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Resource Letter APPO-1: Acoustics for Physics Pedagogy and Outreach

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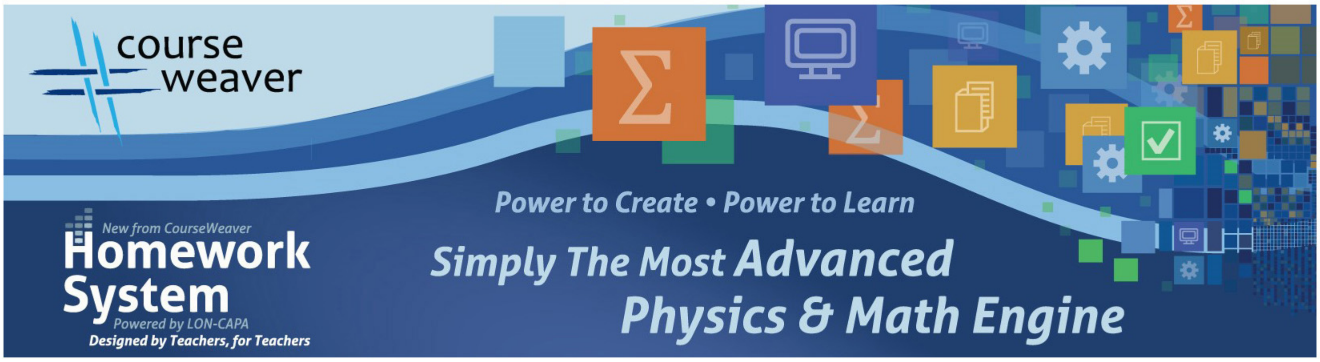

Resource Letter APPO-1: Acoustics for Physics Pedagogy and Outreach

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This Resource Letter provides a guide to the use of acoustics in physics pedagogy, whether in stand-alone courses, or as examples, analogies, or demonstrations in other contexts. Included are the principal journals and conference proceedings in the field, references to descriptions of existing acoustics courses, textbooks at different levels, and myriad online resources appropriate for courses at both the introductory and advanced undergraduate levels and for outreach. Also provided are topic-specific references that are divided into source, resonance, and traveling-wave phenomena. Because of the ability of sound to bridge the gap between mathematical understanding and everyday human experience, acoustical examples and demonstrations may deepen understanding of physical phenomena at all levels.
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I. INTRODUCTION

Acoustics is the study of sound—its generation, transmission, and reception—and includes mechanical compression waves in fluid and solid media. Stemming from the Greek *akoustikos*, meaning "of or for hearing," acoustics originated in the sixth century BCE with Pythagorus, who related musical consonance of different intervals to whole-number ratios. The understanding that sound is a wave can be traced back to Aristotle, who in the third century BCE proposed that sound was generated from a source that compressed the air around it and traveled as a disturbance. Greek and Roman amphitheaters, as well as buildings constructed, for example, by ancient Latin–American civilizations, showed their understanding that an acoustical environment could be changed and designed to achieve desired effects. From the 17th-century studies of the "fathers of acoustics" Marin Mersenne and Galileo Galilei, experimental and theoretical acoustics moved forward through the work of Newton, Hooke, Bernoulli, Laplace, Boltzmann, Poisson, Lagrange, d'Alembert, Ohm, Koenig, Kirchhoff, Stokes, Helmholtz, and Rayleigh, and others.

The etymology of the word *acoustics*, first coined by Joseph Sauveur in 1700, suggests a physical science inherently connected to a person's everyday experiences, from the electromagnetic forces that drive a loudspeaker (electroacoustics) to the enjoyment of a Mozart symphony (psychoacoustics). In 1964, Bruce Lindsay, a physics professor at Brown University, devised a circular diagram showing the broad scope and interdisciplinary nature of the field of acoustics. An adaptation of Lindsay's wheel, shown in Fig. 1, describes different technical areas of acoustics that stem directly from the mechanical vibrations that produce waves and exert an influence on the earth and life sciences, engineering, and the arts. The organization of the Acoustical Society of America (ASA), one of the four founding societies of the American Institute of Physics, reflects this broad scope. Its activities are divided among thirteen technical committees: Acoustical Oceanography, Animal Bioacoustics, Architectural Acoustics, Biomedical Acoustics, Engineering Acoustics, Musical Acoustics, Noise, Physical Acoustics, Psychological and Physiological Acoustics, Signal Processing in Acoustics, Speech Communication, Structural Acoustics and Vibration, and Underwater Acoustics. The ASA also has a committee on Education in Acoustics that promotes education through special sessions at meetings and sponsors a number of outreach initiatives.

Three earlier Resource Letters provide detailed information on specific subdisciplines of acoustics:

1. "Resource letter MA-1: musical acoustics," T. D. Rossing, Am. J. Phys. **45**, 944–953 (1975). (E)
2. "Resource letter MA-2: musical acoustics," T. D. Rossing, Am. J. Phys. **55**, 589–601 (1987). (E)
3. "Resource letter: TA-1: Thermoacoustic engines and refrigerators," S. L. Garrett, Am. J. Phys. **72**, 11–17 (2004). (E)

A related Resource Letter on physics demonstrations contains references, for example, the Physics Instructional

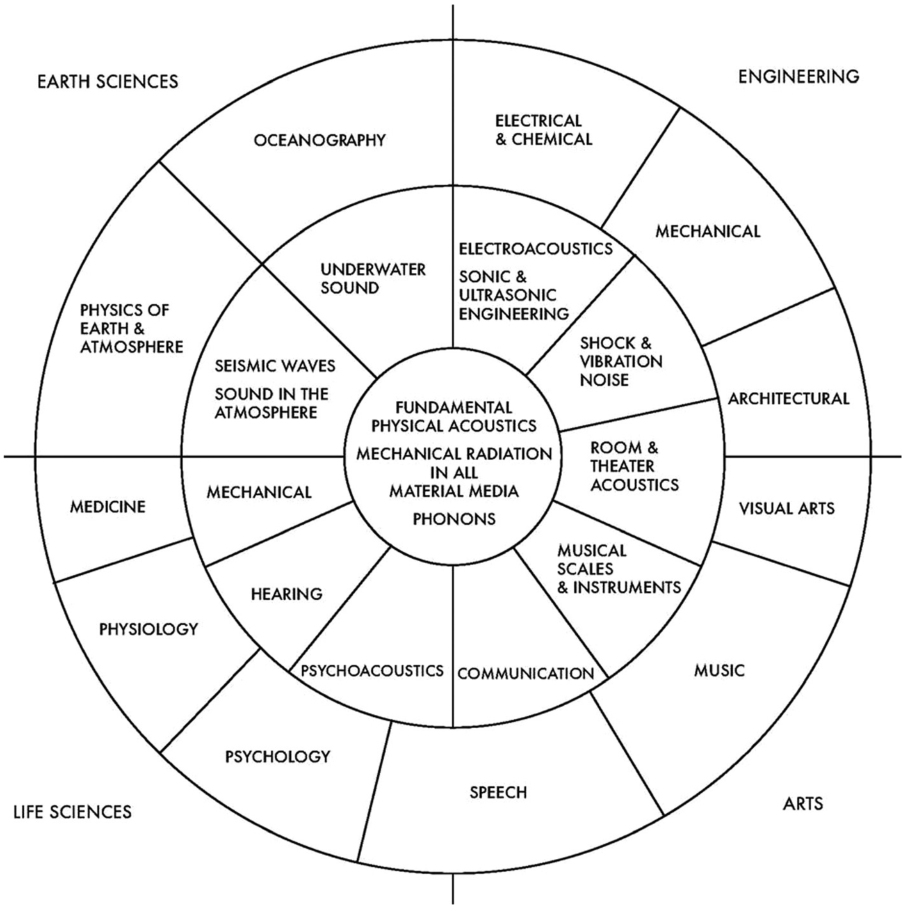

Fig. 1. Lindsay's wheel of acoustics, designed to illustrate the broad scope and interdisciplinary nature of the field.

Resource Association (PIRA) Demonstration Bibliography, that may be mined for numerous resources on acoustics-related demonstrations.

4. "Resource letter PhD-2: physics demonstrations," R. E. Berg, Am J. Phys. **80**, 181–191 (2012). (E)

The Resource Letter is fundamentally different from the earlier ones. A student in physics typically receives only a few weeks of instruction in acoustics, at most, through various courses. The purpose of this Letter is to offer ideas as to how the instruction of any discipline of physics may be enhanced through the use of acoustics examples, demonstrations, and the like.

The fundamentally interdisciplinary nature of acoustics allows significant interconnections to other fields of physics. As Frederick Hunt, a renowned professor of acoustics at Harvard University, wrote "…[A]coustics is characterized by its reliance on combinations of physical principles drawn from other sources; and that the primary task of modern physical acoustics is to effect a fusion of the principles normally adhering to other sciences into a coherent basis for understanding, measuring, controlling, and using the whole gamut of vibrational phenomena in any material." (*Origins in Acoustics: The Science of Sound from Antiquity to the Age of Newton*, Yale University Press, 1978, p. 5). Lindsay also noted the value of acoustics in the physics curriculum.

5. "What does acoustics have to offer?" R. B. Lindsay, Phys. Teach. **1**, 159–163 (1963). Argues that too many regard acoustics as a static science. Offers a survey of acoustical principles and their applications to a variety of physical phenomena. (E)

We approach this Resource Letter based on our experiences at Brigham Young University (BYU), which has one of the largest undergraduate physics programs in the country and a strong optional program in acoustics at the undergraduate and graduate levels. This Resource Letter contains information for those who are interested in developing an advanced undergraduate or graduate acoustics course within their department, incorporating acoustics-based demonstrations into their undergraduate physics courses, or using acoustics to illustrate wave phenomena in advanced contexts. Also included are resources that could help with outreach activities, because of the ability of sound to connect with, and enrich, the human experience. We provide summaries of research journals, courses in acoustics with emphasis on active learning, textbooks, online resources, and demonstrations as they apply to different acoustical phenomena.

II. JOURNALS AND CONFERENCE PROCEEDINGS

Journal articles and conference proceedings in acoustics serve as a valuable window into current research topics and sources for examples. The ASA maintains a list of acoustics-related journals and magazines at http://acoustics.org/.

A. Publications by the Acoustical Society of America

Journal of the Acoustical Society of America—JASA covers the different areas of acoustics described previously, abstracts from ASA meetings, and reviews of acoustical patents. In addition, *JASA* also publishes review articles that are a useful entry point for the topic.

JASA Express Letters—*JASA-EL* consists of short, open-access papers published primarily online.

Acoustics Today—This publication provides a broad perspective on research and other ASA activities.

Proceedings of Meetings on Acoustics—*POMA* is an open-access journal begun in 2007 by ASA. Its papers are linked to ASA meeting abstracts or are from other acoustics meetings and workshops.

B. Other journals and magazines

Given the breadth of acoustics, there are many physics or engineering journals in which sound-related research articles appear, e.g., the AAPT journals, *Journal of Fluid Mechanics*, *Journal of Applied Physics*, *IEEE Journal of Ocean Engineering*, etc. Below is a list of journals whose principal scope is the publication of fundamental and applied research in acoustics.

Acta Acustica united with Acustica—Journal of the European Acoustics Association. Education is not within its scope, but the history of acoustics is.

Journal of Sound and Vibration—Its scope is more limited than *JASA*, and it does not contain papers on education or pedagogy.

Journal of Vibration and Acoustics—Journal of the American Society of Mechanical Engineers.

Journal of the Audio Engineering Society—Includes papers on loudspeaker design and testing, advanced sound recording methods, and improved sound recording environments.

Noise Control Engineering Journal—Journal of the Institute of Noise Control Engineering, an international organization.

Applied Acoustics—A journal of primarily applied studies that aims to provide a forum for the exchange of practical experience in applications of acoustics.

Sound and Vibration—A trade magazine with applied content focused on perspectives, products, and processing techniques useful in industrial measurements and analysis.

International Journal of Aeroacoustics and *Building Acoustics* are examples of specialty journals within acoustics.

C. Conference proceedings

International Congress on Acoustics—Its triennial meetings are sponsored by the International Commission for Acoustics. The 2010 and 2013 proceedings are freely available online. See http://icacommission.org.

Noise-Con and Internoise Proceedings—These U.S.-based (Noise-Con) and international noise-focused conferences are sponsored by the Institute of Noise Control Engineering. See http://inceusa.org.

International Symposium on Nonlinear Acoustics—These triennial conferences attract a variety of papers on the characteristics and applications of high-amplitude sound waves. Some volumes are available as AIP conference proceedings; see http://proceedings.aip.org.

AIAA Aeroacoustics Meetings—These meetings are focused on the generation and propagation of noise by turbulence (e.g., jet noise), by structural interaction with unsteady flow, and the like. Papers are available at www.aiaa.org.

International Conference on Acoustics, Speech, and Signal Processing—Sponsored by the Institute of Electrical and Electronic Engineers. For papers, see http://ieee.explore.org.

Biennial Conference on Mechanical Vibration and Noise—Sponsored by the American Society of Mechanical Engineers; for papers see http://proceedings.asmedigitalcollection.asme.org.

International Congress on Sound and Vibration—Sponsored by the International Institute of Acoustics and Vibration; for proceedings see http://iiav.org.

III. COURSE DESCRIPTIONS

One of the main obstacles to training more students in acoustics is the relatively small number of acoustics courses offered at the undergraduate level.

6. "Acoustics courses at the undergraduate level: How can we attract more students," I. Busch-Visniach and J. E. West, Acoust. Today **3**, 28–36 (2007). Explains the need for training more acousticians and the dearth of acoustics classes at the undergraduate level. Presents several ideas for attracting students to study acoustics: (1) offer more introductory-level acoustics electives; (2) create innovative textbooks with an online component; (3) concentrate on a variety of real-world applications in courses and textbooks; (4) develop websites with supplemental material; and (5) commit to attracting a more diverse student population to acoustics. (E)

A special issue on Acoustics Education was published as part of the *Journal of the Acoustical Society of America* in 2012 and included course descriptions that emphasize the importance of promoting student engagement to facilitate learning.

7. "Creating an active-learning environment in an introductory acoustics course," T. B. Neilsen, W. J. Strong, B. E. Anderson, K. L. Gee, S. D. Sommerfeldt, and T. W. Leishman, J. Acoust. Soc. Am. **131**, 2500–2509 (2012). Describes the course at Brigham Young University, entitled "Descriptive Acoustics," which is an eclectic course that appeals to a wide variety of undergraduate students and uses Ref. 21 as the textbook. Explains efforts to update the course to include active-learning methodology to promote the student-based learning outcomes. An associated online electronic repository contains videos of some demonstrations and additional audio clips. (E)

8. "Overview of a university course on acoustics and noise," N. J. Kessissoglou, J. Acoust. Soc. Am. **131**, 2510–2514 (2012). Describes an upper-level undergraduate and beginning graduate-level course at the University of New South Wales entitled "Fundamentals of Noise." Its ten course units and corresponding learning objectives and assessments are listed. (I)

9. "Acoustic testing and modeling: An advanced undergraduate laboratory," D. A. Russell and D. O. Ludwigsen, J. Acoust. Soc. Am. **131**, 2515–2524 (2012). Presents detailed descriptions of two of the laboratory experiences at Kettering University and discusses how the student requirements, including their laboratory notebooks, are assessed. Also explains the requirement for groups of students to prepare research papers about the agreement between experiment and computational models. (I, A)

10. "Student design projects in applied acoustics," J. Bös, K. Moritz, A. Skowronek, C. Thyes, J. Tschesche, and H. Hanselka, J. Acoust. Soc. Am. **131**, 2525–2531 (2012). Documents the need for highly trained acousticians, to fulfill which students must have meaningful projects and courses that have a balance of theory and hands-on applications. Presents details about the advanced design projects, in which students solve real-world problems that are important to companies and, in which they gain valuable scientific or engineering experience and soft-skills such as teamwork, communication, and presenting their work. (I)

The following articles provide additional information about the use of active-learning techniques.

11. "The state of acoustics education at Brigham Young University," K. L. Gee, S. D. Sommerfeldt, and T. B. Neilsen, Proc. Mtgs. Acoust. **11**, 025002 (2012). Recent enhancements of the acoustics courses offered by the BYU physics department emphasize the importance of hands-on laboratory training to prepare students for internship, entry-level acoustics positions and graduate school. (I)

12. "Application of active-learning techniques to enhance student-based learning objectives," T. B. Neilsen and K. L. Gee, Proc. Mtgs. Acoust. **14**, 025001 (2012). Highlights techniques used in an introductory survey course and an upper-level undergraduate course to enhance active learning and student engagement. (E,I)

13. "Use of a Just-in-Time Teaching technique in an introductory acoustics class," T. B. Neilsen and K. L. Gee, Proc. Mtgs. Acoust. **18**, 025001 (2012). Pre-class learning activities (a variation of Just-in-Time Teaching) have been developed for an introductory acoustics course that provides students with the opportunity to engage with a new topic prior to coming to class. Activities include simple experiments, observational exercises, and interactive online simulations. Students are required to write about their experiences prior to coming to class, which provides the instructor with insights into their level of understanding and increases their ability to communicate with acoustics terminology. (E)

14. "Application of Just-in-Time Teaching to advanced acoustics courses," K. L. Gee and T. B. Neilsen, Proc. Mtgs. Acoust. **18**, 025002 (2012). The principles of Just-in-Time Teaching have been applied in an upper-level undergraduate and a graduate-level acoustics course. Pre-class quizzes have been carefully crafted to probe the students' understanding. The students' responses provide a natural starting point for class discussions. (I)

15. "Graduate and undergraduate laboratory courses in acoustics and vibration," A. A. Glean, J. Judge, J. F. Vignola, P. F. O'Malley, and T. J. Ryan, Proc. Mtgs. Acoust. **12**, 025002 (2012). Describes how acoustics-based experiments are used in a laboratory course at the Catholic University of America to introduce undergraduate mechanical engineering students to acoustics principles with a wide range of applications, including data acquisition, signal digitization and processing. The graduate laboratory course takes these skills to a higher level and emphasizes automated data collection and the manipulation of large data sets. In both courses, students are expected to develop their technical writing skills. (I, A)

16. H. E. Bass, "Research and education in physical acoustics at the University of Mississippi, USA," Appl. Acoust. **41**, 285–293 (1994). Describes the academic program, with its emphasis on the traditional physics program, along with its research opportunities and facilities. (E)

17. O. I. Zaporozhets and V. I. Tokarev, "Acoustics at the Kyiv International University of Civil Aviation," Appl. Acoust. **55**, 89–98 (1998). Founded in 1947, its faculty and students have investigated a wide variety of acoustics problems related to aviation acoustics. Describes examples of their projects. (E,I)

18. R. D. Celmer, M. C. Vigeant, and A. Eckel, "University of Hartford's Acoustics Engineering Lab," Sound Vib. **44**, 6–7 (2010). Program website: http://uhaweb.hartford.edu/celmer/index.htm (Last viewed August 28, 2013). The University of Hartford offers B.S. degrees in mechanical engineering with acoustics concentration, and in engineering with a major in acoustical engineering and music. Both programs provide students with opportunities to gain tools and knowledge needed to be successful in their future careers. The required senior project plays a large part in providing students with real-world experiences. (E)

19. "Experience teaching acoustics at the senior-undergraduate and first-year graduate levels," D. R. Dowling, Proc. Mtgs. Acoust. **19**, 025002 (2013). Describes several low-cost, demonstrations for an undergraduate class and acoustics-related boundary-element and finite-element problems for graduate students. (I,A)

20. "Using your ears: A novel way to teach acoustics," L. Ronsse, D. J. Cheene, and S. Kaddatz, Proc. Mtgs. Acoust. **19**, 025005 (2013). Describes how auditory simulations of the acoustical effects caused by transmission through barriers and varying absorption distribution in rooms are used in an introductory level acoustics class at Columbia College in Chicago. IL. (E)

IV. TEXTBOOKS

Nearly every introductory physics textbook includes a chapter on acoustics and many monographs are specifically dedicated to its science and applications, including handbooks that provide concise information and entry points to many of its topics. The ASA maintains a list of acoustics-related books at http://acoustics.org. Below are listed textbooks at different levels. Topical textbooks that could be used as resources in other advanced physics classes are described in Section VI.

A. Introductory textbooks

These textbooks are appropriate from high school through introductory college-level courses. The mathematical rigor varies. Many of these introductory texts have an emphasis on musical acoustics.

21. **Music Speech Audio**, W. J. Strong and G. R. Plitnik, 4th ed. (Brigham Young University Academic Publishing, Provo, UT, 2013). (E)

22. **The Science of Sound**, T. D. Rossing, F. R. Moore, and P. A. Wheeler, 3rd ed. (Addison-Wesley, Boston, 2001). (E,I)
23. **The Physics of Sound**, 3rd ed., R. E. Berg and D. G. Stork (Addison-Wesley, Boston, 2004). (E)
24. **Introductory Musical Acoustics**, M. J. Wagner, 4th ed. (Contemporary Publishing Co. of Raleigh, 2009). (E)
25. **Signals, Sound, and Sensation**, W. M. Hartmann (American Institute of Physics, New York, 2004). (E)
26. **Fundamentals of Musical Acoustics**, A. H. Benade, 2nd ed. (Dover, New York, 1990). This is a reprint of the 1976 edition; it served as the foundation for other texts on the topic. (E)
27. **Principles of Musical Acoustics**, W. M. Hartmann (Springer, New York, 2013). Treats mechanical vibration and sound waves, properties of standing waves, Fourier analysis, the auditory system, speech, audio, and families of musical instruments. (E)
28. **Basic Acoustics**, D. E. Hall (Harper and Row, New York, 1986). Mixes practical applications with elementary results and quantities then goes on to rigorous mathematical and theoretical discussions. (E,I)
29. **Musical Acoustics**, D. H. Hall, 3rd Ed. (Brooks-Cole, Pacific Grove, CA, 2002). (E)
30. **Why You Hear What You Hear: An Experiential Approach to Sound, Music, Psychoacoustics**, E. J. Heller (Princeton Univ. Press, New Jersey, 2013). Presents acoustical principles with emphasis on real-world applications. Includes helpful diagrams and results from numerical examples. The supplementary online resources found at http://www.whyyouhearwhatyouhear.com/ provide links to additional online material. (E)
31. **Acoustical Design in Architecture**, V. O. Knudsen and C. M. Harris (Acoust. Soc. Am., New York, 1980). Introduces the use of physics to design listening environments. (E,I)

B. Advanced undergraduate textbooks

We take "advanced" to mean that the textbook treats the wave equation and its solutions in a rigorous fashion—students probably would take a class using these textbooks after, or concurrently with an undergraduate mathematical-methods course. We list only texts that primarily treat acoustical waves.

32. **Fundamentals of Acoustics**, L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, 4th ed. (Wiley & Sons, New York, 2000). Covers forced and free simple harmonic oscillators, moves through mechanical vibrations and transverse wave propagation and then into acoustic waves. This text is one of the more widely used textbooks at the advanced undergraduate and beginning graduate levels. (I,A)
33. **The Science and Applications of Acoustics**, D. R. Raichel, 2nd ed. (Springer, New York, 2010). Presented at a less advanced mathematical level than Ref. 32, contains various applications. Comments on a previous edition were published by K. A. Cunefare, J. Acoust. Soc. Am. **126**, 1671–1680 (2009). (I)
34. **Introduction to Acoustics**, R. D. Finch (Pearson/Prentice-Hall, Upper Saddle River, NJ, 2004). Discusses a framework of acoustics from a systems-theory approach. It is aimed more toward the engineer but is valuable for the student researcher in its treatment of acoustical instrumentation and signal analysis. (I)
35. **Noise Control: From Concept to Application**, C. Hansen (Taylor & Francis, London, 2005). Clearly aimed toward the engineer, but does a good job in presenting the student with models that can be used to approximate the essential physics found in real-world scenarios. (I)
36. **An Introduction to Acoustics**, R. H. Randall (Dover, Mineoala, NY, 2005). Reprint of a 1951 edition. Its information on hearing, microphones, and other topics is dated, but its mathematical treatment of vibration and wave phenomena is quite rigorous. (I,A)
37. **Principles of Vibration and Sound**, T. D. Rossing and N. H. Fletcher, 2nd ed. (Springer, New York, 2004). Emphasizes room and musical acoustics, but also contains other topics, for example, transducers, environmental noise, underwater sound. (I)
38. **Acoustics for Engineers: Troy Lectures**, J. Blauert and N. Xiang, 2nd ed. (Springer-Verlag, Berlin, 2009). Treats oscillators, analogous circuits, and transducers before moving into an advanced undergraduate or beginning graduate-level treatment of waves in fluids. Measurement techniques and data processing considerations are mixed in, allowing the student to see applications. Analogies between mechanical, electrical, and acoustical oscillations could help the physics student to establish an overall framework. (I,A)

C. Advanced textbooks

The line between some of the advanced undergraduate and graduate textbooks is somewhat blurred, but the textbooks listed below are used in graduate acoustics courses. They may include more rigorous treatments of nonlinear phenomena, diffraction, and scattering, propagation through inhomogeneous media, and the like.

39. **Acoustics: An Introduction to its Physical Principles and Applications**, A. D. Pierce (Acoustical Society of America, Melville, NY, 1989). Covers the generation of sound by sources in one and more dimensions, propagation in homogenous and inhomogeneous media, with and without losses, in both the linear and nonlinear regimes. Its extensive footnotes lead the reader back to original, historical references. (A)
40. **Fundamentals of Physical Acoustics**, D. T. Blackstock (Wiley & Sons, New York, 2000). Covers acoustic-wave generation and propagation in separable geometries and has detailed treatments of reflection, transmission, and absorption phenomena. Its problem sets are well formulated to provide physical insight. (A)
41. **Acoustics: Basic Physics, Theory, and Methods**, P. Filippi, D. Habault, J. P. LeFebvre, and A. Bergassoli (Academic, London, 1999). Despite its innocuous title, the mathematical and numerical methods used to treat acoustical phenomena are unmistakably at the graduate level. (A)
42. **Theoretical Acoustics**, P. M. Morse and K. U. Ingard (Princeton U. P., NJ, 1987). This 949-page textbook presents an in-depth analytical treatment of many topics in acoustics, including diffraction, scattering, and nonlinearity, and advances in plasma acoustics and acousto-optical interactions. (A)

43. **Elements of Acoustics**, S. Temkin (Acoustical Society of America, Melville, NY, 2001). Approaches advanced acoustics as a subset of fluid mechanics, another topic not heavily treated within the physics curriculum. (A)

44. **Acoustics: Sound Fields and Transducers**, L. L. Beranek and T. J. Mellow (Academic, Oxford, 2012). Focuses mostly on electroacoustics, its in-depth discussion of equivalent circuits would be suitable for a graduate course on instrumentation. (I, A)

45. **Electroacoustics**, M. Kleiner (Taylor & Francis, London, 2013). Use equivalent electrical circuit analogies to teach fundamentals of acoustical and mechanical systems for the advanced undergraduate and graduate student. (I,A)

46. **The Foundations of Acoustics**, E. Skudrzyk (Springer-Verlag, New York, 1971), reprinted by ASA. Advanced coverage of the mathematics and physics of acoustics. Topics include integral transforms and Fourier analysis, signal processing, probability and statistics (relatively unique among acoustics texts), solutions to the wave equation, and radiation and diffraction of sound. (A)

47. **Thermoacoustics: A unifying perspective for some engines and refrigerators**, G. W. Swift (Acoust. Soc. Am., New York, 2002). Concentrates on thermoacoustics, but also contains lumped-element approach to acoustical analysis and discusses simple harmonic motion, ideal gas laws, heat transfer, and the like, from an acoustical perspective. (A)

48. **Fundamentals of Acoustic Field Theory and Space-Time Signal Processing**, L. J. Ziomek (CRC Press, 1995). Covers sources, arrays and signal processing with primary application to underwater acoustics. (A)

D. Handbooks

In addition to textbooks, there are some comprehensive handbooks that provide a suitable starting point for a seminar or short course on a specific topic in acoustics.

49. **Encyclopedia of Acoustics**, edited by M. J. Cocker (John Wiley and Sons, New York, 1997).

50. **Springer Handbook of Acoustics**, edited by T. D. Rossing (Springer, New York, 2007).

51. **Handbook of Noise and Vibration Control**, edited by M. J. Crocker, Ed. (Wiley and Sons, New York, 2007).

52. **Handbook of Acoustical Measurements and Noise Control**, edited by C. M. Harris (Acoustical Society of America, Melville, NY, 1998).

53. http://www.bksv.com/library/primers. Contains links to the Bruel and Kjaer primers on topics such as sound intensity, hearing testing, and human vibration and handbooks on acoustical measurement theory, techniques, and analysis.

V. ONLINE COURSE CONTENT

Two websites that contain databases to online resources are:

54. http://www.compadre.org. This repository for the physics-education community has numerous resources for teaching acoustics and wave physics.

55. http://www.merlot.org. This electronic-resource repository is more general, but an "acoust*" keyword search yielded many helpful resources.

The references below are dedicated to course content and resources. The following one is an unique example of using social media to help students engage in the material and incorporate classroom experiences into their everyday acoustical experiences.

56. "Acoustic tweets and blogs: Using social media in an undergraduate acoustics course," L. M. Wang, Proc. Mtg. Acoust. **18**, 025005 (2012). Explains the author's efforts to use tweets and a class blog to supplement students' experiences in a undergraduate architectural acoustics course and help them to more closely observe acoustical phenomena in their everyday experiences. (E)

A. Complete courses

Resources for a number of acoustics-related courses are found online in the form of notes and videotaped lectures, laboratory exercises, and the like. General resources are listed below; topic-specific references are found in Sec. VI.

57. http://usna.edu/Users/physics/ejtuchol/teaching/SP436.php. This advanced undergraduate course uses Ref. 32 as a textbook and contains a significant laboratory component. This website contains slides and laboratory handouts. (I)

58. http://ocw.mit.edu/courses/physics/8-03-physics-iii-vibrations-and-waves-fall-2004/. This is one version of an MIT introductory waves course, including acoustics, as archived through their OpenCourseWare. Another (spring 2003) has a more complete version of lecture notes: http://ocw.mit.edu/courses/physics/8-03-physics-iii-spring-2003/lecture-notes/. (I)

B. Freely available online texts

59. http://en.wikibooks.org/wiki/Acoustics. This presently is a featured book on the wikibooks website because of its substantial content and formatting. Although it is not a complete book in terms of flow, its authors have pulled together resources from a variety of fields to create a valuable tool for the student of acoustics. (I)

60. http://www.indiana.edu/~emusic/etext/toc.shtml. This e-book has been developed as part of a class project. After an introduction to acoustics at a basic level, it focuses on audio acoustics, from synthesis to recording. (E)

61. http://www.compadre.org/precollege/items/detail.cfm?ID=3612. **Physics of Music and Musical Instruments**. D. Lapp (Tufts University, 2003). Written at a high-school level or at a general-education science level, this book serves as an invaluable resource for connecting with a younger audience through outreach activities. (E)

62. http://www.people.fas.harvard.edu/~hgeorgi/onenew.pdf. Free wave physics textbook, with a chapter on acoustics. (E,I)

C. Animations and audio and video clips

63. http://www.acs.psu.edu/drussell/demos.html. Dan Russell's award-winning website containing animations related to acoustics and vibrations, as well as links to videos on his YouTube channel. (E,I)

64. http://phet.colorado.edu. This website containing interactive animations on Fourier series and other acoustics or wave phenomena. (E)

65. http://falstad.com/mathphysics.html. Paul Falstad has a number of outstanding interactive resources that demonstrate wave concepts in one, two, and three dimensions. Particularly applicable to acoustics are his three-dimensional mode animations, an acoustic interference demonstration, and his vocal tract model that shows how different vowels are formed. (E,I)

66. "Physclips: Multimedia, multi-level learning, and teaching resources," J. Wolfe and G. Hatsidimitris, Proc. Mtgs. Acoust. **18**, 025003, 1–7 (2012). Physclips, developed at the School of Physics, University of New South Wales, provides multimedia resources for the mechanics, waves and sound topics in introductory physics courses. The physclips consist of ten-minute audio-visual learning experiences. See http://www.animations.physics.unsw.edu.au/. Volume II deals specifically with waves and sound. (E)

67. http://physics-animations.com/Physics/English/waves.htm. In addition to other animations, this website contains a simple but particularly effective illustration of the Doppler shift. (E)

68. http://www.acoustics.salford.ac.uk/feschools/. Contains a large number of videos and animations used to explain acoustical phenonema. (E)

Though unavailable for electronic download, the following two links are to resources on CD/DVD format:

69. http://www.physics.umd.edu/lecdem/services/refs/DIAdescrip.htm. **Demonstrations in Acoustics**, R. E. Berg and D. G. Stork (Physics Department, University of Maryland, 1979, 2004). Two 2-hour DVDs with demonstrations in vibrations, waves, and sound, at the introductory level. (E)

70. http://www.abdi-ecommerce10.com/asa/. The Acoustical Society of America has published a CD containing tracks related to the perception of sound, entitled "Auditory Demonstrations Compact Disc." (E)

D. Freely distributed software

While software packages and computer technology are continually changing, the following references are examples of software that can be used to generate, record, or analyze sounds.

71. "Acoustics education: experiments for off-campus teaching and learning," G. Wild and G. Swan, in *Proceedings of 20th International Congress Acoustics* (2010), pp. 1–5. Home-based labs with free software for PCs to study musical instruments and standing waves. (E)

72. "Educational analysis of a first year engineering physics experiment on standing waves: based on the ACELL approach," X. R. Bhathal, M. D. Sharma, and A. Mendez, Eur. J. Phys. 31, 23–35 (2010) Illustrates the use of a sound card and PC-based oscilloscope. Provides an example of a simple experiment to investigate tube resonances of a musical instrument. (E)

73. http://www.lanl.gov/thermoacoustics/DeltaEC.html. This software was developed for modeling thermoacoustic engine and refrigerator performance, but can be used to model simpler resonator or branch networks. Includes a 300-page users' manual with a tutorial and mathematical algorithms. (I,A)

74. http://www.sillanumsoft.org/. Visual Analyzer provides a simultaneous display of oscilloscope and spectrum analyzer. (E,I)

75. http://www.qsl.net/dl4yhf/spectra1.html. Spectrum Laboratory is a spectrum analyzer with real-time waterfall spectrogram display options. (E,I)

76. http://www.arizona-software.ch/audioxplorer/?ref=fr. AudioXplorer was developed to run for Mac OS X; although it is freely available, it is no longer being supported. (E)

77. "The hope of Audacity® (to teach acoustics)," J. Groppe, Phys. Teach. **49**, 99–102 (2011). Describes how the freely available software package Audacity® can be used as a signal generator and to demonstrate destructive interference and beat freuqencies. Explains how a laser show kit can be driven by Audacity® to visualize how frequencies combine to make music. (E)

78. http://www.fon.hum.uva.nl/praat/. Praat is an excellent speech-analysis software package that is available on multiple platforms. This could be used to help extract the vocal tract resonances in a physics setting. (I)

79. http://www.hometheatershack.com/roomeq/. The Room EQ Wizard is a multiplatform room-acoustics-analysis software package, but also contains a full-feature sound level meter and spectrum analyzer. (E,I)

80. http://audacity.sourceforge.net/. Audacity® is an open-source, multiplatform sound recording and editing package. (E)

81. "Four free software packages related to the physics of sound," D. Oliver, J. Underwood, D. Marotta, J. Kane, and M. Scott, Phys. Teach. **51**, 101 (2013). References four basic signal-generation and analysis packages, appropriate for simple uses. (E)

82. http://www.faberacoustical.com/mac_apps/ While the full package does is not free, free trials of the signal generator, real-time spectrum analyzer, and acoustical measurement toolbox designed for Macs can be useful in a classroom setting. The accompanying website http://www.faberacoustical.com/ios_apps/ lists software available at the iTunes store for iPads and iPhones. (E,I)

83. "Creating interactive acoustics animations using Mathematica's Computable Document Format," D. A. Russell, Proc. Mtgs. Ac. **19**, 025006 (2013). Explains how Compatible Document Format (CDF) can be used to create interactive *Mathematica®* plots, calculations, and animations that can be exported as stand-alone objects and imbedded in webpages. A step-by-step example is provided. (E,I)

VI. TOPIC-SPECIFIC RESOURCES

Resources to specific sub-topics might serve as examples or analogies in an acoustics or other physics course. We primarily list relatively recent publications that likely use up-to-date laboratory equipment and software packages. Our nonexhaustive list below is divided into three principal categories: sources, resonance phenomena, and acoustic propagation.

A. Acoustical sources

Simple sources of sounds, like monopoles and dipoles, build student intuition of radiated power and source directivity. Creation of higher-order sources forms the basis of active noise control and underlies the decomposition of complex sources in terms of equivalent simple sources, as in acoustical holography. Arrays of phased sources produce directional radiation patterns that can be steered electronically and can serve as the basis for effective demonstrations and laboratory exercises.

84. "Acoustic monopoles, dipoles, and quadrupoles: An experiment revisited," D. A. Russell, J. P. Titlow, and Y. J. Bemmen, Am. J. Phys. **67**, 660–664 (1999). Desribes a relatively simple set-up that allows students to hear and measure the directivity of monopoles, dipoles, and quadrupoles. (E,I)

85. "A Helmholtz resonator experiment for the Listen Up project," C. A. Greene, T. F. Argo and P. S. Wilson, Proc. Mtgs. Acoust. **5**, 025001 (2009). Provides a description of a simple experiment that offers students insights into the physics of Helmholtz resonators using water bottle and pitch generator. The Helmholtz resonator is a simple model that has applications resonances of the body of string instruments, whistling in air ducts, and bass traps in architectural acoustics. (E)

86. "The minimum power output of free field point sources and the active control of sound," P. A. Nelson, A. R. D. Curtis, S. J. Elliott, and A. J. Bullmore, J. Sound Vib. **116**, 397–414 (1987). Shows how the addition of closely spaced, secondary sources with proper amplitudes and phases may be used to create higher-order sources and minimize the radiated power from the system. This paper has been the foundation for a series of studies on the active control of fan noise. (A)

87. "Study of the comparison of the methods of equivalent sources and boundary element methods for near-field acoustic holography," N. P. Valdivia and E. G. Williams, J. Acoust. Soc. Am. **120**, 3694–3705 (2006). Introduces the concept of representing distributed sources by equivalent monopoles and compares the holographic reconstruction against another solution technique. (A)

88. "Loudspeaker line array educational demonstration," B. E. Anderson, B. Moser, and K. L. Gee, J. Acoust. Soc. Am. **131**, 2394–2400 (2012). Describes an audio-frequency demonstration of arrays of compact sources that includes theoretical vs. measured response curves. This demonstration can be used to motivate discussion of multisource interference and the importance of effective phase relationships between sources. (I)

89. "Classroom demonstrations of acoustic beamforming," J. C. Carman, J. Acoust. Soc. Am. **131**, 2401–2404 (2012). Describes a portable beamforming demonstration that shows the principles of wave interference and the resulting focusing of the energy into an angularly dependent beam pattern. The effect of the spacing between elements and the number of elements are also illustrated. (I)

Other laboratory sources of sound include tuning forks, singing rods, and loudspeakers, both modern and primitive.

90. "Ten things you should do with a tuning fork," J. Lincoln, Phys. Teach. **51**, 176–181 (2013). (E)

91. "Vector acoustic intensity around a tuning fork," D. A. Russell, J. Junell, and D. O. Ludwigsen, Am. J. Phys. **81**, 99–103 (2013). The vector intensity radiated by a tuning fork provides a way to visualize the difference between the regions that exhibit the characteristics of near-field and far-field radiation. (I)

92. "Demonstrating superposition of waves and Fourier analysis with tuning forks and MacScope II," M. C. LoPresto, Am. J. Phys. **79**, 552–555 (2013). Describes straightforward exercises to show wave phenomena using the tuning fork as a source. (E)

93. "A craft-project loudspeaker to serve as an educational demonstration," S. P. Porter, D. J. Domme, A. W. Sell, and J. S. Whalen, J. Acoust. Soc. Am. **131**, 2431–2434 (2012). Provides directions for making a loudspeaker in which its enclosure is a shoebox and the acoustic radiator is a compact disc. (E,I)

94. "The acoustically driven vortex cannon," S. B. Perry and K. L. Gee, Phys. Teach. **52**, 146–147 (2014). Describes a subwoofer-controlled vortex cannon that can produce several vortex rings per second, which are visible when fog is injected. (E)

95. "The song of the singing rod," B. E. Anderson and W. D. Peterson, J. Acoust. Soc. Am. **131**, 2435–2443 (2012). Discusses the longitudinal waves in aluminum rods as well as the bending and torsional ones excited when large amplitude noises are produced. (I, A)

96. "Analysis of a homemade Edison tinfoil phonograph," J. D. Sagers, A.R. McNeese, R. D. Lenhart, and P. S. Wilson, J. Acoust. Soc. Am. **132**, 2173–2183 (2012). Presents the history of Edison's landmark tinfoil phonograph and the authors' reproduction of it. Also provides an analogous circuit model of the phonograph and scanning Doppler laser vibrometer measurements. (E, I, A)

An acoustic source, borrowed from chemistry, is the hydrogen-filled balloon. When ignited, it produces an impressive explosion. When the hydrogen is mixed with increasing amounts of oxygen up to the stoichiometric limit, the chemical reaction occurs more quickly and the sound levels are increased dramatically.

97. "Auditory risk of exploding hydrogen-oxygen balloons," K. L. Gee, J. A. Vernon, and J. H. Macedone, J. Chem. Educ. **87**, 1039–1044 (2010). (E)

98. "Acoustical characterization of exploding hydrogen-oxygen balloons," J. A. Vernon, K. L. Gee, and J. H. Macedone, J. Acoust. Soc. Am. **131**, EL243–EL249 (2012). (I)

The following two articles provide examples of explanations of perceptual phenomena arising from physical interactions of acoustic sources.

99. "Haunted buildings and other acoustical challenges," R. Vinokur, Sound Vib. (12), 5–6 (2005). A number of ghostly noises due to vibrations are explained, including haunted buildings, ghost cages and involuntary ghosts. (E)

100. "Overcoming naïve mental models in explaining the Doppler shift: An illusion creates confusion," J. G. Neuhoff and M. K. McBeath, Am. J. Phys. **65**, 618–621 (1997). A common misunderstanding regarding the Doppler shift is tied to the dependence of the perception of pitch on both frequency and loudness. Gives an explanation of the factors underlying this confusion. (E,I)

In addition, there are resources that further describe the Doppler shift and the extreme case, the sonic boom.

101. "Experiments using cell phones in physics classroom education: The computer-aided *g* determination," P.

Vogt, J. Kuhn, and S. Müller, Phys. Teach. **49**, 383–384 (2011). Describes a lab in which the students use the Doppler shift of a free-falling cell phone, which is emitting a 4 kHz tone, to calculate the acceleration due to gravity. (E)

102. "Calculating *g* from acoustic Doppler data," S. M. Torres and W. J. González-Espada, Phys. Teach. **44**, 536–539 (2006). Demonstrates a PC-based lab to measure the acceleration due to gravity by detecting small frequency changes (from 3500 Hz to 3450 Hz). (I)

103. "What are the effects of a sonic boom?" L. Hodges, Phys. Teach. **23**, 169,171 (1985). Provides a concise, elementary explanation of the overpressures present in a sonic boom and its relation to the Doppler shift. (E)

With the exception of aeroacoustic sources, sound radiates from structural vibrations. However, because of its complexity, many acoustics textbooks do not treat the connection between the mechanical vibration of a structure and its subsequent radiation. This is a topic with significant physical depth, including the material properties and influence of boundary conditions that cause dispersive flexural wave propagation and result in radiation vs. near-field evanescence.

104. **Sound, Structures, and Their Interaction**, M. C. Junger and D. Feit, 2nd ed. (MIT Press, Cambridge, MA, 1986). (A)

105. **Sound and Structural Vibration**, F. Fahy and P. Gardonio, 2nd ed. (Academic Press, London, 2007). (A)

106. http://ocw.mit.edu/courses/mechanical-engineering/2-067-advanced-structural-dynamics-and-acoustics-13-811-spring-2004/. These are materials from an advanced course on structural acoustics, archived through MIT's OpenCourseWare. (A)

B. Resonance: standing waves

Resonance, standing wave demonstrations are common in acoustics and can be applied to various concepts. The next five references deal with one-dimensional systems.

107. "Standing wave measurements in tubes," S. A. Cheyne and W. C. McDermott, Proc. Mtgs. Acoust. **11**, 025001 (2011). Explains how to measure standing waves in tubes in conjunction with the Acoustical Society of America's Project Listen Up kits. (E)

108. "Acoustic resonators with variable nonuniformity," B. Denardo and S. Alkov, Am. J. Phys. **62**, 315–321 (1994). Explains the design of acoustic resonators with variable cross section whose resonances correspond to musical intervals. Each two-piece resonator can be assembled in four configurations. Contains calculation of the resonance frequencies using the wave equation, the Rayleigh integral method, and the adiabatic invariance method. (I,A)

109. "Demonstration comparing sound wave attenuation inside pipes containing bubbly water and water droplet fog," T. G. Leighton, J. Jiang, and K. Baik, J. Acoust. Soc. Am. **131**, 2413–2421 (2012). Describes a set of two pipes that demonstrate the effect of fog on resonances in a column of air and of bubbles in a column of water. Provides the qualitative explanation and applications given to children and non-scientific audiences, as well as indications of the more complex physics involved. (E,I,A)

110. "Analysis of standing sound waves using holographic interferometry," D. A. Russell, D. E. Parker, and R. S. Hughes, Am. J. Phys. **77**, 678–682 (2009). Describes how optical methods can be used to visualize standing wave fields in a tube. (I)

111. "Combining theory and experiment to teach acoustic concepts," S. D. Sommerfeldt, Proc. Mtgs. Acoust. **19**, 025003 (2013). Presents a demonstration of the modes of a forced vibrating string as an example of the usefulness of visual, hands-on reinforcement of the mathematical descriptions of physical and acoustical phenomena. (I)

The Rubens flame-tube demonstration is a popular way of introducing audiences to standing waves.

112. "An investigation of Rubens flame tube resonances," M. Gardner, K. L. Gee, and G. Dix, J. Acoust. Soc. Am. **125**, 1285–1292 (2009). The resonances of a Rubens flame tube provide a good visual representation of standing modes in a tube, but care must be taken in assigning physical phenomena to the peaks and troughs of the flames. Explores the inharmonicity of the resonances in a typical tube, and provides a physical explanation of it. (E,I)

113. "The Rubens tube," K. L. Gee, Proc. Mtgs. Acoust. **8**, 025003 (2011). Summarizes the history and results from studies of this fascinating demonstration. The reference list includes the known studies regarding this demonstration. (E,I)

Beyond one-dimensional systems, the richness of resonances can be examined in a variety of geometries, from Chladni plates, to wine glasses, to a variety of cavities.

114. "Chladni plates revisited," J. R. Comer, M. J. Shepard, P. N. Henriksen, and R. D. Ramsiera, Am. J. Phys. **72**, 1345–1350 (2004). Describes how including dust particles along with large grains (such as salt) when exciting the modes of the Chaldni plate can help students understand that areas of maximum displacement correspond to regions of low pressure. (E,I)

115. "Why does water change the pitch of a singing wineglass the way it does?" Y. Y. Chen, Am. J. Phys. **73**, 1045–1049 (2005). The resonances of a wineglass change in the presence of an incompressible liquid. Gives a mathematical description of how the pressure on the glass increases and, thus, retards the vibrational frequencies of the glass. (I,A)

116. "Coupling between two singing wineglasses," T. Arane, A. K. R. Musalem, and M. Fridman, Am. J. Phys. **77**, 1066–1067 (2009). Describes an example of coupled oscillators altering the behavior of neighboring wineglasses. (I)

117. "Plastic CD containers as cylindrical acoustical resonators," M. J. Moloney, Am. J. Phys. **77**, 882–885 (2009). A cylindrical case, like the packaging for stacks of 50 CDs, can be used in conjunction with a loudspeaker and microphone to monitor the frequency and angular dependence of the acoustic modes of a cylindrical resonator. (I)

118. "Basketballs as spherical acoustic cavities," D. A. Russell, Am. J. Phys. **78**, 549–554 (2010). Striking a basketball with a metal rod excites the acoustic modes of the interior corresponding to its spherical interior. The analysis of these modes provides an opportunity to explore a physical application of the spherical Bessel functions and Legendre functions associated with the three-dimensional wave equation. Presents the experimental set-up, theory and a comparison between the measured and predicted resonance frequencies. (I,A)

119. "Time-reversal breaking of acoustic waves in a cavity," V. Bertaix, Am J. Phys. **72**, 1308–1311 (2004). Presents a time-reversal experiment with a single transducer that also demonstrates acoustics in a cavity. (A)

120. "Lowest modes of a bottle," F. S. Crawford, Am. J. Phys. **56**, 702–712 (1988). Describes generalizations to the Helmholtz model to predict the lowest cavity modes of a wine bottle. (I)

121. "Holographic study of a vibrating bell: An undergraduate laboratory experiment," K. Menou, B. Audit, X. Boutillon, and H. Vach, Am. J. Phys. **66**, 380–385 (1998). Time-average holographic interferometry allows students to visualize the acoustic modes of a vibrating bell. (I)

122. "Learning acoustic phonetics by listening, seeing, and touching," T. Arai, Proc. Mtgs. Acoust. **19**, 025017 (2013). A sliding vocal-tract model is used to demonstrate the resonances of the human vocal tract. While this is typically used with students in speech-related fields, it also is a good example of a variable cross-section duct that has analogies in electromagnetics and plasma. (I,A)

123. "Visualization of resonance phenomena for acoustic education," S. Sakamoto, K. Ueno, and H. Tachibana, Proc. Int. Congr. Acoust. **3**, 2311–2313 (2004). Explains how to visualize the sound field in an enclosure using a dust model. Principles associated with Helmholtz resonators and active noise control can also be shown with this model. (I,A)

Many advanced topics, for example in quantum mechanics, plasma physics, and thermoacoustics, involve resonance phenomena.

124. "Acoustic analog to quantum mechanical level splitting," S. A. Hilbert and H. Batelaan, Am. J. Phys. **75**, 1003–1008 (2007). The resonances of a pipe are analogous to the energy modes of an infinite square well. Presents pertubative and analytical derivations of how a disk containing a hole and placed in the center of the pipe acts like a delta-function perturbation to the potential well and is analogous to level splitting in quantum mechanics. (I,A)

125. "Ion acoustic wave experiments in a high school plasma physics laboratory," W. Gekelman *et al.*, Am. J. Phys. **75**, 103–110 (2007). Describes an alliance between a university research laboratory and a high-school physics class. The experiments performed describe ion acoustic waves, the ion natural frequency, and the change in wave speed with frequency. (E, I)

Reference 3 contains a wealth of information regarding thermoacoustics, which could be used as an example of a heat engine. The following are three additional resources:

126. http://www.acs.psu.edu/thermoacoustics/refrigeration/laserdemo.htm. "The thermoacoustics group at Penn State distributes kits for building thermoacoustic "lasers" for a reasonable cost. (E)

127. "A thermoacoustics oscillator power by vaporized water and ethanol," D. Noda and Y. Ueda, Am. J. Phys. **81**, 124–126 (2013). Demonstrates an experiment suitable for an upper-level undergraduate class, the reduction in the temperature gradient necessary to drive the oscillator when water or ethanol is used in place of air. (I)

128. "Synchronization of a thermoacoustic oscillator by an external sound source," G. Penelet and T. Biwa, Am. J. Phys. **81**, 290–297 (2013). Shows nonlinear mode locking using two different sound sources. It is an appropriate demonstration for a nonlinear dynamics course. (A)

Sonoluminescence is an example of energy conversion, from sound to light, that occurs with a bubble repeatedly forming and collapsing in a fluid-filled container at resonance.

129. "Sonoluminescence: Sound into light," S. J. Putterman, Sci. Am. **272**, 46–51 (1995). One of the canonical references on sonoluminescence for the lay audience. (E,I)

130. http://www.techmind.org/sl/. Contains information and instructions on building a sonoluminescence device. (I)

131. "Synchronous sonoluminescece in acrylic resonant chambers," F. B. Seeley and C. K. Joens, Am. J. Phys. **66**, 259–260 (1998). Describes a design for achieving sonoluminescence in an undergraduate laboratory class that can be used with a rectangular, spherical, or cylindrical chamber. (I)

C. Propagation: Traveling waves

One of the fundamental properties of acoustic waves is the determination of the wave speed by the properties of the medium. In air, this includes the adiabatic relationship between pressure and temperature. In water, the presence of salinity, bubbles, and the like, can change the speed of sound.

132. J. H. Giraud, K. L. Gee, and J. E. Ellsworth, "Acoustic temperature measurement in a rocket noise field," J. Acoust. Soc. Am. **127**, EL179–EL184 (2010). Students often mistakenly assume that sound propagation is isothermal. This same assumption caused Newton to calculate a sound speed that was significantly lower than measured values. Demonstrates the adiabatic variation of temperature with pressure in a sound field, using a low-frequency, high-amplitude noise source as an example—a full-scale solid rocket motor. (I)

133. "Classroom measurements of sound speed in fresh/saline water," J. C. Carman, J. Acoust. Soc. Am. **131**, 2455–2458 (2012). Explains a hands-on, in-class lab in which students take measurements and calculate the variation in sound speed due to the salinity of the water. (E)

134. "Undergraduate experiment to measure the speed of sound in liquid by diffraction of light," D. A. Luna, M. A. Real, and D. V. Durán, Am. J. Phys. **70**, 874–875 (2002). An ultrasonic acoustic source excites standing waves in a water-filled tube, which when illuminated with a laser beam provides a diffraction pattern from which the wavelength of the standing wave can be estimated. The product of the known ultrasonic frequency and the measured wavelength produce an estimation of the sound speed in the water. (E,I)

135. "Hot chocolate effect," F. S. Crawford, Am. J. Phys. **50**, 398–404 (1982). Because the speed of sound in a bubbly liquid is different from that in a liquid free from bubbles, the resonances of a glass containing hot chocolate or other beverage changes as the bubbles are introduced and subsequently reduced. This phenomena and its qualitative explanation would be appreciated by a general audience. In addition, an explanation is presented based on the compressibility of fluids is presented and a mathematical derivation concerning dynamics. (E,I,A)

136. "An audible demonstration of the speed of sound in bubbly liquids," P. S. Wilson and R. A. Roy, Am. J. Phys. **76**, 975–981 (2008). When bubbles are introduced into a fluid-filled waveguide, the speed of sound varies with the gas-volume fraction, and the resonances of the waveguide change. The resulting audible frequency shifts are predicted by a simple mathematical model. (I,A)

137. "The use of extra-terrestrial oceans to test ocean acoustics students," T. G. Leighton, J. Acoust. Soc. Am. **131**, 2551–2555 (2012). Because students become familiar with typical environments in the course of their homework assignments, it is often useful for them to predict the behavior of acoustical phenomena in different environments. Examples are provided using parameters found in extraterrestrial oceans to investigate refraction, attenuation, and other propagation effects. (I)

The frequency dependence of sound speed in air is not treated in introductory courses. Dispersion exists in free atmospheric propagation, but is significantly greater in the presence of a waveguide.

138. "Dispersion in acoustic waveguides—A teaching laboratory experiment," K. Meykens, B. Van Rompaey, and H. Janssen, Am. J. Phys. **67**, 400–406 (1999). The propagation of acoustic waves down a rectangular waveguide provides an opportunity for students in an undergraduate lab class to measure the frequency dependence of the phase and group speed for different acoustic modes and to investigate the resulting distortion in the signal. (I, A)

Demonstrations and examples of acoustic reflections in traveling waves can be particularly enlightening for the student and provide real-world applications, from echolocation to SONAR.

139. "How can humans, in air, hear sound generated underwater (and can goldfish hear their owners talking)?" T. G. Leighton, J. Acoust. Soc. Am. **131**, 2539–2542 (2012). An exploration of the question posed in the title addresses some common misconceptions regarding the reflection and transmission of waves at the air-water interface. (I)

140. "The physics of bat echolocation: Signal processing techniques," M. Denny, Am. J. Phys. **72**, 1465–1477 (2004). Discusses applications of remote sensing, for example, correlation, integration, Doppler shift and frequency modulation, in terms of the echolocation mechanisms used by bats. (I)

141. "Time reversal," B. E. Anderson, M. Griffa, C. Larmat, T. J. Ulrich, and P. A. Johnson, Acoust. Today **4**(1), 5–15 (2008). Reviews the history of time-reversal methods and explains how they are performed. Presents examples of how time reversal is used to locate earthquakes, cracks in solids, and other acoustic sources. (I)

142. "Educational ultrasound nondestructive testing laboratory," V. Genis and M. Zagorski, J. Acoust. Soc. Am. **124**, 1411–1418 (2008). This laboratory course targets applied-engineering students at Drexel University's Goodwin College of Professional Studies and helps provide technical, hands-on training that is badly needed. The labs include measuring sound speed, attenuation, directivity patterns of ultrasound as well as ultrasound nondestructive testing using state of the art equipment. (I)

143. "Illuminating sound: imaging tissue optical properties with sound," T. W. Murray and R. A. Roy, Acoust. Today **3**(7), 17–24 (2007). Explains how traditional ultrasound can be enhanced with an acousto-optical imagining system that provides higher resolution images of the optical properties of human tissues. (I)

144. "A low cost remote sensing system using PC and stereo equipment," J. F. Campbell, M. A. Flood, N. S. Prasa, and W. D. Hodson, Am. J. Phys. **79**, 1240–1245 (2011). Presents instructions on how to make an acoustic (sonar) system analogous to the LIDAR systems used to sense CO_2 concentrations in the atmosphere and examples of how it has been used. (A)

As in other areas of physics, image sources are used in acoustics to model a rigid reflector, both in free space and in waveguides.

145. "Simple-source model of high-power jet aircraft noise," J. Morgan, T. B. Neilsen, K. L. Gee, A. T. Wall, and M. M. James, Noise Control Eng. J. **60**, 435–449 (2012). Gives a detailed example used in an advanced undergraduate course of how image-source theory can be used to model complex sound-field environments. Describes how the radiated field from a military jet aircraft in the presence of a hard reflecting surface can be modeled with monopoles by including image sources. (I, A)

146. "On the use of the method of wave images to introduce students to acoustics," J. H. Ginsberg, J. Acoust. Soc. Am. **131**, 2543–2550 (2012). Extends an earlier treatment of d'Alembert's solution in semi-infinite and infinite waveguides for cases where the velocity at the end of the waveguide is given. Discusses the general applicability of these techniques in introducing and explaining acoustical phenomena. (A)

147. "Lloyd's mirror-image interference effects," W. M. Carey, Acoust. Today **5**(4), 14–20 (2009). The reflection of an underwater sound source off the water-air interface at the surface can be represented by an image source that is out of phase with the original source as with a Lloyd's mirror. Explains the principles, applications, and history of Lloyd's mirror. (E)

Acoustic scattering demonstrations and examples can provide insight into electromagnetic and quantum-mechanical systems.

148. "A balloon lens: Acoustic scattering from a penetrable sphere," D. C. Thomas, K. L. Gee, and R. S. Turley, Am. J. Phys. **77**, 197–203 (2009). Sound passing through a balloon filled with a gas other than air can be explained, to first-order, using an analogy to geometric optics. However, scattering theory is required to explain the experimental results. The demonstration and discussion presented here can be adapted to students on many levels. (I,A)

149. "A ray model of sound focusing with a balloon lens: An experiment for high school," C. E. Dean and K. Parker, J. Acoust. Soc. Am. **131**, 2459–2462 (2012). Gives a description of the acoustic balloon-lens experiment, as it might be presented to school-age children, along with practical advice on how to provide guidance to minimize unwanted effects during the demonstration. (E)

150. "Animations for visualizing and teaching acoustic impulse scattering from spheres" C. Feuillade, J. Acoust. Soc. Am. **115**, 1893–1904 (2004). Presents how Anderson's fluid sphere theory was used to model the interaction of a plane wave with a rigid sphere and a pressure release sphere, which accounts for the forward and backward scattering and diffraction around the sphere. Images based on the ray-path scatter method help visualize the scattering effect. (A)

151. "Acoustic scattering from a spherical lens irradiated by a finite transducer: Focusing effect and refraction," M. A. Parrales Borrero, M. Perez-Saborid, and J. M. Fernandez Garcia, Am J. Phys. **79**, 401–408 (2011). Focusing and refraction effects of a sound wave by an acoustic lens provide a means to explain how rays and wave packets can be produced in such cases. (A)

152. "Acoustic radiation force due to a diverging wave: Demonstration and theory," B. C. Denardo, S. G. Freemyers, M. P. Schock, and S. T. Sundem, Am. J. Phys. **82**, 95–101 (2014). Describes a demonstration of acoustic radiation force of a loudspeaker on a styrofoam ball suspended from a string. When the amplitude is sufficiently large, the loudspeaker exerts an attractive force on the ball. An explanation of this phenomena using Bernoulli theory is compared to rigorous scattering calculations. (I, A)

153. "Acoustic interference and diffraction experiments in the advanced laboratory class," Andrew Morrison, Proc. Mtgs. Acoust. **19**, 025004 (2013). Explains how low-cost ultrasonic transducers can be used to illustrate single-slit diffraction and double-slit interference. Lab activities are provided that range from introductory to advanced and cover numerous applications, including Lloyd's mirror. (E,I)

A number of other phenomena, including refraction, are present in atmospheric and ocean sound-wave propagation.

154. "Refraction of sound in the atmosphere," T. B. Gabrielson, Acoust. Today **2**(4), 7–17 (2006). Recounts the 250-year-long search for an understanding of the effect of the atmosphere on sound propagation. Mistaken originally for an unpredictable absorption effect, then for flocculence, the bending of the sound waves due to variations in the wave speed, due to wind and temperature gradients, were eventually uncovered. In addition to providing many examples of where refraction leads to counterintuitive results, this is a good example of how the scientific method often works, with many twists and turns along the way. (E)

155. "Infrasound," H. E. Bass, H. Bhattacharyya, M. A. Garcés, M. Hedlin, J. V. Olson, and R. L. Woodward, Acoust. Today **2**(1), 9–19 (2006). Infrasound can travel over thousands of kilometers because of refraction in the atmosphere. Thus, infrasound provides a way to monitor global infrasonic noise from, for example, volcanoes, earthquakes, meteors, tsunamis, and nuclear test-ban-treaty violations. One component of the international monitoring system is a network of microbarometers that are continually monitoring infrasonic noise. Explains the infrasound-monitoring procedure, refraction in the atmosphere, and natural sources of infrasound. (E)

156. "Outdoor sound propagation in the U.S. civil war," C. D. Ross, Appl. Acoust. **59**, 137–147 (2000). The outcomes of several battles in the civil war were influenced by the conditions that controlled the propagation of the sound. Discusses the principle of outdoor sound propagation, absorption, refraction, and the resulting acoustic shadow zones, as they influenced seven of these battles. (E,I)

157. "Infrasound," T. B. Gabrielson in Ref. 49, pp. 367–372. (I)

158. "High-altitude infrasound calibration experiments," E. T. Herrin *et al.*, Acoust. Today **4**(4), 9–19 (2008). The propagation of infrasound through the atmosphere is a complex problem involving both refraction and scattering. Signals from the White Sands missile range are used to illustrate these properties and address fundamental questions. (E,I)

159. **Computational Atmospheric Acoustics**, E. M. Salomons (Kluwer Academic Publishers, Dordrecht, The Netherlands, 2001). Reviews the phenomena influencing atmospheric propagation and covers numerical methods for its solution. (A)

The following five references relate to ocean propagation.

160. **An Introduction to Underwater Acoustics: Principles and Applications**, X. Lurton (Springer-Praxis, Chichester, UK, 2002). Covers the fundamentals of acoustics and then moves into topics of importance to underwater acousticians, including multipath propagation, scattering, the SONAR equations, and the like. (I,A)

161. **Computational Ocean Acoustics**, F. B. Jensen, W. A. Kuperman, M. B. Porter, and H. Schmidt (Springer-Verlag, New York, 2000). After a mathematical introduction to acoustic propagation and a discussion of relevant phenomena, discusses waveguide solutions, ray-tracing methods, and wavenumber-integration techniques. (A)

162. **Ocean and Seabed Acoustics**, G. V. Frisk (Prentice Hall, Upper Saddle River, NJ, 1994). Takes a unique approach by connecting the acoustic, electromagnetic, and quantum-mechanical regimes before considering solutions to the wave equation. Homogeneous, inhomogeneous, and stratified media are considered with Greens functions, normal mode solutions, Hankel transforms, and ray and WKB approximations. (A)

163. http://ocw.mit.edu/courses/mechanical-engineering/2-068-computational-ocean-acoustics-13-853-spring-2003/. This is a MIT OpenCourseWare course that goes along with Ref. 161. (A)

There have been efforts to develop inquiry-based software to prompt understanding of underwater acoustic phenomena.

164. "Ocean Sound Lab: A software environment for introduction to underwater acoustics," M. Kalogerakis, E. Skarsoulis, G. Piperakis and E. Haviaris, Proc. Mtgs. Acoust. **17**, 070008 (2012). An accessible software package has been developed that contains tutorials about sounds in the sea and interactive simulations that show ray-tracing results in ocean environments found in different parts of the world. In addition, prerecorded or user-generated sounds can be used as an input waveform in the selected ocean environment. A free demonstration is available at http://osl.iacm.forth.gr/. (E,A)

165. "Using game-based learning with integrated computer simulation to teach core concepts in underwater acoustics," J. Summers, T. K. Meyer, and D. T. Redmond, Proc. Mtgs. Acoust. 20 (in press). Describes an interactive three-dimensional, video game framework for teaching principles in underwater acoustics. (E)

Acoustical experiments and demonstrations can be used to show the physical principles of tunneling in wave transmission.

166. "A demonstration apparatus of the cochlea," R. M. Keolian, J. Acoust. Soc. Am. **101**, 1199–1201 (1997). Describes a demonstration of a hydrodynamic analog to the frequency response of the basilar membrane in the mammalian cochlea, where varying mass and stiffness produce a propagating wave with complex phase speed and eventual evanescent decay. Presents a mathematical model using a wave equation for a string with variable bulk modulus. Although tunneling is not demonstrated, the evanescent decay represents a stop-band region that varies as a function of frequency. (I,A)

167. "Near-field imaging with sound: An acoustic STM model," M. Euler, Phys. Teach. **50**, 414–416 (2012). Describes the set-up and results from an acoustic-imaging demonstration that reflects the properties of scanning-tunneling microscopy. (E)

168. "Breaking the sound barrier: Tunneling of acoustic waves through the forbidden transmission region of a one-dimensional acoustic band gap array," W. M. Robertson, J. Ash, and J. M. McGaugh, Am. J. Phys. **70**, 689–693 (2002). In this acoustic analogy, sound pulses sent through a pipe with and without extra open pipes exhibit the same features as band gaps in materials with discrete forbidden-transmission regions. Explores the concepts of tunneling time, group velocity, and pulse reshaping. (I,A)

169. "Acoustic impulse response method as a source of undergraduate research projects and advanced laboratory experiments," W. M. Robertson and J. M. Parker, J. Acoust. Soc. Am. **131**, 2488–2494 (2012). The coherent-averaging impulse response measurement technique described here has been used to introduce students to signal-processing techniques in the investigation of periodic and nonperiodic signals that are analogous to a variety of physical systems that exhibit tunneling, band gaps, dispersion, wave packets, group delays, and phase jumps. (I,A)

Acoustics is closely tied to probing condensed-matter and solid-state systems, and recent work involves cloaking using metamaterials.

170. "Listening to materials: From auto safety to reducing the nuclear arsenal," V. M. Keppens, J. D. Maynard, and A. Migliori, Acoust. Today **6**(4), 6–13 (2010). Describes the process of resonant ultrasound spectroscopy to study the elastic response of a material. The elastic constants and sound velocity of the material, which determine the mechanical resonances of a material, can be evaluated as a function of temperature and in some cases give insights into materials (such as invar and plutonium) with unusual thermal behavior. (E, I)

171. **Physical Acoustics in the Solid State**, B. Luthi (Springer-Verlag, Berlin, 2005). Provides an advanced introduction to the properties of sound waves in materials, including phase transitions, semiconductors, and various experimental techniques. (A)

172. **An Introduction to Metamaterials and Waves in Composites**, B. Banerjee (Taylor and Francis, Boca Raton, FL, 2011). Introduces the reader to periodic materials, metamaterials, and layered composites. In addition to acoustic waves, elasticity and electromagnetic waves are also considered. (I, A)

173. **Acoustic Metamaterials and Phononic Crystals.** Edited by P. Dymier (Springer-Verlag, Berlin, 2013). This text provides an introduction to phononic crystals, with an emphasis on negative refraction and scattering. (A)

Nonlinear acoustics, which is required for modeling acoustic propagation when pressure oscillations can no longer be considered infinitesimal, is responsible for fascinating phenomena and a number of practical applications, particularly in biomedical ultrasound.

174. "Not your ordinary sound experience: A nonlinear acoustics primer," A. A. Atchley, Acoust. Today **1**(1), 19–24 (2005). Introduces the fundamental physics of nonlinear acoustic propagation and various implications and applications of associated phenomena. (I)

175. "Educational demonstration of a spherically propagating acoustic shock," M. B. Muhlestein, K. L. Gee, and J. H. Macedone, J. Acoust. Soc. Am. **131**, 2422–2430 (2012). The large-amplitude sounds from exploding, gas-filled balloons often used in chemistry demonstrations provide a means of investigating the predictions of nonlinear acoustic-propagation theory. (A)

176. "What is ultrasound?" T. G. Leighton, Prog. Biophy. Mol. Biol. **93**, 3–83 (2007). Review that starts with basic principles of intensity and impedance and then introduces nonlinear propagation and cavitation in explaining the use of ultrasound. (I)

177. **Nonlinear Acoustics**, edited by M. F. Hamilton and D. T. Blackstock (Acoustical Society of America, Melville NY, 2008). Contains chapters by experts in the field that cover the theoretical foundation for nonlinear waves in fluid media. Describes in detail the model equations and analytical solutions for finite-amplitude wave propagation, as well as computational methods for their solution. Also described in detail are radiation pressure, acoustic streaming, and other phenomena. (A)

178. **Nonlinear Acoustics**, R. T. Beyer (Acoustical Society of America, Melville, NY, 1997). Older than Ref. 177, but approaches nonlinear acoustics from a different, nonlinear dynamics perspective. (A)

179. "Acoustic radiation pressure in a traveling plane wave," J. A. Rooney and W. L. Nyborg, Am. J. Phys. **40**, 1825–1830 (1972). Though undergraduate physics students are usually introduced to radiation pressure in the context of electromagnetic radiation, its presence in the acoustic regime is typically discussed only in the context of a second-order nonlinear phenomenon. (I)

180. "An acoustic radiometer," B. Denardo and T. G. Simmons, Am. J. Phys. **72**, 843 (2004). Demonstrates an acoustic analog to the electromagnetic pressure demonstrated by Crookes's radiometer. (I)

181. "A demonstration of acoustical levitation," R. Cordaro and C. F. Cordaro, Phys. Teach. **24**, 416 (1986). Describes a straightforward setup for achieving acoustical levitation. However, the explanation of the phenomenon is simplified to the point of being incomplete. Acoustical levitation relies on an acoustic potential well created by the (nonlinear) non-zero, time-averaged squared acoustic velocity in a standing-wave field large enough to overcome the gravitational potential and hold the object suspended near a pressure node. (E)

VII. RESOURCES FOR OUTREACH

Outreach is an important part of physics pedagogy. Because of the sensory nature of acoustical phenomena, acoustics-based demonstrations provide a natural vehicle for sharing the wonders of physics with the general public. In addition to Ref. 4, there are numerous examples and ideas in *The Physics Teacher* and some in other journals.

182. "Raising public awareness of acoustic principles using voice and speech production," D. M. Howard, J. Acoust. Soc. Am. **131**, 2405–2411 (2012). Gives examples of demonstrations appropriate for outreach and describes survey results after applying these demonstrations. (E)

183. "Help! There are 60 screaming kids in my lab!—Outreach activities for 5th graders," C. M. Darvennes, J. Acoust. Soc. Am. **117**, 483–485 (2005). Describes ten acoustical activities for fifth and sixth graders and provides good examples of how hands-on participation can be achieved during outreach efforts. (E)

The Acoustical Society of America (ASA) offers two outreach sessions in conjunction with its semiannual conferences in which local junior-high-science classes and Girl Scout troops participate in hands-on demonstrations.

184. "Development of educational stations for Acoustical Society of America outreach," C. T. Vongsawad, T. B. Neilsen, and K. L. Gee, Proc. Mtgs. Acoust. 20, in press (2014). Describes recent efforts to create inquiry-based education stations relating to real-world applications for outreach workshops at semiannual ASA meetings. (E)

In addition, the ASA has created activity kits to support K-12 teachers in their efforts to engage students in scientific discovery.

185. "Classroom Materials from the Acoustical Society of America," W. K. Adams, A. Clark, and K. Schneider, Phys. Teach. **51**, 348–350 (2013). An activity kit for teachers that contains materials and lesson plans for students in grades K-12. (E)

While many of the elementary online resources listed previously are suitable for outreach, additional websites are designed with a general audience in mind.

186. www.exploresound.org. Sponsored by the ASA, this website is a great resource for introducing K-12 students to acoustics. (E)

187. http://www.dosits.org/. Discovery of Sound in the Sea (DOSITS) contains an introduction to sound, discussions of the influence of underwater noise, as well as a large database of sound recordings from underwater creatures. (E)

188. http://buyquietroadmap.com/. Contains resources regarding noise and hearing, including two activity worksheets for children and a game regarding hearing conservation. Many of these resources are appropriate for outreach. (E)

189. http://www.silcom.com/~aludwig/. Contains basic information regarding acoustics, in addition to an "advanced" page that contains mathematical underpinnings appropriate for advanced undergraduate or graduate students. (E, I,A)

190. "It's a noisy planet: Two stellar years of protecting young ears," J. Wenger, Acoust. Today **6**(10), 11–18 (2010). In 2008, the National Institute on Deafness and Other Communication Disorders, one of the National Institutes of Health launched a campaign called "It's a Noisy Planet. Protect Their Hearing" to increase awareness of noise-induced hearing loss among young people, in particular. They have a helpful, informative webpage: www.noisyplanet.nidcd.nih.gov. (E)

191. www.dangerousdecibels.org. Sponsored by the Oregon Health and Science University, seeks to educate the public about the risk of noise-induced hearing loss. Among other information, they have classroom programs, educator-training workshops, and a personal audio-testing mannequin dubbed JOLENE, with instructions on how to create a look-alike. (E)

192. http://buyquietroadmap.com/334/animated-auditory-demonstrations-ii-challenges-to-speech-communication-and-music-listening/. Animated Auditory Demonstrations II: Challenges to Speech Communication and Music Listening. NASA Glenn Research Center Imaging Technology Center, Nicholas Hawes, 2006. An earlier volume (Auditory Demonstrations in Acoustics and Hearing Conservation) was produced for the NASA Glenn Research Center and is also available. (E)

193. http://www.phys.unsw.edu.au/music/. Contains resources on acoustics, the physics of musical instruments, and hearing. (E)

194. http://www.concerthalls.unomaha.edu/. Developed by students and faculty at the University of Nebraska-Lincoln, contains information and audio clips demonstrating the effect of design parameters on concert-hall sound. (E)