, Lamb expresses his hope that "the book may fairly be described as elementary and that it may serve as a steppingstone to the study of the writings of Helmholtz and Lord Rayleigh, to which I am myself indebted for almost all that I know of the subject."

In that same preface, Lamb is explicit in his neglect of "experimental methods" that he claims are "lying outside my province." Two features of Lamb's treatment that are sadly absent from subsequent textbooks are his application of the approximation techniques developed by Rayleigh in *The Theory of Sound* and Lamb's discussion of the elasticity theory before addressing waves in thin bars.

Philip Morse

By the mid-1950s, Morse's position as a leading American theoretical physicist was established by his publication, with Herman Feshbach, of the two-volume *Methods in Theoretical Physics* (Morse and Feshbach, 1953). Five years earlier, Morse published his second edition of *Vibration and Sound* (Morse, 1948). That textbook had a much greater long-term influence over acoustics education than might be appreciated because it was the template for *Fundamentals of Acoustics* (Kinsler and Frey, 1962). The theoretical focus of Morse's approach was clear in the title of his expanded "third edition," coauthored with K. Uno Ingard and retitled *Theoretical Acoustics* (Morse and Ingard, 1968).

Vibration and Sound was written as an introductory "textbook for students of physics and communication engineering" who were attending the Massachusetts Institute of Technology (MIT), Cambridge, where Morse had been teaching a course on acoustics for several years before the first edition was published in 1936. As stated in the preface, one aim of his textbook was "to give the student a series of examples of the *method* [Morse's italics] of theoretical physics; the way a theoretical physicist attacks a problem and how he finds its solution." It included problems for students at the end of each chapter and began with an introductory chapter that addressed units and "a little mathematics."

Other than the introductory (math) chapter, *Vibration and Sound* followed the same sequence of chapters as Lamb's *Dynamical Theory of Sound*. Lamb included Fourier's theorem as a separate chapter after his chapter on strings, and Morse combines both in his chapter on strings. Lamb's Chapter IX is titled "Pipes and Resonators," whereas Morse's Chapter VIII is titled "Standing Waves of Sound," but this is primarily a semantic difference.

Vibration and Sound has about 50% more pages than *The Dynamical Theory of Sound*. The increase in its bulk was due to the inclusion of some material on electroacoustics (e.g., piezoelectric transducers, condenser microphone), electrical analogs, and some additional applications requiring more advanced mathematical techniques (e.g., the stiff string, transient response, propagation in horns, density of modes in three-dimensional enclosures, reverberation time and steady-state response in auditoria, and normal mode frequencies for a kettle drum).

In the preface to the 1981 reprint of the second edition of *Vibration and Sound* by the Acoustical Society of America (ASA), Morse credited his first edition with making MIT an acoustics research center during and after World War II. Morse claimed, in the preface to the 1981 reprint, that by the 1960s, "it appeared that the textural popularity of the book had waned" (Morse, 1948, 1981).

Kinsler and Frey

The reason for the decline in the popularity of *Vibration and Sound* during the 1960s was the appearance of *Fundamentals of Acoustics* by Kinsler and Frey (1962), both physics professors at the Naval Postgraduate School (NPS), in Monterey, California. When their first edition was published in 1950, it was sent by the book review editor of *The Journal of the Acoustical Society of America* (*JASA*) to Morse for review because he was the author of the leading acoustics textbook at that time. Morse refused to write a review for *JASA* because he felt that it was improper for him to review his own textbook (Garrett, 1990).

In fact, the bulk of *Fundamentals of Acoustics* was taken directly from the second edition of *Vibration and Sound*, although many of the applications requiring more challenging mathematical techniques (e.g., scattering of sound from spheres and cylinders, modes of cylindrical enclosures) were absent from the Kinsler and Frey version. Several end-of-chapter problems were taken *verbatim* from Morse, although in the second edition, the units were changed from centimeter/gram/second (CGS) to meter/kilogram/second (MKS). The conventions for expression of variables were also updated (e.g., frequency was abbreviated as *f* instead of ν; vectors, phasor, and other complex variables were distinguished by **bold** fonts). Kinsler and Frey also added stand-alone chapters on applications like loudspeaker, microphones, speech, hearing, community noise, and architectural acoustics. Most importantly, from the perspective of the NPS was a detailed chapter on underwater acoustics that included attenuation in seawater, transmission loss and the SONAR equation, refraction in a constant or piecewise-linear sound speed gradient, bottom and surface scattering, and ambient noise.

The third (1982) and fourth (2000) editions were produced by two other NPS physics faculty members, Alan B. Coppens and James V. Sanders, who are listed as coauthors. The third edition deleted some calculations (e.g., correction to frequency due to the spring's mass in a harmonic oscillator) and expanded the underwater acoustics chapter. The fourth edition added an introduction to detection and estimation theory to the underwater acoustics chapter and added two more chapters. The first new chapter, titled "Selected Nonlinear Acoustic Effects," introduced some weak shock theory and the parametric array. The second, titled "Shock Waves and Explosions," was a topic that was included in the acoustics curriculum at the NPS but is not a subject that was commonly taught to the larger audience of acoustics students.

Only Fluids

Several other acoustics textbooks were produced that did not follow the Lamb template because they only addressed acoustics in fluids. Two of the most influential of those textbooks include Blackstock's textbook, *Fundamentals of Physical Acoustics* (2000) that introduces the wave equation for fluids on page 2 and Pierce's *Acoustics* (2019) that was first published in 1981 and introduces it on page 17. Both Pierce and Blackstock included more advanced topics, as did Skudrzyk (1971), Lighthill (1978), and Temkin (1981), so they were frequently used for more advanced courses.

An Alternative to the Legacy of Mid-Atlantic Theoreticians

For over sixty years, the four editions of *Fundamentals of Acoustics* have dominated acoustics education for students of science and engineering between 1960 and 2020. In addition to asking why that textbook was so successful, it may be important to consider the possibility that the perspectives and prejudices that are perpetuated in Kinsler and Frey's incarnation of the Lamb/Morse tradition are not optimal in an age dominated by computers. As D. A. Brown of the University of Massachusetts-Dartmouth likes to say, "Virtually every engineering problem is [now] solved with an 'Enter' key," and "Engineering without physics is faith" (email to author, April 7, 2021).

As argued in **Historical Context**, the sequence of acoustics textbooks that followed *The Theory of Sound* in the twentieth century were written by individuals who considered themselves to be theoreticians, even though Rayleigh was a champion of both rigorous experimental investigations and structured laboratory classes. Those textbooks were written in the glow of the "golden age" of analysis. In addition to Rayleigh's *Theory of Sound* and Lamb's *Hydrodynamics*, Love published the first edition of *A Treatise on the Mathematical Theory of Elasticity* in 1893 (Love, 1927). The turn of that century was an era when the methods developed for the solution of differential equations were being successfully exploited to unify a mind-boggling number of physical problems in the mechanics of continua.

This theoretical prejudice was "baked in" by the Lamb/Morse textbooks that include Kinser and Frey for the reasons already presented. Even though Kinsler and Frey taught in Monterey, California, their treatment reflected the mid-Atlantic perspectives that were formulated in the United Kingdom and Cambridge, Massachusetts. But starting in the 1950s, there was an authentically "Californian" alternative perspective that was emerging in the physics department at the University of California, Los Angeles (UCLA) that was already a leading force in architectural acoustics (Knudsen and Harris, 1950) and cinema under the direction of Knudsen and DelSasso (Shaw, 2011).

In 1948, after completing his PhD under Knudsen's supervision and wartime research at Pennsylvania State University, University Park (Schilling, 1950), Isadore Rudnick was hired as a junior faculty member in the physics department at UCLA, where he spent the remainder of his career (Garrett et al., 2017). In 1970, immediately after completing his Ph.D. on superfluid hydrodynamics (Putterman, 1974) under the supervision of the great Dutch physicist G. E. Uhlenbeck, Putterman was hired to work primarily as the theoretician for the Rudnick group. Uhlenbeck was a student of Ehrenfest, and Ehrenfest was a student of Boltzmann, so the arrival of Putterman in the Rudnick group brought a "genealogical" link to kinetic theory, the Ehrenfest-Boltzmann adiabatic principle (Putterman, 1988), and the fluctuation-dissipation theorem (Uhlenbeck and Goudsmit, 1929).

This created an "environment" where acoustics was taught as an application of continuum mechanics, "An acoustician is merely a timid hydrodynamicist." The textbooks that supported those classes and seminars were those by Lev Landau, who had received the Nobel Prize in Physics in 1962 for his two-fluid model of superfluidity in liquid helium. *Mechanics* (Landau and Lifshitz, 1960), *Theory of Elasticity*, *Statistical Physics*, and most importantly, *Fluid Mechanics* (Landau and Lifshitz, 1959) were all part of the graduate-level acoustics curriculum at UCLA. Students in that curriculum referred to the Landau and Lifshitz *Course of Theoretical Physics* as the "Wisdom of the Western World in Seven Volumes."

Understanding Acoustics

This West Coast alternative to the Morse/Kinsler and Frey approach to acoustic education was supposed to be documented in a new textbook that was to have been written by Rudnick and his son, Joseph Rudnick, who was also a physics professor at UCLA. Unfortunately, the onset of dementia around the time when the older Rudnick turned 70 made it impossible for him to write the planned textbook.

As I approached retirement in my own academic career, it became clear that I was the last of Rudnick's and Putterman's graduate students who was in a position to write such a textbook if the UCLA perspectives on acoustics had any possibility of being preserved for future generations. Fortunately, I had been Rudnick's teaching assistant when he last offered his upper-division course on acoustics and I had taken every course Putterman offered while I was a graduate student. The result was *Understanding Acoustics: An Experimentalist's View of Sound and Vibration* (Garrett, 2020).

As with the mid-Atlantic theorists, there was great reverence within Rudnick's research group for the works of Rayleigh. Unlike those mid-Atlantic theorists, the Rudnick group's concept of mathematics went beyond differential equations to included Rayleigh's prejudices regarding approximation techniques and the use of dimensional analysis (i.e., similitude).

> "In the mathematical investigations I have usually employed such methods as present themselves naturally to a physicist. The pure mathematician will complain, and (it must be confessed) sometimes with justice, of deficient rigor. But to this question there are two sides. For, however important it may be to maintain a uniformly high standard in pure mathematics, the physicist may occasionally do well to rest content with arguments which are fairly satisfactory and conclusive from his point of view. To his mind, exercised in a different order of ideas, the more severe procedures of the pure mathematician may appear not more but less demonstrative. And further, in many cases of difficulty, to insist upon the highest standard would mean the exclusion of the subject altogether in view of the space that would be required" (Strutt, 1894).

> "I have often been impressed by the scanty attention paid even by original workers in physics to the great principle of similitude. It happens not infrequently those results in the form of 'laws' are put forward as novelties on the basis of elaborate experiments, which might have been predicted a priori after a few minutes of consideration" (Strutt, 1915).

Tom Gabrielson put Rayleigh's sentiment more succinctly: "The dance between math and physics can be a thing of beauty but not if you force the feet of math to trample on the toes of physics" (email to author, April 30, 2021).

Understanding Acoustics incorporates an introduction to similitude and the use of the Buckingham π theorem (Buckingham, 1914) for problems in acoustics and vibration in its introductory mathematics chapter entitled "Comfort for the Computationally Crippled." That math chapter also stresses statistical concepts that apply to error analysis and to the least-squares fitting of data to mathematical functions.

The approximation methods that Rayleigh created, as well as fundamental principles such as adiabatic invariance (Rayleigh, 1902), are of particular importance in an era where many solutions to problems of interest are performed by a computer. In *Understanding Acoustics*, approximation techniques are introduced using problems for which an exact answer can be calculated to provide the student with an appreciation of their accuracy. Had Morse

(1948, 1981) used Rayleigh's "energy method" to determine the modes of a stiff string, he might have realized that his analysis gave the wrong frequencies (Garrett, 2020).

Unlike the damped simple harmonic oscillator in the Morse and the Kinsler and Frey treatments, the addition of the resistive element to the mass-spring oscillator opens a two-way street for the exchange of energy with the environment (Uhlenbeck and Goudsmit, 1929). Heat is generated in the mechanical resistance (i.e., dashpot; R_m,) that escapes to the surroundings, but that path also connects the oscillator to "the environment," which must share energy with the oscillator by virtue of the fact that the absolute (Kelvin) temperature of the environment and R_m are both nonzero.

For example, the mean potential energy of a spring with stiffness K that is in thermal equilibrium with its surroundings at absolute temperature T has an average mean-squared displacement of $\langle x^2 \rangle = k_B T / \mathrm{K}$, where $k_B \equiv 1.380649 \times 10^{-23}$ J/K (Boltzmann's constant). The mass never comes to rest! In vibroacoustic systems, our "uncertainty principle" is controlled by Boltzmann's constant, not Planck's constant. The growing availability of microphones and accelerometers based on microelectromechanical systems (MEMS) has renewed interest in the fundamental limitations imposed by thermal noise (Gabrielson, 1993).

The general lack of awareness of the coupling between fluctuations and dissipation has led some investigators to spurious conclusions in their evaluation of acoustical sensor performance: "...it appears that fiber sensors operating at room temperature offer detection sensitivities comparable to or exceeding cryogenic SQUID technology, which normally operate between 4 and 10 K" (Giallorenzi et al., 1982).

Similar errors arise resulting from the Morse/Kinsler and Frey failure to demonstrate the interrelationships of elastic moduli, particularly for isotropic solids, which have an elastic response that is completely specified by only two independent elastic moduli. Good evidence of the need for a new acoustics textbook is the large number of professionals, including acoustics faculty, who do not realize that a plane wave involves both hydrostatic compression and shear deformations: "If the propagation is truly planar, then shear stress is zero." That statement is not correct and is followed in a recent acoustics textbook by other justifications for sound attenuation due to "viscous effects [that] also arise as frictional resistance to expansion and contraction" (Ginsberg, 2019).

A separate chapter on elasticity in *Understanding Acoustics* also provides the opportunity to introduce viscoelasticity and a single-relaxation-time model using a simple combination of a spring and dashpot in series placed in parallel with another spring. Such an analysis leads to the "discovery" of the Kramers-Kronig relationships (Kronig and Kramers, 1928) that is important for understanding attenuation due to "bulk viscosity," which is the "resistance to expansion and contraction" through a relaxing variable in the equation of state (Landau and Lifshitz, 1959), not "viscous effects." It also allows discussion of rubber springs that simultaneously provide both stiffness and damping. Rubber springs play an important role in commercial vibration-isolation products.

Another change in the traditional sequence of topics places the theory of Helmholtz resonators before introduction of the wave equation, starting with a chapter that is dedicated to the ideal gas laws as a prototypical equation of state. Derivation of the isothermal and adiabatic gas laws also provides the opportunity to demonstrate the complimentary functions of the microscopic theory (i.e., kinetic theory and quantum mechanics) and the phenomenological theory (i.e., thermodynamics).

The linearized continuity equation is associated with the concept of acoustical compliance (i.e., the gas spring), and the linearized Euler equation introduces the concept of acoustical inertance. The combination provides an example of the fluidic equivalent of the simple harmonic oscillator known as a Helmholtz resonator (Helmholtz, 1885). More importantly, it provides a firm understanding of the equation of state, the continuity equation, and the momentum conservation equation before they are linearized and combined to produce the wave equation. If masses and springs are always analyzed before the vibration of strings, wouldn't it make sense to study Helmholtz resonators before introducing one-dimensional wave propagation in a fluid?

Discussion of the dissipative processes in fluids due to irreversibility, quantified by thermal conductivity and viscosity, is another area that is overlooked in the Morse/Kinsler and Frey treatment. The diffusion equation is just as easy to solve using a harmonic substitution as is the wave equation. Just as the wave equation introduces the wavelength as a "scale length" for propagation, the Fourier diffusion equation produces the thermal penetration depth and the Navier-Stokes equation introduces the viscous penetration depth as their relevant scale lengths (Landau and Lifshitz, 1959).

Failure to take these effects into account led Kinsler and Frey to calculate the quality factor of a Helmholtz resonator based only on radiation losses (Kinsler and Frey, 1962). In a typical Helmholtz resonator, viscous dissipation in the neck and thermal relaxation at the surface of the volume overwhelm the losses due to radiation, which comes in a distant third in its contribution to the reduction of the quality factor. Having been on the physics faculty at the NPS from 1982 to 1995, I was able to convince Coppens and Sanders to correct that error in the fourth edition.

Fundamental Defenses Against Erroneous Results

> "Thermodynamics is the true testing ground of physical theory because its results are model independent. It is the only physical theory of universal content which I am convinced will never be overthrown, within the framework of applicability of its basic concepts" (Einstein, 1979).

What do all of the discussions in this article have to do with the statement that was placed at its start: "A computer can provide the wrong answer with 7-digit precision a thousand times each second" (Garrett, 2020)? In this era where "Virtually every engineering problem is [now] solved with an 'Enter' key," it is more important than ever to have fundamental principles that are "model independent," thus not depending on any specific algorithm, to provide a check on computer-generated results. To paraphrase the comedian P. J. O'Rourke, "without those principles, giving a student access to a computer is like giving a teenager a bottle of whisky and the keys to a Ferrari."

For example, the Kramer-Kronig relationships restrict the real (i.e., in-phase) and imaginary (i.e., quadrature) components of any "susceptibility" that links stimulus to response in a linear-response theory. That result is dependent only on causality; an effect cannot precede its cause. Although Kramers and Kronig applied their discovery to the absorption and dispersion of X-ray spectra (Kronig and Kramers, 1928), it applies equally to the elastic moduli and loss tangents of an elastomer, the radiation resistance and hydrodynamic mass of a vibrating piston, and the sound speed and attenuation in a relaxing medium, among many other systems of interest to acousticians. In the Rudnick group, I was first introduced to its consequences when trying to understand the maximum attenuation per wavelength in a porous waveguide filled with superfluid helium. That maximum was related only to the speed of propagation in the limit where the flow resistance of the porous medium was zero (i.e., first sound) or infinite (i.e., fourth sound). The energy difference between X-rays (~10 keV) and a quantum liquid close to absolute zero temperature (~100 μeV) is gargantuan (Tarantino, 2004).

Similitude depends only on the units that are used to express parameters and variables in a model. Adiabatic invariance is a consequence of any change to a vibrating system's constraints that are made slowly enough that the normal mode shape remains unchanged (Strutt, 1902). It guarantees that the ratio of the energy to the frequency remains constant (Landau and Lifshitz, 1960). Adiabatic invariance applies to the transformation of a mode that is a solution in an enclosure with boundaries that can be expressed in one of the 11 coordinates in which the wave equation is separable (Eisenhart, 1934), to a shape like that of the Space Shuttle's cargo bay, having a cross section described by a hemiellipse on top of a truncated irregular octagon. It can also be used to relate the frequency shift in a resonator, due to the position of an object, to the radiation force on that object (Putterman et al., 1989).

Conclusions

The Morse and the Kinsler and Frey textbooks have launched the careers of many of us who now use acoustics in our careers. I used it as the primary textbook in the introductory acoustics courses I taught at the NPS (1982 to 1995) and in the Graduate Program in Acoustics at Penn State (1995 to 2010). I would tell my students that "Kinsler and Frey is the Listerine of acoustics; nobody likes the taste, but they use it twice each day." It contained most of the necessary results, but few of the reasons. On occasion, I would refer to it as the "satanic verses" (Rushdie, 1988), for example, when it incorrectly calculated the quality factor of a Helmholtz resonator, a result that would never had been accepted had the authors been experimentalists who actually measured the Q.

This article has attempted to show that the textbooks used to introduce many students to vibrating systems and sound propagation all have been tied to the insights of Lord Rayleigh. It also has shown that the textbooks from Lamb's *Dynamical Theory of Sound* (1925) through Kinsler and Frey's *Fundamentals of Acoustics* (1962) focused on Rayleigh's theoretical insights but knowingly neglected treating the approximation methods he introduced to applied mechanics and his experimental acumen. Acoustics was taught differently at UCLA. There, much attention was paid to the greater scope of Rayleigh's contributions, along with the introduction of more modern principles like the fluctuation-dissipation theorem, irreversibility and transport phenomena, linear-response theory (e.g., Kramers-Kronig relationships), viscoelasticity, and adiabatic invariance. With the rise in the use of computers to solve problems in science and engineering, I have argued that those fundamental principles and approximation techniques provide a necessary check on computers' abilities "to provide wrong answers to 7-digit precision."

Acknowledgments

Most of the historical content of this paper that describes Rayleigh's work was taken from R. B. Lindsay's "Historical Introduction" to the 1945 Dover edition of *The Theory of Sound*. The perspective I developed in my textbook was nurtured by my experience as a graduate student at UCLA under the supervision of Isadore Rudnick, Seth Putterman, and Martin Greenspan and by my long-term collaboration with Gregory Swift, starting from our time together in the physics department at the University of California, Berkeley in 1979. I am grateful to the support of the Penn State College of Engineering, which provided a year of sabbatical leave to get me started on my textbook project, and to the Paul S. Veneklasen Research Foundation, which helped support the production of my first edition and then provided a substantial subsidy to Springer to release the second edition as the first "open access" acoustics textbook.

References

Beers, Y. (1957). *Introduction to the Theory of Errors*, 2nd ed. Addison-Wesley, Cambridge, MA.

Blackstock, D. T. (2000). *Fundamentals of Physical Acoustics*. John Wiley and Sons, New York, NY.

Buckingham, E. (1914). On physically similar systems; Illustrations of the use of dimensional equations. *Physical Review* 4(4), 345-376.

Einstein, A. (1979). *Autobiographical Notes: A Centennial Edition*. Translated and edited by P. A. Schlipp. Open Court Publishing, Chicago, IL.

Eisenhart, L. P. (1934). Separable systems in Euclidean 3-space. *Physical Review* 45(6), 427-428.

Gabrielson, T. B. (1993). Mechanical-thermal noise in micromachined acoustic and vibration sensors. *IEEE Transactions on Electron Devices* 40(3), 903-909.

Garrett, S. L. (1990). *Oral History – Isadore Rudnick*. Interview of Isadore Rudnick by Steven L. Garrett on July 3, 1990. Niels Bohr Library & Archives, American Institute of Physics, College Park, MD. Available at https://acousticstoday.org/rudnick.

Garrett, S. L. (2020). *Understanding Acoustics: An Experimentalist's View of Sound and Vibration*, 2nd ed. Springer International Publishing jointly with the ASA Press, New York, NY. Free ebook version available at https://www.springer.com/in/book/9783030447861.

Garrett, S. L., Maynard, J. D., and Putterman, S. J. (2017). Isadore Rudnick (1917-1997): Acoustics in the service of physics. *Acoustics Today* 13(4), 12-20.

Giallorenzi, T. G., Bucaro, J. A., Dandridge, A., Sigel, G. H., Jr., Cole, J. H., Rashleigh, S. C., and Priest, P. G. (1982). Optical fiber sensor technology. *IEEE Journal of Quantum Electronics* QE-18(4), 626-665.

Ginsberg, J. H. (2019). *Acoustics – Textbook for Engineers and Physicists, Vol. I: Fundamentals*. Springer International Publishing jointly with the ASA Press, New York, NY.

Helmholtz, H. I. F. (1885). *Die Lehre von den Tonempfindungen* (*On the Sensations of Tone as a Physiological Basis for the Theory of Music*), 2nd ed. Longmanns & Co., London, UK.

Hunt, F. V. (1978) *Origins in Acoustics*. Yale University Press, Hartford, CT.

Kinsler, L. E., and Frey, A. R. (1962). *Fundamentals of Acoustics*, 2nd ed. John Wiley and Sons, New York, NY.

Knudsen, V. O., and Harris, C. M. (1950). *Acoustical Designing in Architecture*. John Wiley and Sons, New York, NY.

Kronig, R., and Kramers, H. A. (1928). Absorption and dispersion in X-ray spectra. *Physikalische Zeitschrift* 48, 174.

Lamb, H. (1925). *The Dynamical Theory of Sound*, 2nd ed. Constable & Co, London, UK.

Lamb, H. (1932). *Hydrodynamics*, 6th ed. Cambridge University Press, Cambridge, UK.

Landau, L. D., and Lifshitz, E. M. (1959). *Fluid Mechanics*. Pergamon Press, New York, NY.

Landau, L. D., and Lifshitz, E. M. (1960). *Mechanics*. Pergamon Press, New York, NY.

Lighthill, J. (1978). *Waves in Fluids*. Cambridge University Press, Cambridge, UK.

Love, A. E. H. (1927). *A Treatise on the Mathematical Theory of Elasticity*, 4th ed. Constable & Co., London, UK.

Morse, P. M. (1948). *Vibration and Sound*, 2nd ed. McGraw-Hill, New York, NY.

Morse, P. M., and Feshbach, H. (1953). *Methods of Theoretical Physics*. McGraw-Hill, New York, NY.

Morse, P. M., and Ingard, U. K. (1968). *Theoretical Acoustics*. McGraw-Hill, New York, NY.

Penelet, G., and Garrett, S. (2019). Periodic self-modulation of an electrodynamically-driven heated wire near resonance. *Journal of the Acoustical Society of America* 145(2), 998-1017.

Pierce, A. D. (2019). *Acoustics: An Introduction to Its Physical Principles and Applications*, 3rd ed. Springer International Publishing jointly with the ASA Press, New York, NY.

Putterman, S. J. (1974). *Superfluid Hydrodynamics*. North-Holland Publishing, Amsterdam, The Netherlands.

Putterman, S. J. (1988). Adiabatic invariance, the cornerstone of modern physics. *The Journal of the Acoustical Society of America Supplement 1* 83, S39.

Putterman, S., Rudnick, J., and Barmatz, M. (1989). Acoustic levitation and the Boltzmann-Ehrenfest principle. *The Journal of the Acoustical Society of America* 85(1), 68-71.

Rushdie, S. (1988). *The Satanic Verses*. Viking Press, London, UK.

Schilling, H. K. (1950). *Atmospheric Physics and Sound Propagation – Final Report*. Department of Army Project 3-99-04-022, Acoustics Laboratory, Department of Physics, The Pennsylvania State College, University Park.

Shaw, N. A. (2011). Up in Knudsen's attic: Some private papers of Vern O. Knudsen. *Acoustics Today* 7(1), 29-35.

Skudrzyk, E. (1971). *The Foundations of Acoustics: Basic Mathematics and Basic Acoustics*. Springer-Verlag, New York, NY.

Strutt, J. W. (Lord Rayleigh) (1894). *The Theory of Sound*, 2nd ed. Macmillan, New York, NY.

Strutt, J. W. (Lord Rayleigh) (1902). On the pressure of vibrations. *Philosophical Magazine* III, 338-346.

Strutt, J. W. (Lord Rayleigh) (1915). The principle of similitude. *Nature* 95, 66.

Tarantino, Q. J. (2004). *Kill Bill*, vol. 2. A Band Apart, Los Angeles, CA.

Temkin, S. (1981). *Elements of Acoustics*. John Wiley and Sons, New York, NY.

Uhlenbeck, G. E., and Goudsmit, S. (1929). A problem in Brownian motion. *Physical Review* 34, 145-151.

Wente, E. C. (1917). A condenser transmitter as a uniformly sensitive instrument for the absolute measurement of sound intensity. *Physical Review* 10, 39-63.

About the Author

Steven L. Garrett
sxg185@psu.edu

Pine Grove Mills,
Pennsylvania 16801, USA

Steven L. Garrett received his PhD in physics at the University of California, Los Angeles in 1977. He continued research in quantum fluids at the University of Sussex, Brighton, United Kingdom, as the first Hunt Fellow of the Acoustical Society of America, followed by two years at the University of California, Berkeley as a Fellow of the Miller Institute. Dr. Garrett joined the faculty of the Naval Postgraduate School in 1982 and became the United Technologies Professor of Acoustics in the Graduate Program in Acoustics at Penn State University, University Park, in 1995. He retired from Penn State in 2016 and is now a freelance physicist. Have calculator, will travel!