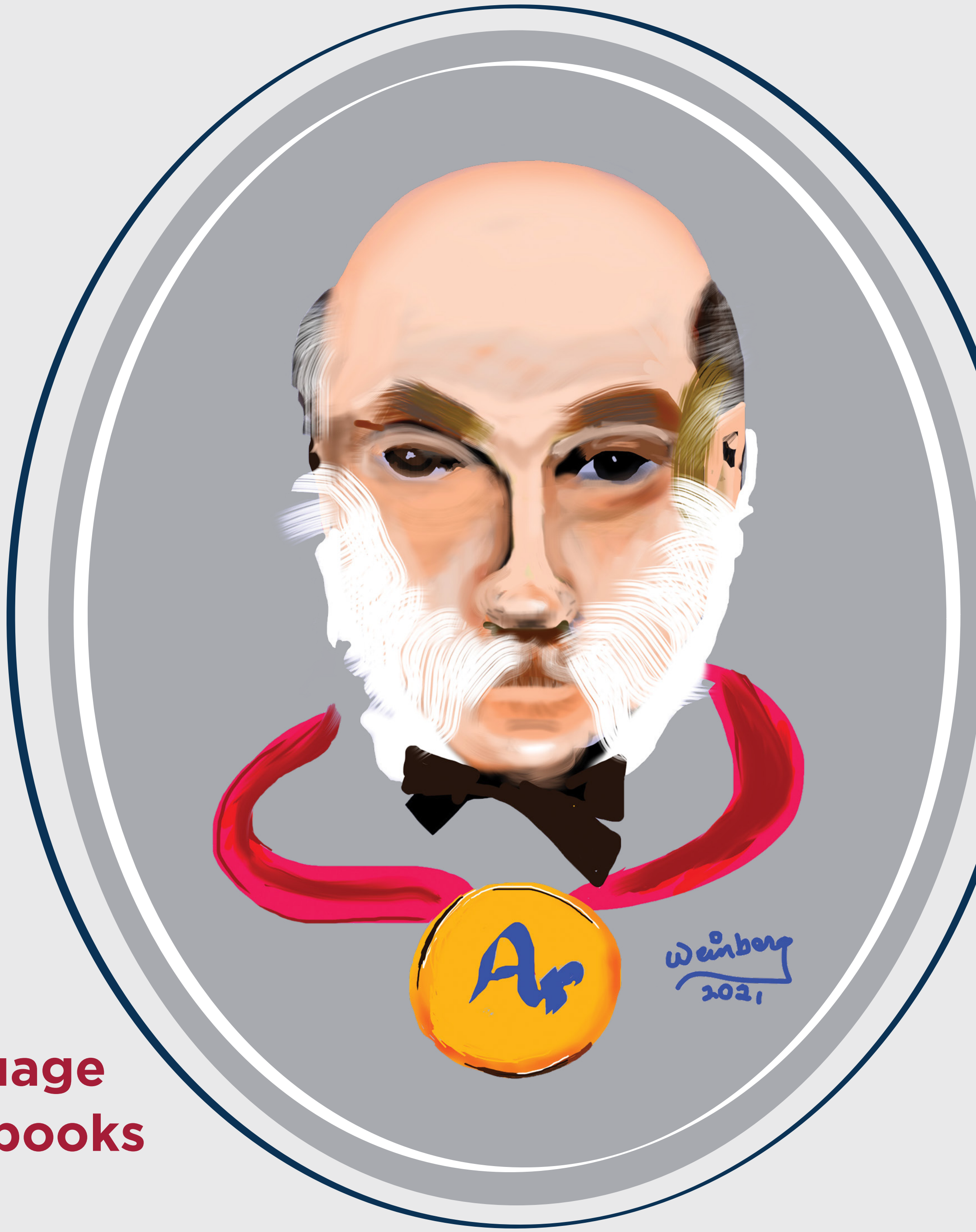
Acoustics Today

Fall 2021 Volume 17, Issue 3

ASA
ACOUSTICAL SOCIETY
OF AMERICA

An Acoustical Society of America publication



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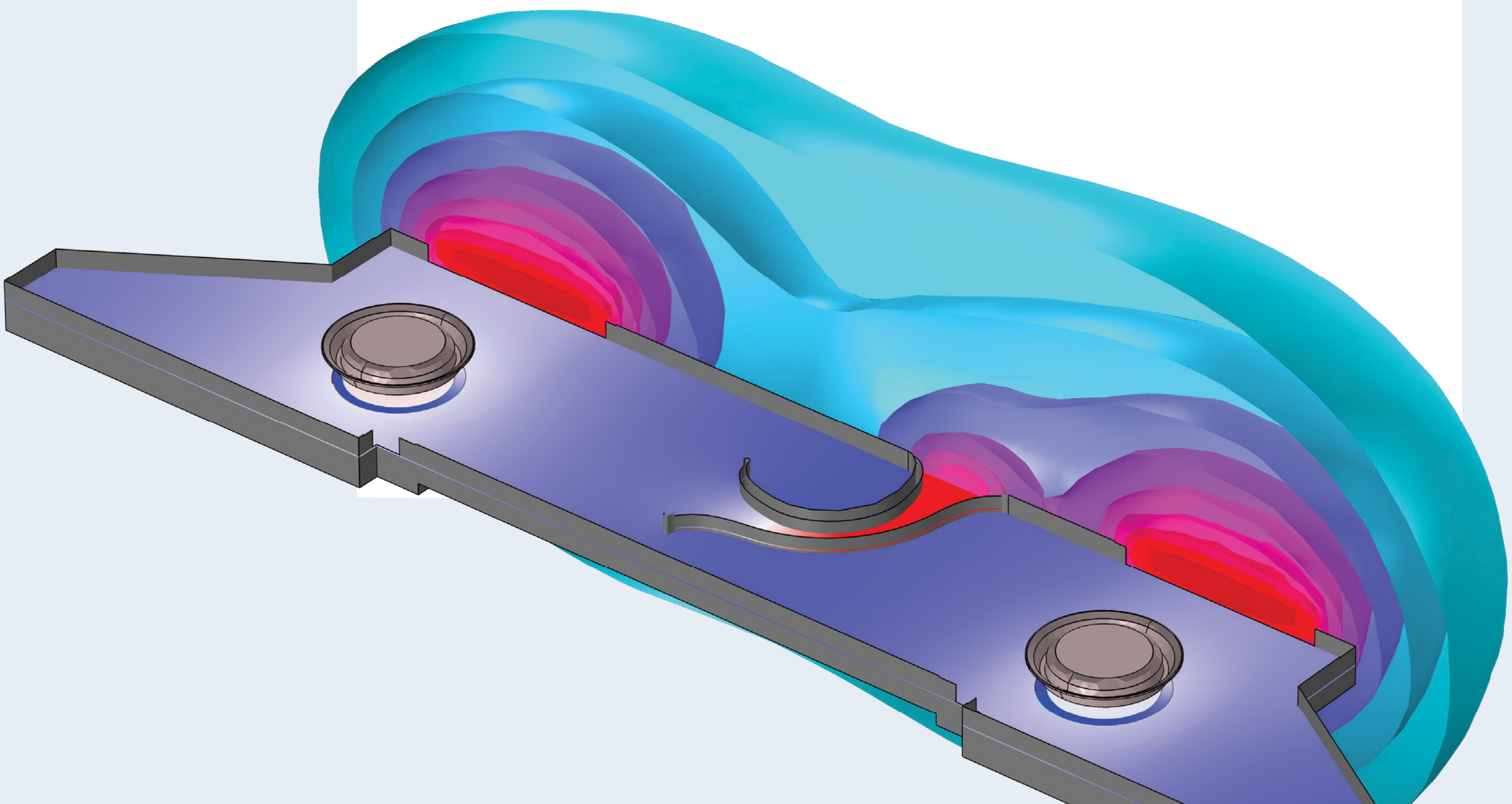

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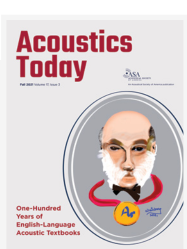

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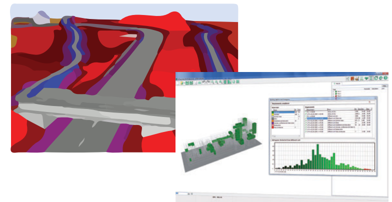

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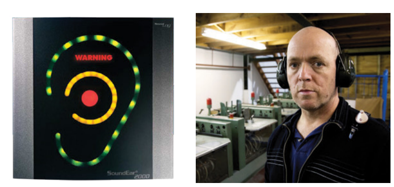

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From the Editor

Arthur N. Popper

Acoustics Today Collections

I am pleased to announce a new web-based initiative that provides access to past articles from *Acoustics Today* (*AT*) on specific topics. This initiative, "*AT* Collections" (available at bit.ly/AT-Collections), is for anyone who wants to learn about various topics in acoustics.

Although we envision "*AT* Collections" as particularly useful for supplemental reading for classes in college or graduate school, we anticipate that "*AT* Collections" will also be invaluable for anyone else wanting to learn about a particular topic. Indeed, for those of my generation, the "model" we have in mind are the course packets of offprints from articles in *Scientific American* that we used in various college and graduate school classes.

The inception for "*AT* Collections" was the realization that the magazine has almost 300 scholarly articles (plus numerous essays) covering a wide range of topics. However, if someone wants to find all the articles and/or essays on a particular topic, they have to go through 17 years of back issues. A formidable task! (Though browsing back issues is fun since you may find something interesting to read that you never saw before.)

So, to help potential users of back articles in *AT* find all the material on a particular topic, we have set up "*AT* Collections" pages so that they have links to all the past articles on a specific topic. Thus, as I write this, collections include musical instruments, animal hearing, and concert hall design. By the time you read this, we hope to have additional pages. Moreover, we are asking your help to add many additional pages on topics that members may find useful for their teaching or work.

In addition, we are using "*AT* Collections" to bring together information about the Acoustical Society of America (ASA) such as pages featuring all past essays about Technical Committees, ASA Administrative Committees, and Standards.

Suggest Topics for "*AT* Collections"

In order to add pages to "*AT* Collections," we ask readers to suggest new ideas for pages, perhaps based on the kind of material that would serve a particular course you have taken or are teaching or a work-related issue (e.g., anthropogenic sound and marine animals for regulators). Send your suggestions and a rough idea of the topic you would like to cover to me at apopper@umd.edu. If we decide to use the suggested page, we will ask you to put together a full list of articles and, if you like, to write a short paragraph about the topic that will be featured (over your name!) describing the page.

Finally, we do not limit the number of articles in a collection but suggest no more than 10-15. But the topic should be relatively specific.

Now for the Fall Issue

The first article in this issue is by Andrea Alù, Chiara Daraio, Pierre A. Deymier, and Massimo Ruzzene on topological acoustics. The authors discuss a new field of research that manipulates sound using topological concepts.

This is followed by an article by Steven L. Garrett who shares the history of textbooks on acoustics. I think that every reader, no matter their discipline, will find the story of the evolution of acoustics texts from the first by Lord Rayleigh to the new open-source text by Steven (an ASA Press book) quite interesting.

AT has had a number of articles on the acoustics of built spaces, but this has never included a discussion of the unique acoustics of worship spaces. So, in his article, David W. Kahn shares insights into the very fascinating differences in the acoustics design of a concert hall to that of churches and synagogues. I don't think I'll ever walk into a worship space again without renewed interest in its acoustics, and I suspect that other readers will find they come away from this article feeling the same way.

In the fourth article, Robert (Bob) Ruben writes about the origin and history of ways to determine hearing loss. Bob not only talks about the design of instruments to measure hearing loss but also considers broader issues of hearing loss over centuries. The origin of this article is that Bob has been a practicing otolaryngologist (and active hearing researcher) for many years and also has a long-held passion for the history of hearing studies. Talking with Bob as this article evolved was immense fun and allowed me to renew a friendship of many years.

The fifth article is about former ASA president and Gold Medal recipient David M. (Dave) Green. Dave's former colleagues William A. (Bill) Yost, Roy D. Patterson, and Lawrence L. (Larry) Feth share Dave's history as a pioneer in the study of psychoacoustics and signal detection theory. They also give insights into some of Dave's most critical contributions to our understanding of hearing.

The last article by Zhaoyan Zhang is on vocal health. Zhaoyan gives great insight into the mechanisms by which humans make sounds. Although I was familiar with some of the mechanics, what I find particularly fascinating are the insights into the health of the human vocal system and some of the clinical mechanisms used to maintain health.

This issue of *AT* also includes, as we do in every Spring and Fall issue, a list of recent ASA award winners and new Fellows. I congratulate these colleagues on their achievements.

As usual, our first "Sound Perspectives" essay is "Ask an Acoustician" as coauthored by *AT* Associate Editor Micheal Dent. This essay is about Kathleen J. (Kathy) Vigness-Raposa. Kathy's work focuses on underwater acoustics, with a particular interest in anthropogenic sound. In addition, Kathy is one of the leads on the "Discovery of Sound in the Sea" web page (see www.dosits.org) and, through that, makes major contributions to the understanding of acoustics by millions of people around the world each year.

Each year, the ASA participates in the International Science and Engineering Fair that encourages the interest of precollege students from around the world in science and engineering. The ASA presents a number of awards in the area of acoustics. These are shared in a "Sound Perspectives" essay by ASA Committee Chair Laurie Heller.

The next "Sound Perspectives" essay is by two neuroscience graduate students, Ira Kraemer and Elizabeth Kolberg. Ira and Elizabeth write about supporting people with disabilities in academia and other professions. I decided to invite this article after I read a piece about the disability issues by one of the authors, and it struck me that the ASA interest in diversity extends to people who have various disabilities. Although Ira and Elizabeth focus on academia, many of the basic issues they raise, and even some of the solutions, apply in most work environments.

The next essay, by Brenda L. Lonsbury-Martin, is about the ASA Medals and Awards Committee. It is part of the series of essays in *AT* about various ASA committees (all listed on our "*AT* Collections" page). In the essay, Brenda talks about how to apply or nominate someone for various ASA awards.

This is followed by another administrative essay by James H. Miller. In his essay, Jim provides his annual update on the status of the ASA Foundation Fund, the very important group that provides critical funding for so many ASA members and activities.

The last essay is by Neil A. Shaw. Readers may remember that we held a mini contest in the Spring 2021 issue of *AT* to translate an advertisement that Neil placed. He wanted to give away his very extensive library of books on acoustics. Neil tells me that the library has found a home. But I got so curious about the library that I asked Neil to write an essay to give a taste of what he amassed over the years. If you read this essay and the article by Steve Garrett, you will find names of people and books in common.

I have to mention the cover of this issue, of Lord Rayleigh. The picture was inspired by Rayleigh being discussed in both an article and an essay in this issue of *AT*. Although Lord Rayleigh's work was not all in acoustics, he certainly had an immense influence on our field (as you will read). The cover is by my friend Mark Weinberg, the artist who has done several other covers for *AT*. You can view all of Mark's work, including his paintings of other famous historical figures, at edgieart.squarespace.com.

I will end by again inviting members to suggest topics for "*AT* Collections." It is easy to look back at past issues of *AT* because they all are online on our web page. We particularly look forward to suggestions from students about collections that might have served them or will serve them in their education.

From the President

Maureen Stone

Greetings! Because this is my first column in *Acoustics Today* as president of the Acoustical Society of America (ASA), let me introduce myself to those that don't know me. I study the human tongue at the University of Maryland School of Dentistry, Baltimore. My focus is on speech motor control and how tongue motion, deformation really, shapes the vocal tract tube during speech. In addition to normal function, I study the effects of tongue cancer surgery on tongue anatomy and motion patterns in order to interpret the resulting speech acoustics and perception outcomes. I have been a member of the ASA since I was a student and have been fascinated and impressed by the remarkably accessible organizational structure. Any member can be active to any extent in this Society.

I am excited about the year ahead. We have a lot of interesting work from the past year to continue, and after such a tough year, this is a good time to take stock of our current policies and approaches. I imagine that we all feel as if we are emerging from a Covid cocoon. Covid caused the ASA to significantly modify its meetings and activities, as you have no doubt noticed. So, as the Society begins to return to its previous routines, this is also an ideal time to consider new approaches to meet our potential as a thriving Society.

ASA Finances

Let's start by considering the finances of the ASA. The main source of operating revenue is from *The Journal of the Acoustical Society of America* (*JASA*), and the ASA has used this resource to good effect by sponsoring programs that support our mission: to generate, disseminate, and promote the knowledge and practical applications of acoustics. Naturally, many of these programs are not revenue producing, such as outreach and education nor are they expected to be. However, the growth of *JASA* revenue has not kept pace with our needs, in part because payment structures for journals have changed and in part because our expenses grow yearly. As with all organizations, it is easier to start new endeavors than to end old ones that may no longer be serving the ASA mission. The overall result is that for the past 10 years we have been outspending our revenue.

To address this issue, the ASA Finance Committee, chaired by Anthony Atchley, formed a subcommittee to undertake an in-depth examination of the finances and make recommendations to the Executive Council (EC), which is the ASA governing body. The report concluded that expenses have been growing in every segment of the ASA. There is no one program or operation that we can eliminate that would result in a break-even operating budget; everything must be in our sights. Therefore, to guide the EC's strategic planning and financial stewardship, a financial consultant group was engaged in March of this year and has been working with the ASA staff and officers to optimize the financial operations, long-term budget planning, and strategic use of its reserves.

Adding Value and Revenue to the ASA

This effort will take some time, but we have begun, and we are establishing plans to turn the financial ship, so to speak, and adjust our financial model into a fiscally stable position. At present, we are introducing new activities and features that will bring value to our members and also additional revenue.

One new source of revenue is "advertorials," such as the one by COMSOL in the Summer 2021 issue (pp. 40-41) of *Acoustics Today*. Advertorials provide information about an organization or product that is more detailed and analytical than in typical advertisements and may lead to collaborations with industry that benefit both academia and industry.

Another potential source of revenue is the ASA Academy, which, as a pilot program, is currently in development under the direction of Michael Vorländer and Task Force B: Better Engagement of Industry and Practitioners, with input from several interested Technical Committees (TCs). The long-term goal is to offer various sorts of continuing education programs in acoustics to acoustician and nonacoustician practitioners in education, industry, consulting, and research and development to provide them with useful in-service learning and advancement in their fields.

Our third endeavor is to offer new ASA meeting sponsorship opportunities, starting with the next ASA meeting in

Seattle, Washington. Susan Fox, our executive director, is leading this work with private sponsors, and Task-Force B is working to find additional interested parties in the private sector. We continue to seek new ideas.

Of course, in addition to increasing revenue, we also need to reduce our expenses where possible over the coming years. Our ASA meetings are among the most important and popular features of the Society and directly serve our mission. We love them, and we want to continue them as they are, if at all possible, but this comes at substantial and increasing overall costs as prices rise each year. Our meetings are rarely cost effective and usually lose money. We are revisiting the costs of our currently planned meetings, and we will continue to look for additional ways to generate new revenue (such as meeting sponsorships) and to reduce expenses going forward to stabilize our budget while not reducing the overall value of our meetings to attendees.

Meet Me in Seattle

Turning to the Seattle meeting, I hope you are as ready and excited for it as I am! Seattle will be our first live meeting in two years, and we want it to be as terrific as our previous in-person meetings. We are, however, aware of the Covid-19 and Delta variant challenges that await us this fall, including the possibility that the State of Washington will prohibit live meetings. We are currently developing contingency plans that would allow us to switch to an all virtual format and still hold as complete a meeting as possible.

Although we know the that virtual meetings in the Fall 2020 (Acoustics Virtually Everywhere [AVE]) and Spring 2021 (Acoustics in Focus [AiF]) had many positive features, several obstacles will prevent us from making Seattle a hybrid meeting. First, the Pacific Time Zone makes it difficult for people outside the United States to access the meeting in real time. For example, 11 a.m. in Seattle is 8 p.m. in Europe and 4 a.m. in Japan. Second, live broadcasts of technical sessions and other events increase meeting planning and expenses substantially, given that a hybrid meeting incurs all the fixed expenses of an in-person meeting *plus* the personnel, software, and hardware necessary to support the virtual components.

Nonetheless, we know there are ASA members for whom virtual sessions are truly an advantage, and for this reason, the Meetings Reimagined Ad Hoc Committee, chaired by Scott Sommerfeldt, and supported by the Virtual Technology Task Force Ad Hoc Committee, chaired by Andrew Piacsek, is hard at work considering the options for future meetings, including how to best utilize many of the successful virtual features, new meeting styles and schedules, and how to make our future meetings (including international and joint meetings) revenue neutral or even revenue positive while supporting the ASA mission and bringing value to attendees.

To that end, I am pleased to report that we plan to continue several features from the last two virtual meetings, AVE and AiF. First, holding the Administrative Committee meetings before the main ASA meeting allowed committee members to attend all of the technical sessions at AVE and AiF. We polled the committee members, and many of these committees have elected to continue meeting virtually in advance of the Seattle meeting.

A highlight of the AVE and AiF meetings was the successful introduction of keynote presentations by Past President Diane Kewley-Port, and we will continue to showcase keynotes as we go back to in-person meetings. Although the open TC meetings were broadcast live during AiF to all ASA members, including those who did not register for the meeting, in Seattle, we will return the TC meetings to their usual early evening times, which would make a live broadcast impractical for those outside the Pacific Time Zone.

ASA Is Your Organization. Participate in It!

As I end this column, let me leave you with some thoughts about how I hope you will get involved in the direction of the ASA. As most of you know, the ASA is largely a grassroots volunteer organization supported by an outstanding staff. This makes serving on ASA committees both rewarding and important. There are many opportunities for ASA members to join committees that actively contribute to the current operations and future direction. I want to particularly encourage new members to consider one of the following ways to become involved in the Society.

The entry level for volunteering is through your technical interest area. When you joined the ASA, you indicated one or more areas of interest and became an interest member, such as a Speech Communication interest member.

Each of the 13 technical interest areas has a Technical Committee (TC), usually composed of a subset of the interest members. To become a TC member, you must be recommended by the TC chair and then appointed by the President.

The TCs hold open meetings at each ASA meeting, and the technical interest members are invited to attend, as are all ASA members. At these meetings, the TC chairs often need volunteers for tasks and committees of all sorts. Do volunteer for anything of interest to you.

The ASA also has Administrative Committees. To learn about all the committees in more detail, take a look at the new online series in *Acoustics Today* called the "*AT* Collections" (see bit.ly/AT-Collections). The main page has links to articles that describe the work of all the TCs and Administrative Committees in great detail. Check them out to find a good fit for your interests.

I invite and encourage each of you to review the committee opportunities on the volunteer web page (see acousticalsociety.org/volunteer). Fill out the volunteer form linked to that page and join the great bunch of people who are already active in the TCs and the varied Administrative Committees. Only a few volunteers are accepted to a committee each year, and volunteering for a committee doesn't guarantee you a slot, but you do get on a list for the future.

If you believe you have expertise appropriate to an Administrative Committee listed on the volunteer or "*AT* Collections" web page, but it is *not* specifically listed on the volunteer form, please write to asa@acousticalsociety.org or to me at president@acousticalsociety.org.

A special opportunity for students is the Student Council (see bit.ly/Student_Council), a great place to meet other students, to network, and to start getting involved in the ASA.

My final suggestion for volunteering is to join one of the four Strategic Planning Task Forces. Information about them can be found at acousticalsociety.org/Strategy.html. The Task Forces have a Champions meeting at every ASA meeting, including in Seattle. This meeting is open to all and provides opportunities to learn what they do and their progress and to brainstorm with current members and others who want to bring in new ideas.

I look forward to working with you all this year. Contact me at president@acousticalsociety.org with any thoughts or ideas, and if you see me in Seattle come say hi!

Core Values of the Acoustical Society of America

(Adopted by the ASA Executive Council, July 19, 2021)

Sound is a ubiquitous phenomenon that permeates the natural and anthropogenic worlds. Thus, the core values that drive the actions, policies, and objectives of the ASA include

(1) Dedication to excellence as a premier global organization that serves the worldwide acoustics community with integrity and transparency;

(2) Broad, open, honest, respectful, and accessible inquiry into the science and practical applications of acoustics through thoughtful and tolerant oral and written discourse;

(3) A welcoming atmosphere of openness and inclusion for all members, potential members, authors, meeting attendees, those who interact with the ASA, and those who have an interest in acoustics regardless of status or capability;

(4) Advocacy for wide dissemination of acoustical knowledge at the local, state, national, and international levels to generate, promote, and advance the science and applications of acoustics;

(5) Provision of information and policy reviews to inform societal decision making on how acoustics, acoustical principles, and standards can be used to sustainably improve the human condition and preserve and restore acoustical environments;

(6) Service to current and future generations through the promotion, publication, and archival documentation of the science and applications of acoustics supported by a fair, deliberative, and rigorous review process; and

(7) Attraction, development, encouragement, education, and mentoring of current and future generations of acousticians from diverse backgrounds.

Topological Acoustics

Andrea Alù, Chiara Daraio, Pierre A. Deymier, and Massimo Ruzzene

Introduction

The field of topology studies the properties of geometric objects that are preserved under continuous deformations, for example, without cutting or gluing. A cup with a handle is topologically equivalent to a donut (or a bagel if you live in New York) because one shape can be deformed into the other while preserving their common *invariant* hole. Exotic topological shapes, such as vortices, knots, and mobius strips, can be globally analyzed using the mathematical tools offered by topology. The connection between topology and acoustics may appear far-fetched, yet recent developments in the field of condensed matter physics and quantum mechanics have been inspiring exciting opportunities to manipulate sound in new and unexpected ways based on topological concepts.

The field of topological acoustics has been inspired by the discovery in condensed matter of *topological insulators*, a class of materials that support highly unusual electrical conduction properties. Like conventional semiconductors, topological insulators are characterized by a gap in electron energy (bandgap) that separates their valence and the conduction bands. For electron energies within this bandgap, topological insulators are not electrically conductive in their bulk, hence their name. However, any finite sample of such materials necessarily supports conduction currents along its physical boundaries; the topological features of the valence and conduction bands ensure the existence of these boundary currents. Therefore, these currents exist independent of the boundary shape or the presence of continuous defects and imperfections that do not affect the bandgap topology. Knowing this feature, we can predict the existence of conduction currents flowing along the boundaries of any finite sample of such materials by simply analyzing the topological features of the bands of the infinite medium (Thouless et al., 1982; Haldane, 1988). As a result, these currents show an unusual robustness to defects and disorder. The electron spin plays a fundamental role in defining the topological response of these materials.

In recent years, there has been a strong interest in exploring analogies for these topological concepts in other realms of physics, in particular, in the context of optics (Raghu and Haldane, 2008; Wang et al., 2009) and acoustics (Fleury et al., 2016; Zangeneh-Nejad et al., 2020). Given that sound does not possess an intrinsic spin, in this quest the role of the electron spin is replaced by the notion of *acoustic pseudospins*. These pseudospins include angular momentum (Fleury et al., 2014), geometrical asymmetries (Xiao et al., 2015; Ni et al., 2018), structured space- and time-dependent material properties (Trainiti et al., 2019; Darabi et al., 2020), and asymmetric nonlinearities (Boechler et al., 2011; Hadad et al., 2018).

These explorations have been enabling new opportunities to route sound in novel and unintuitive ways. For example, topological sound can propagate only in one direction (forward, not backward), and it can take sharp turns following the arbitrary boundaries of an acoustic material just like the boundary currents of topological insulators. These exotic propagation modalities are unaffected by the presence of defects or imperfections that sound may encounter along the way, for example, in the form of localized scatterers or material heterogeneities.

Figure 1a shows one example of an acoustic topological insulator formed by an ordered array of subwavelength resonators whose properties are modulated in space and time with precise patterns to impart angular momentum (Fleury et al., 2016). As a result of the interplay between the array geometry and the angular momentum imparted by the modulation, topological sound propagation is achieved through the pressure fields that travel unidirectionally along the array boundaries (see **Figure 1a**).

In recent years, topological sound has expanded its realms, leading to the exploration of topological features not only in the bands of periodic structures, like the one in **Figure 1a**, but also in real space and parameter space. For example, **Figure 1b** shows the evolution of the eigenvalues of a system as two generic degrees of freedom or

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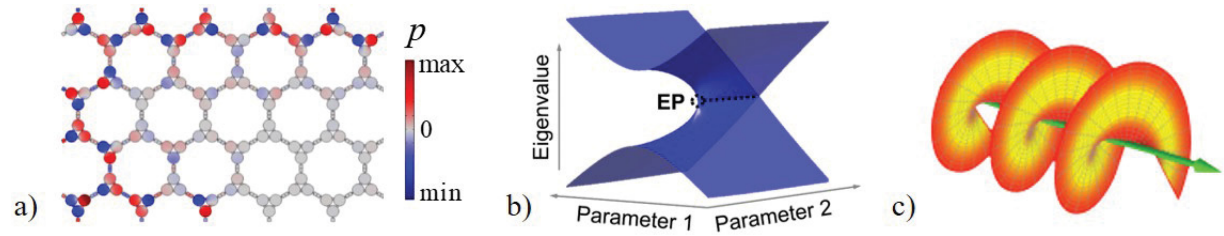


Figure 1. *Exotic acoustic phenomena enabled by topological concepts.* ***a:*** *Pressure field* (p) *distribution in a phononic topological insulator formed by an array of subwavelength resonators whose properties are modulated in space and time to impart a pseudospin in the form of angular momentum. The result is a one-way, edge-bound propagation of acoustic pressure (Fleury et al., 2016).* ***b:*** *Topological features around an exceptional point (EP) in the space formed by changing two independent parameters in an acoustic system, for example, a pair of coupled resonators whose resonant features can be controlled by changing two geometrical parameters (Miri and Alù, 2019).* ***c:*** *Pressure distribution (**yellow**, larger pressure fields) forming an orbital angular momentum sound beam. See text for detailed explanations.*

as parameters controlling the system are changed. This may correspond to two coupled acoustic cavities, which we can independently tune through geometric changes. Through proper design, the coupled cavity system can support an *exceptional point* (EP) in the space spanned tuning the two geometric parameters. At the EP, the eigenvalues of the system and the corresponding eigenmodes coalesce and become degenerate. As a result of this degeneracy, the system effectively loses one dimension. This singularity is associated with highly nontrivial topological properties (Xu et al., 2016) that can again provide unusual robustness of the response and at the same time offer opportunities for sensing (Shi et al., 2016; Miri and Alù, 2019).

Finally, topological features can also emerge in real space. **Figure 1c** shows an example of sound propagation with a nonzero orbital angular momentum (OAM) and the pressure distribution of an OAM sound wave traveling in free space. A carefully controlled array of sound emitters can emit such a vortex sound beam whose acoustic phase fronts are characterized by a nonzero topological charge, which can be leveraged to enhance the channel capacity in multiplexing applications and for robust sound propagation (Wang et al., 2018). In this article, we dive deeper into a few applications afforded by topological sound that may be of interest to the acoustics community at large.

Applications

Topological Sound Transport Based on Pseudospin Bias

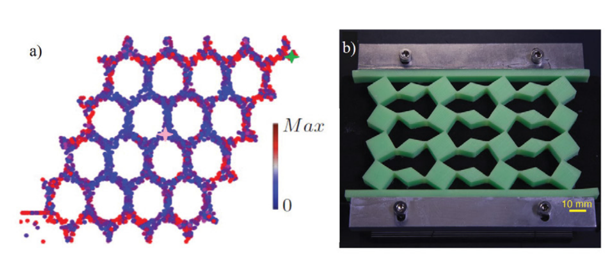
Acoustic waveguides are inherently prone to disorder and imperfections that impact the quality and efficiency of sound transport. Undesired back reflections and scattering can cause interference and distortions that impact several applications. Topological sound has been opening new opportunities for robust information transfer, multiplexing and processing, and data storage and manipulation. The simplest form of pseudospin to enable topological sound relies on geometrical asymmetries, for example, an acoustic array of subwavelength resonators with carefully tailored asymmetries act like a spin on sound waves (Ni et al., 2018). The resulting devices are passive and support topological boundary sound waves somewhat robust to disorder. Their main limitation stems from the fact that these acoustic topological insulators obey time-reversal symmetry, requiring that for any given wave supported in a certain direction and characterized by one pseudospin, the structure also supports an oppositely propagating wave with a reversed pseudospin. In the ideal case, the two modes are orthogonal to each other, but when disorder and imperfections are considered, their asymmetry may couple the two, limiting the overall robustness.

In contrast, topological sound enabled by pseudospins that break time-reversal symmetry, such as angular-momentum bias (Khanikaev et al., 2015) or rotating spatiotemporal modulation patterns (**Figure 1a**) (Fleury et al., 2016; Darabi et al., 2020), provide a stronger form of topological robustness because the corresponding boundary waves are truly unidirectional. The absence of such backward modes and of bulk modes ensures truly robust one-way boundary sound propagation, irrespective of the form of disorder and imperfections.

Figure 2a shows measurements on a practical example of this type of topological insulator for elastic waves, realized by electrically controlling a two-dimensional array of piezoelectric patches, similar to the design in **Figure 1a**, with electrical modulation signals suitably varying in space and time to impart a form of synthetic rotation that induces the desired pseudospin and breaks reciprocity (Darabi et al., 2020). **Figure 2a** shows the measured displacement extracted with a laser vibrometer, demonstrating that signals travel unidirectionally along the array boundaries.

Nonlinearities combined with geometrical asymmetries can also support pseudospins supporting nontrivial topological sound (Hadad et al., 2018). Although these systems are passive and obey time-reversal symmetry (as long as the nonlinearity is instantaneous), the combination of nonlinearities and geometrical asymmetries breaks reciprocity and enables unidirectional sound transport along the boundaries. An extreme example, seen in **Figure 2b**, shows a mechanical metamaterial made from a three-dimensional printed polymer, which supports a topological response at zero frequency. Mechanical nonlinearities are amplified at the small hinges connecting the diamond-shaped regions in **Figure 2b**, and the tilted elements introduce carefully tuned asymmetries that enable nonreciprocal transport of mechanical displacement when a force is applied to the structure from opposite sides. Interestingly, it can be shown that maximum nonreciprocity is achieved at the transition when the metamaterial changes the topological state, as controlled by the underlying geometrical asymmetries (Coulais et al., 2017). This metamaterial supports an unusual mechanical response; it strongly transmits displacement in one direction, but it dampens it in the opposite one.

Figure 2. ***a:*** *Elastic displacement measured with a laser vibrometer over a spatiotemporally modulated array of piezoelectric patches, demonstrating the emergence of a one-way topological boundary propagation of sound (Darabi et al., 2020).* ***b:*** *A topological mechanical metamaterial made of a three-dimensional printed elastic polymer based on asymmetric nonlinearities (Coulais et al., 2017).*



Radio-Frequency Technology Based on Topological Sound

The pseudospins discussed previously can robustly break reciprocity, enabling fundamental functionalities for several electronics and electromagnetics technologies. For example, nonreciprocity can be used to isolate transmitter and receiver modules in our cell phones, an important functionality in modern communication systems to avoid interference between the strong transmitted signals and the stream of weak signals received from the cell phone tower (Kord et al., 2020). Acoustic signals offer several opportunities in this context because of their small wavelengths and lower rate of energy loss compared with electromagnetic components. These properties have been harvested, for example, in surface acoustic wave (SAW) or bulk acoustic wave (BAW) filters used to process the radio-frequency (RF) signal received by antennas in portable communication devices. However, current solutions rely on linear, passive, single-frequency devices that are unsuitable for the next generation of RF systems because they have a limited range of functionalities and require integration with ever more complex electronic components. More desirable features, ideal for agile communication systems with enhanced data rates and serving many users, target narrowband, low-loss filters, with a small size and a tunable center frequency.

Topological acoustics provides fertile ground to advance these technologies and address current technological challenges. For example, topological acoustics reduces scattering and enables devices approaching the theoretical limits of the intrinsic material losses. The natural robustness to defects associated with topological properties can decrease manufacturing costs, reducing the requirements for high fabrication tolerance. Topological properties also allow for phase control and latency, functionalities not available in acoustic devices today.

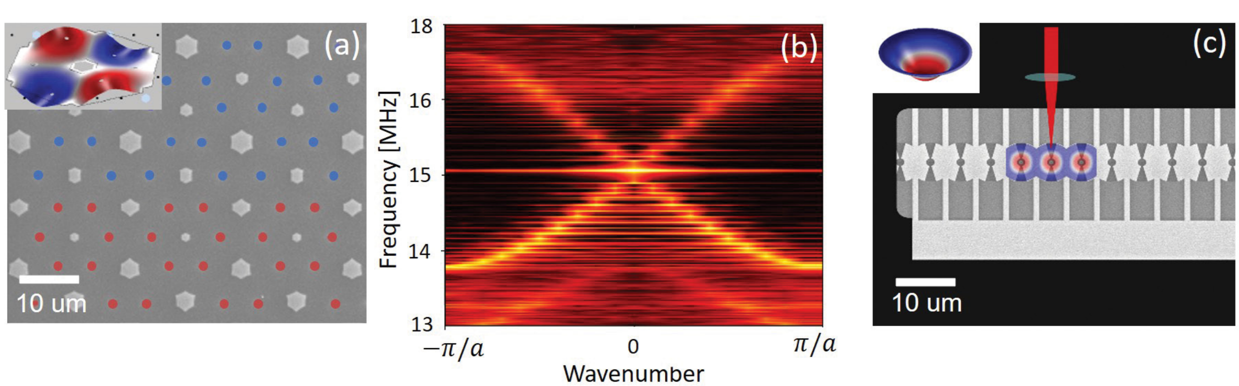
Nanoelectromechanical lattices (NEMLs) of resonators (**Figure 3a**) have demonstrated topologically robust waveguides using two-dimensional periodic arrangements of mechanically coupled, free-standing nanomembranes with circular clamped boundaries (Cha and Daraio, 2018). Such NEMLs form flexural phononic crystals with well-defined dispersion features, which can be used to tailor topological bandgaps (**Figure 3b**) offering a pathway toward the miniaturization of even more complex acoustic topological insulators, like the ones in **Figure 3b**. An additional advantage arising from these miniaturized acoustic devices is the possibility to transduce energy between different physical domains (Hackett et al., 2021). For example, nanomembranes can convert optical, magnetic, or electrical signals into mechanical strains and vice versa. These couplings can, in turn, be used to introduce nonlinearities (**Figure 2a**), modulation, and tunability of the fundamental resonant frequencies and the dispersion of the devices (Cha et al., 2018). The functionalities of these new acoustic devices can extend beyond conventional filtering, enabling complete networks and circuitry transporting pseudospins as a degree of freedom carrying information.

The potential of topological acoustics for RF communication systems opens a path toward a new technological landscape with lower energy consumption, smaller form factors, and larger bandwidths. Such opportunities also come with challenges, including design and fabrication complexity. Miniaturized topological acoustic metamaterials need to rely on advances in multimaterial fabrication capabilities to accomplish design flexibility, nonlinearity and dissipation control, and new strategies to impart the pseudospins of choice.

Information Science Based on Topological Sound

Sound is naturally used to encode and convey information. Human speech supported by sound carries information because our voice varies continuously in time and amplitude. Acoustic cues such as frequency and amplitude modulation allow communicators to derive meaning. Although this form of communication is based on analog signals, most information encoding, transmission, and processing techniques today are carried out in the digital domain, where signaling cues are restricted to discrete values. Modern digital information processing relies on electronic digital logic circuits, whose elementary units are Boolean logic gates and use the binary numbers 0 and 1 to implement Boolean functions such as the NOT, AND, and OR gates. Consequently, processing of sound-encoded

Figure 3. ***a:*** *Scanning electron microscope (SEM) image of a topological waveguide.* ***Red and blue dots****, lattice points of membranes with slightly different geometries. Flexural membrane motions (****inset****) were excited by simultaneously applying a DC/AC voltage (Cha and Daraio, 2018).* ***b:*** *Dispersion of topological edge modes experimentally measured in the geometry of panel* ***a****, where a is the lattice period.* ***Yellow*** *and* ***red****, modal resonances.* ***c:*** *SEM image of a nonlinear nanoelectromechanical lattice (NEML) (Cha et al., 2018).* ***Red arrow****, localized probe exciting the structure.* ***Inset:*** *geometrical nonlinearity induced by electrostatic softening.* ***Red*** *and* ***blue****, field maxima and minima, respectively. See text for further explanation.*



information in conventional electronic systems necessitates the conversion of sound into electrical signals.

Topological acoustics enables new forms of acoustic information processing that rely on integrated circuits. The development of acoustic metamaterials has provided physical platforms for the realization of acoustic Boolean logic gates. By exploiting their unique spectral, refractive, and phase properties, we can tailor the constructive or destructive interference of input and control acoustic waves to achieve Boolean functions of choice (Bringuier et al., 2011). Similarly, interference has been used to demonstrate Boolean logic gates in acoustic metamaterials (Zhang et al., 2016), and acoustic logic elements have been demonstrated in driven chains of spherical particles (Li et al., 2014).

Until recently, all these acoustic information processing elements have made use of the spectral and refractive properties of composite materials. Topological acoustics enables all-acoustic information processing that goes beyond the canonical attributes of sound, that is, frequency, wave vector, and dynamical phase (Deymier and Runge, 2017). The pseudospins enabling topological sound can be used as new degrees of freedom for information transport, realizing a wide range of acoustic Boolean logic elements with enhanced robustness and operating with low-energy requirements.

Interestingly, the features of topological acoustics offer avenues to go even beyond Boolean logic to pursue sound-based quantum-like information processing. In contrast to conventional computing, where a bit can be in a zero or one state, quantum computing processes a zero and a one at the same time by using a coherent superposition of states. Topological acoustic quantization, for example, based on two opposite pseudospins, coherence and correlations, can be harnessed to overcome stability and scalability challenges in current approaches to massive-data information processing, within the context of the second quantum revolution (Dowling and Milburn, 2003).

The pseudospin degrees of freedom of topological sound offer intriguing opportunities to achieve quantum-like phenomena like entanglement. Entanglement occurs when the state of a composite system composed of subsystems cannot be described in terms of the states of independent subsystems. Entangled superpositions of quantum states exhibit the attributes of *nonlocality* and *nonseparability*. Nonlocality is a unique feature of quantum mechanics that Einstein dubbed a "spooky action at a distance." Nonlocality allows, for example, two photons of light to affect each other instantly, irrespective of their distance of separation. Acoustic waves, because of their nonquantum nature, that is, their "classical character," are limited to local interactions. Nonetheless, nonseparability or *classical entanglement* can be realized in systems supporting classical waves, including sound.

An acoustic wave propagating in a cylindrical pipe can be represented by the product of three functions, each dependent on three degrees of freedom: one variable describing the pipe along its length and radial and angular variables characterizing the pipe through its cross section. In this sense, conventional guided acoustic waves are separable. A nonseparable acoustic wave, in contrast, is represented by a wave function that cannot be factored into a product of functions. Such waves can be created in externally driven systems composed of parallel arrays of waveguides coupled elastically and uniformly along their length (Hasan et al., 2019). These classically nonseparable states are constructed as a superposition of acoustic waves, each a product of a plane wave and a spatial degree of freedom analogous to OAM (**Figure 1c**). The plane wave portion describes an elastic wave propagating along the waveguides, and the spatial degree of freedom characterizes the amplitude and phase profile across the array of waveguides (**Figure 4a**). These nonseparable and therefore nonindependent degrees of freedom are the classical analogue of two correlated qubits. The amplitude of the nonseparable acoustic state is then analogous to the simplest examples of quantum entanglement of two qubits, known as Bell states in quantum mechanics. The displacement fields of the modes supported in the array of coupled waveguides are shown in **Figure 4, b-d**. Although **Figure 4, b and d**, shows separable OAM and plane wave states, characterized by symmetric patterns, **Figure 4c** shows a nonseparable and largely asymmetric linear combination of waves, with distinct momentum and OAM degrees of freedom. This type of acoustic superposition of states dramatically expands the opportunities for massive information storage and processing (Deymier et al., 2020).

Implementation of quantum-like algorithms necessitates the manipulation of nonseparable classical states, providing the parallelism required to achieve the goals of quantum information science (Jozsa and Linden, 2003). The analogies between quantum mechanics and classical wave physics have been recently exploited to emulate

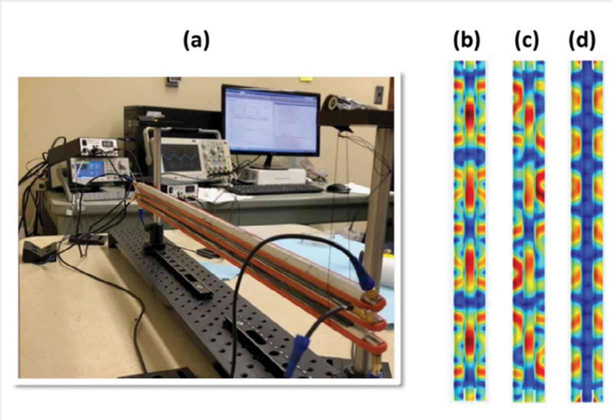


Figure 4. ***a:*** *Parallel array of three elastically coupled waveguides (aluminum rods glued with epoxy), driven at their ends by piezoelectric transducers (black structures at the bottom right of picture), designed to support acoustic analogues of quantum Bell states (Hasan et al., 2019).* ***b*** *and* ***d:*** *Color maps of the magnitude of the displacement field calculated using the finite-element method in the array of coupled waveguides in separable orbital angular momentum (OAM) and plane wave states.* ***Red and blue****, large and low magnitudes of displacement, respectively. Separability is visualized as symmetric color patterns across the array of rods.* ***c:*** *A nonseparable linear combination of waves, each with a different momentum and OAM degrees of freedom. The loss of symmetry in the color pattern across the array of rods is indicative of nonseparability.*

quantum phenomena in classical settings. For instance, optical metamaterials have been able to simulate a quantum algorithm with electromagnetic waves (Cheng et al., 2020). However, these simulations have relied on wave superposition and interference to realize algorithms that do not require entanglement. In contrast to electromagnetic waves, the stronger nonlinearities and robustness arising in topological acoustics offer unique opportunities to realize nonseparable states for algorithms harnessing entanglement to speed up computational tasks beyond Boolean operations.

Sensing with Topological Sound

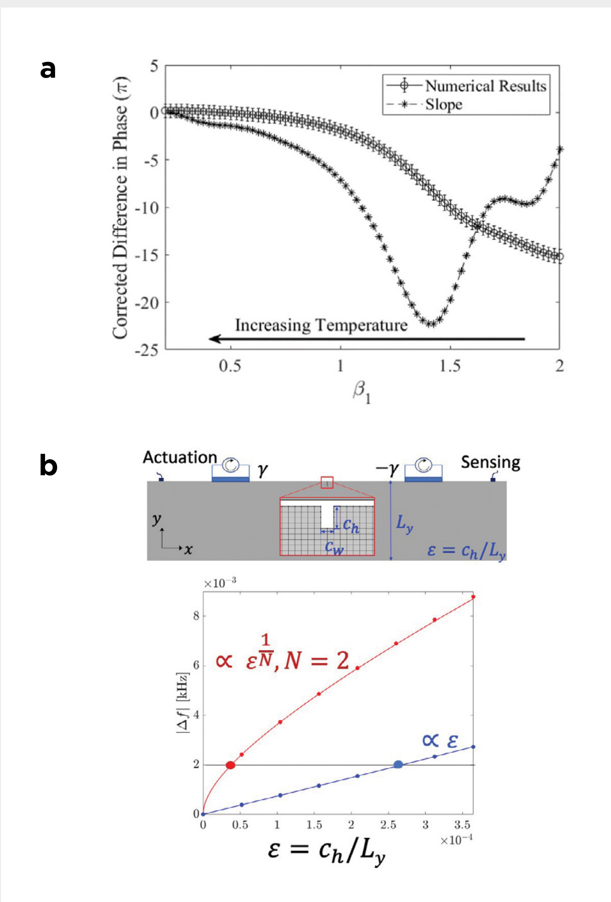
Topological acoustic attributes, such as pseudospin as well as amplitude, wavelength, and the frequency of sound, provide access to the global physical properties of a material or of a system. This allows transduction and encoding of information over a broad range of frequencies and implies the ability of observing features at multiple length scales and resolutions. Thus, the ability to observe and measure these attributes holds the promise for unparalleled sensitivity and resolution in acoustic-based sensing and imaging. For example, the emerging literature on the sensitivity to the *geometric phase* as a form of acoustic pseudospin is already making an impact in the areas of ecological and environmental sciences, aimed at measuring changes in temperature, density, or stiffness of the underlying medium. A recent study (Lata et al., 2020) has exploited the sensitivity to the geometric phase of ground-supported long-wavelength acoustic waves, such as seismic waves, in a forest environment, an acoustic medium where trees act as scatterers.

In the era of climate change, melting permafrost poses significant challenges to local Arctic communities. New technologies are needed to provide reliable ways to monitor and characterize the global properties of permafrost such as temperature and thawing state. This is vital to the management of natural and built environments in Arctic regions. Current techniques relying on data collected through boreholes and drilling sites produce rough permafrost maps and are not suitable for continuous monitoring. Also, remote sensing based on aerial and satellite imaging that indirectly measures ground characteristics through the reflection of electromagnetic waves, for example, using LiDAR technology, require a direct field of view and therefore are not suitable for forested areas. In contrast, the variation of the geometric phase as a function of frequency is experimentally measurable through distributed arrays of ground transducers. These can operate in *active* mode, according to pulse/echo schemes that employ transmitter and receiver transducer pairs, or in a *passive* modality, whereby the transducers receive and correlate the diffuse acoustic field corresponding to the ambient seismic noise. Through geometric phase monitoring, large detectable changes in phase in response to changes in ground stiffness/temperature (up to $3\pi/1°C$ have been predicted for frequencies near resonance of trees (**Figure 5a**).

Topological acoustic attributes may also be employed for monitoring any type of built or natural structures in the broader context of acoustics-based nondestructive testing, which is a multibillion industry. For example, recent findings in the field of topological physics have revealed how enhanced sensing may be achieved by exploiting the unprecedented sensitivity around EPs to perturbations associated with small changes in physical properties

(Chen et al., 2017; Hodaei et al., 2017; Miri and Alù, 2019). The degeneracy at EPs emerges in physical systems characterized by underlying symmetries; breaking these symmetries as a result of external perturbations produces shifting and splitting of the coincident resonant frequencies of a cavity where EPs are formed. The shifts and splits of these resonances can be exploited for the detection and possibly for the quantification of such perturbations (**Figure 1b**). Many conventional sensors rely on the detection of shifts in resonances that are typically linearly proportional with respect to the perturbations that cause them.

Figure 5. ***a:*** *Permafrost monitoring using geometric phase: difference in geometric phase for a model forest of uniformly dispersed trees, and the local slope versus ground stiffness (β_1; corresponding temperature range from 0 to −12°C) (Lata et al., 2020).* ***b:*** *Schematic for crack detection through EP evaluation.* ***Top:*** *elastic domain with microscopic crack monitoring.* ***Bottom:*** *variation of Δf in terms of crack depth for EP perturbation (**red**) and traditional single mode shift (**blue**) showing the different orders (Rosa et al., 2021).*



In contrast, the separation of resonances around EPs is *superlinear* and, therefore significantly more sensitive to changes. A new class of sensing concepts may emerge by not solely relying on these pronounced shifts but also exploiting the underlying nontrivial topological features. These concepts may find applications in temperature, flow, and pressure sensing, among others (Xiao et al., 2019; Kononchuk and Kottos, 2020). The generation of EPs can occur in systems obeying parity-time (PT) symmetry, which feature balanced distributions of gain and loss (Bender and Boettcher, 1998).

In the context of active sensing, gain and loss can be introduced in acoustic platforms in the form of arrays acting as transmitters and receivers, which are properly placed within a medium to be monitored (Fleury et al., 2015). The medium may be subjected to property changes due to material degradations, the onset of damage or environmental changes (e.g., temperature, pressure).

Recently, the ultrasonic detection of a crack developing in a metallic structural component (**Figure 5b**) has been observed through transducer arrays that both actively monitors the propagation of an ultrasonic wave and implements gain and loss along the wave path to induce an EP (Rosa et al., 2021). The crack perturbs the EP symmetry, inducing two resonant peaks separated by a frequency interval ($\Delta f \propto \epsilon^{1/2}$). Here, ϵ is a small perturbation quantifying the crack depth (**Figure 5c**, *red line*). The spectral shifts that would be observed in a conventional sensor not involving an EP only vary linearly with (**Figure 5c**, *blue line*). Given a specific Δf, for example, that defines the resolution of a detection device translates into the ability of the EP sensor to detect smaller cracks. For $\Delta f = 2$ Hz as the available resolution, for example, this translates into the ability to detect cracks that are 85% smaller than those detectable through conventional sensors. It should be mentioned here that there is an ongoing debate regarding the actual superiority of EP sensors compared with other sensing techniques because a superlinear frequency splitting does not necessarily translate into enhanced sensor precision in the presence of realistic noise (Langbein, 2018; Wiersig, 2020). This debate is driving additional explorations devoted to reducing the effects of noise while maintaining the attractive sensitivity properties associated with EPs.

Outlook

In this article, we have offered an overview of the powerful opportunities offered by topological concepts in acoustics to manipulate and control sound in fundamentally new ways. This emerging area of research takes inspiration from groundbreaking advances in condensed matter physics, quantum mechanics, and photonics and leverages the properties of acoustic metamaterials to enable new forms of sound transport. Pseudospins emerging from geometrical asymmetries, external bias, spatiotemporal modulation, and nonlinearities can be leveraged to enable topological sound, benefiting a broad range of applications from sound transport robust to defects, noise, and disorder to multiplexing, information processing, data storage and manipulation, and sensing. We expect the field of topological acoustics to open disruptive directions for sound control, with an impact on basic science and applied technologies.

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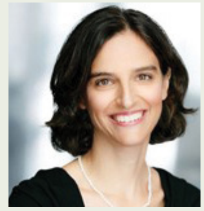

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One-Hundred Years of English-Language Acoustics Textbooks

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

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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

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How Room Acoustics Design of Worship Spaces Is Shaped by Worship Styles and Priorities

David W. Kahn

Introduction

The room acoustics design of concert halls is a topic much written about in the acoustics literature (Kierkegaard and Gulsrud, 2011; Hochgraf, 2019). Not only is concert hall design of great interest to many acoustics professionals but it also rightfully garners the attention of musicians, other design professionals such as architects, and the music-loving public. Articles on the room acoustics design of concert halls often appear not only in professional journals such as *The Journal of the Acoustical Society of America* (e.g., Beranek, 2016; Lokki et al., 2020) but also in the popular media (e.g., Wagner, 2019).

In contrast, the acoustical design of worship spaces receives little attention in professional acoustics journals, and it is possible that there have never been any articles published on the topic geared toward the general public (but see Bradley et al., 2016 for a popular treatment). This is curious given how many more worship spaces than concert halls there are and that most members of the general public spend more time in worship spaces than in concert halls. Certainly, the acoustics of worship spaces has as much of an impact, if not more, on the experience of worshippers during a service as does the impact of performance space acoustics on the experience of those same people in a concert hall.

There are many religions, each of which has unique ways of worshipping. This article addresses only those with which I am professionally familiar, which are primarily Christian and Jewish worship services.

Design Considerations

From the viewpoint of an acoustics designer of worship spaces, the acoustics design of concert halls is simple. The nature of the sound sources is well-known, and the nature of the sounds emitted by those sources (usually an orchestra) is fairly consistent. In addition, there are only rare occasions where some of the sound sources are placed "off stage" in a very limited number of works. Furthermore, the audience experience is not participatory; attendees simply listen to the sound being emitted from the performance platform.

Contrast that to a worship space, where the situation is quite different. First, congregations often participate in worship; they are not always just listening. Their audible experience of hearing themselves and others in the congregation is a key element of the worship experience.

Second, although much of the activity in a worship service takes place on a platform at the front of the sanctuary similar to the stage at the front of a concert hall, many worship spaces have musicians' areas (e.g., instruments, singers) that are not integrated into this area but are elsewhere. One example is the Church of the Resurrection in New Albany, Ohio, where the musicians are off to the left of the sanctuary (**Figure 1**). Pipe organs are often integrated into worship spaces, but unlike concert halls where the pipe organ is located on the upstage wall, pipe organs in churches are often also located elsewhere in the space.

Third, in a concert hall, the acoustics designer focuses on the quality of music and is much less concerned about the quality or intelligibility of the *spoken* word because this is rarely a key component of an event in a concert hall. In contrast, in a worship space, the acoustical quality and intelligibility of the spoken word is almost always of importance. Consequently, one important distinction between worship spaces and concert halls is that the former must support both music and the spoken word equally well.

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Figure 1. *Musicians play from a position off the central axis of the sanctuary (**left**) at the Church of the Resurrection in New Albany, Ohio.*

Concert halls also support diverse programming that may range from chamber music to full orchestra to a "pops" concert that includes some amplification. That is why some concert halls, and particularly halls designed in the last few decades, include adjustable acoustics design elements. Incorporating adjustable acoustics design elements into a worship space, however, is less common, even though there is often an even greater programmatic need for acoustical adjustability.

Background/History

Unlike concert halls, worship spaces have their roots in prehistory, whereas the concert hall as a dedicated building is a product of the eighteenth century, during which (at least in the West and, more specifically, in England) the live performance of commissioned music morphed from an affair by invitation in private music rooms for small audiences into events for the paying public in larger quarters (e.g., Forsyth, 1985).

Continuing with our comparison of worship spaces and concert halls, a fourth point is that the style of music can vary dramatically from one worship space to the next. Concert halls host a wide range of musical styles also, but the range is generally not as dramatic as is found in worship spaces. Some worship services use rock bands to lead music; this is most prevalent in some of the more seeker-targeted, nondenominational Christian ministries. Some Baptist churches as well as churches of other denominations have large orchestras on most Sundays that are more like those in concert halls. Of course, many Christian services have choirs, and many Christian worship spaces also include organs. Jewish worship spaces can have a fairly broad range of music included in their services; however, although the range is generally not as wide as with Christian worship spaces, some less traditional Jewish synagogues that include organs and choirs are not unusual, at least for some services.

If a worship space has a consistent worship style from week to week, one can develop an acoustical design to suit that particular music style, but, to complicate matters, some worship spaces have multiple services. It is not uncommon for one church to have both a "traditional" worship service that features primarily choral and organ music in addition to a "contemporary" service that features an amplified rhythm section similar to the instrumentation of a typical rock band.

Yet music itself is older than either concert halls or houses of worship. Music came before buildings of any kind, and the point of intersection between music and architecture is when we first see music in worship spaces.

Because only much later did music come to be performed indoors for its own sake outside the context of worship, it is not a stretch to say that for most of music history, composers wrote music primarily to be played outside or in buildings not explicitly designed for music performance.

Today, a rich and extremely varied repertoire of sacred and liturgical music exists and it continues to evolve, but it is important to remember that almost none of this repertoire was written to be performed in the spaces where it is performed today. An acoustics designer of worship spaces must be knowledgeable about this repertoire, its history, and its variety, because they relate to the faiths and denominations with which the designer is working. An acoustician must also be capable of designing a worship space to accommodate the full breadth of activity and worship styles that may occur within any given space.

Perhaps the most significant modern development affecting the acoustics of worship spaces and, indeed, nearly all gathering spaces is the advent of electronic sound reinforcement systems. Yet their adoption has not been

Table 1. *Worship priorities*

	Acoustical Characteristics	Architectural Elements Needed To Create This
Traditional music with orchestra and choir	Balance of early-arriving sound reflections and late-arriving reverberant energy, resulting in high levels of clarity and long reverberation times (1.8–2.2 s)	Generally rectangular in plan Compact/efficient seating layout with shallow floor slope Sound-reflecting surfaces located close to congregation and platform: balconies, soffits, ceiling elements
Contemporary music (amplified)	Low levels of reverberation (<1.2 s typical) Minimize discrete echoes from loudspeakers back to platform	Minimized room volume Low ceiling Sound-absorbing wall and ceiling treatments Wall shaping to avoid echoes and late-arriving sound energy
Preaching	High speech intelligibility Acoustic feedback from the room/congregation Acoustic and visual intimacy between preacher and congregation	Minimized footprint Sound-reflecting surfaces located close to the congregation including balconies, soffits, and ceiling elements that direct sound back to the platform
Congregational participation	Early sound reflections between members of the congregation	Minimized footprint Sound-reflecting surfaces located close to the congregation including balconies, soffits, and ceiling elements that direct sound back to the congregation
Thin apace (high aesthetic)	Cathedral-like sound Highly reverberant (>3 s) Poor speech intelligibility	Large acoustic volume Tall ceilings Sound-reflecting materials (wood, stone, concrete, glass)

universal; even today, Orthodox Jewish congregations do not use sound reinforcement systems for their services.

Priorities

When a space is used for multiple activities and if those multiple activities do not all have the same acoustical requirements, the acoustics designer must choose which activity to design for. In our work, we like to engage the owner in this process. Ideally, the owner will provide not only a list of the anticipated activities that take place in that space but will also prioritize those uses. This is a great benefit to the acoustics designer and can help to determine, for example, the need for adjustable acoustics finishes or the need for a supplementary electronic sound system to provide for a way to adjust the acoustical environment to better support a wider range of uses.

The balance in importance between the spoken word and music varies from ministry to ministry. Similarly, the importance of congregational participation varies. For example, in some ministries, the role of the congregation in the worship service is as important as the clergy's role. In others with a far more presentational worship style, the importance of congregational participation is quite low. The nature of the worship service and the prioritization of the typical elements of a worship service can have a profound impact on the acoustical design strategy. **Table 1** lists the typical elements of a worship service and the acoustics and architectural design considerations associated with each.

Acoustical Design Strategies

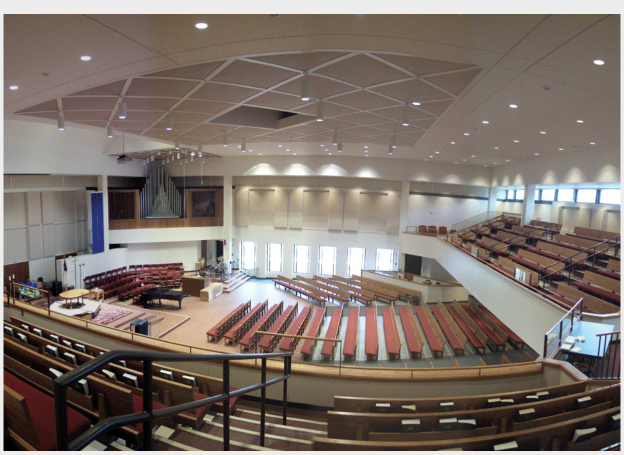
Adjustable Reverberation Time

In a traditional room acoustics design context, the challenge of balancing support for the spoken word versus music is one of choosing the appropriate compromise between a room whose reverberation time is too long for good speech intelligibility and a room whose reverberation time is too short to enhance the music. Some modern concert halls have adjustable acoustics curtains, banners, or panels that allow the reverberation time to be adjusted depending on the music to be played at that performance.

However, even if these elements were to be incorporated into a worship space, it is not practical to adjust them during the worship service, for example, extending curtains for the sermon and retracting them for the music. There are some worship spaces, however, that do incorporate adjustable acoustics curtains and panels. One example is the Roseville Lutheran Church in Roseville, Minnesota (**Figure 2**). Adjustable elements were incorporated because this church has both traditional (choir and pipe organ) worship services as well as a contemporary worship service with a "praise band."

This church knew from experience, before embarking on the design of a new worship space, that there were some very significant challenges involved in supporting both a traditional service with choir and organ and a contemporary service with an amplified praise band with keyboards, electric guitars, amplified vocalists, and more. My acoustics consulting firm, Acoustic Distinctions, worked collaboratively with the architects from the outset to develop a new worship space design that incorporated adjustable acoustics elements, including hinged panels that could easily be opened or closed between services and a large volume above the ceiling and below the roof with a large opening over the location occupied by the pipe organ and the choir. There are large, motorized curtains in this volume that can be extended or retracted.

Figure 2. *The Roseville Lutheran Church in Roseville, Minnesota, is an example of the rare worship space with adjustable acoustics. Acoustic panels behind the platform and seating areas are shown in the open (absorptive) position.*



Use of Partially Coupled Reverberation Chambers

A partially coupled reverberation chamber is a large, very reverberant space (a space with all very reflective finishes, such as a shower stall) that is physically connected to another large space (typically, the seating area of a concert hall, theater, or worship space). The concept of the partially coupled reverberation chamber is to efficiently increase the reverberation time of the primary space. For example, rather than increase the ceiling height within a space to get more volume (volume is directly correlated with reverberation time), acoustically coupling the space to an adjacent volume (perhaps above the ceiling) and using that additional volume as a reverberation chamber can increase the reverberation time of the primary space with less total volume than would be required using just a single architectural volume. The effect of these reverberation chambers can be minimized by providing adjustable sound absorption in the chamber. A coupled reverberation chamber is a cost-effective way to achieve an acoustic goal that might otherwise be impossible because there are usually limits to the size a building can be made due to budgetary or other constraints.

The use of partially coupled reverberation chambers is an acoustical design technique pioneered to a large extent by Russell Johnson (see bit.ly/3cE2Ir3). This technique was first developed to solve the acoustical design challenge of multipurpose halls used both as theaters and concert halls. The volume of the stagehouse below the proscenium opening but outside the orchestra shell was developed into a partially coupled reverberation chamber to enhance reverberation for music when these theaters were used as concert halls.

The acoustical design concept is to have a relatively short reverberation time to support clarity but a long audible reverberant tail that is most audible after a terminal chord is released. Reverberation time is defined as the time for sound to decay by 60 dB. In the coupled situation, greater time elapses before the sound decays to that degree, but the initial constant decay is maintained.

Partially coupled reverberation chambers have been incorporated into the acoustical design of some churches where, in general, the reverberation chamber is created by the space between the ceiling and the roof, such as in the Roseville Lutheran Church (**Figure 2**). The acoustical benefits of this design approach as it relates to worship spaces is that the room's natural acoustics provide for better clarity and therefore better natural support of the spoken word. They also allow the efficient development of a very long reverberation time to support choral and organ music (longer reverberation times can be achieved with less overall volume).

One of the challenges of a reverberation chamber is making sure that enough sound energy gets into the chamber to have an audible impact. When the reverberation chamber is formed by the lower section of the stage house in a multipurpose auditorium, it is easy to get enough energy into that chamber due to its proximity to the performance platform. Similarly, at the Roseville Lutheran Church, the pipe organ and choral loft were located directly below a large opening into the reverberation chamber.

The Perimeter Church north of Atlanta, Georgia, is another example of a worship space where the void between the ceiling and the roof was utilized as a reverberation chamber (**Figure 3**). Unlike most churches, the Perimeter Church built a theater with a fully rigged stage house to support their large-scale dramatic productions; therefore, there is not much, if any, acoustical connection between the stage, where the sound originates, and the ceiling void over the audience seating area. The ceiling has discrete openings that allow the reverberant energy in this void/reverberation chamber to add to the audible reverberant tail as heard by the congregation, similar to the effect that reverberation chambers have in multipurpose performance spaces and concert halls. The challenge at the Perimeter Church was to get sufficient sound energy from the stage up into this void, which was solved with a simple sound reinforcement system. Microphones placed over the musicians amplify their signal, which is then played into a series of loudspeakers located above the ceiling void.

Figure 3. *Recesses in the ceiling of the Perimeter Church north of Atlanta, Georgia, are actually "windows" coupling the main sanctuary volume with a reverberation chamber between the ceiling and the roof.*

Sound Reinforcement Systems

The advent of electronic sound reinforcement systems has helped to increase intelligibility of the spoken word, particularly in larger and more reverberant spaces. Large cathedrals are spaces where, historically, the spoken word was not intelligible other than to perhaps a small congregation located close to the pastor. Understanding the spoken word has generally become a higher priority in both Christian services and Jewish services. Furthermore, sermons have grown in significance and have become a more important, if not *the* most important, element of a service.

Most of these large cathedrals, many of which were constructed several hundred years ago, have added sound reinforcement systems in more recent years; Notre Dame in Paris, France, is one example. This has allowed larger congregations who may gather in these spaces for special events to all hear and understand the spoken word.

Before the development of electronic sound reinforcement systems, attempts were made to improve the intelligibility of the spoken word through the use of sound-absorbing finishes. There are many examples

Figure 4. *The vaulted ceiling surfaces at the Riverside Church in New York City are Guastavino tile that required sealing after sound reinforcement was added to the sanctuary.*

of churches in the United States that incorporated Guastavino tile in the form of Akoustolith (a product developed in the early 1900s expressly for the purpose of limiting undesirable reflections in spaces with vaulted ceilings), usually in the ceiling, to reduce the reverberation time. But these finishes improved one acoustic parameter at the expense of another; the acoustical quality of the spaces where they were installed declined for music and, in particular, choral and organ music, both of which are typically the primary, and sometimes only, source of music in these spaces. One example is the Riverside Church in New York City (**Figure 4**).

As the quality of sound reinforcement systems increased, many of the churches that incorporated Guastavino tile, including the Riverside Church, have decided to go back and use multiple coats of special clear sealants to *increase* the reverberation to provide better acoustical support of music. However, one challenge with sound reinforcement systems is that they can increase loudness but not necessarily speech intelligibility.

In order to increase intelligibility, these systems must provide a significant increase in the loudness of the *direct* sound (the sound that travels to a congregant's ears directly from the loudspeaker), with a smaller increase in the loudness of the reverberation. One way to do this is to provide small loudspeakers close to the congregants. These systems are known as pew-back systems. If the speaker is close to the congregant, it is easier to improve the loudness of the direct sound compared with the loudness of the reverberant sound. Still, pew-back systems are expensive and tend to sound unnatural, but as electronic sound reinforcement technology improves, it is becoming more possible to attain the elusive combination of natural sound, lower cost, and better speech intelligibility.

As sound reinforcement systems developed, many churches suspended large speakers or arrays of speakers over the platform or otherwise mounted them at a distance from the congregants. These systems often increased the level of reverberation as much as the level of direct sound; as a result, many of these attempts were not successful.

One of the most significant advances in the design of loudspeakers that is continuing to improve to this day is better directional control over a wider frequency bandwidth. This allows a loudspeaker to aim a larger percentage of sound energy into the sound-absorptive seating area, with a smaller percentage of sound energy going into the

Figure 5. *Steerable arrays in the ceiling permit a minimal suspended speaker array system at the Church of the Resurrection in Leawood, Kansas, to serve a large congregation, aiming sound toward the absorptive seating areas and away from the reflective surfaces.*

sound-reflecting wall, floor and ceiling surfaces. This provides a greater increase in the loudness at the listener's ears between the direct sound from the speaker and loudspeakers relative to the loudness of reverberant sound in the room. As this technology improves, it becomes possible to suspend a smaller number of speakers over the performance platform to enhance the intelligibility of the spoken word to larger congregations.

One recent example of the successful use of steered arrays is the United Methodist Church of the Resurrection in Leawood, Kansas (**Figure 5**). The loudspeakers allow a great deal of directivity pattern flexibility. As a result, the sound energy emanating from them covers the wide wraparound seating area, with minimal sound spill onto reflective surfaces such as the walls outside the seating area, the platform, and the ceiling.

Natural Enhancement of Speech Intelligibility

The acoustical design of modern Jewish Orthodox synagogues is one unique challenge that deserves its own discussion. One challenge is that some of these spaces are quite large; providing good speech intelligibility to hundreds of people for unamplified speaking is a formidable challenge. Keeping background noise levels very low (e.g., from the building's HVAC systems, outside noise) is one essential design consideration because high speech intelligibility requires a good signal-to-noise ratio. Because the loudness of the signal (unamplified speaking) is limited, with no ability to boost the level with an electronic sound reinforcement system, the "noise" must be as low as possible to increase the signal-to-noise ratio in the worship space.

The room shaping must be designed to reflect the sound of a person speaking into the congregational seating area. The sooner those reflected sounds arrive, the louder they will be. Also, our auditory system integrates reflected sounds arriving soon after the direct sound more effectively than later-arriving reflected sounds to improve speech intelligibility.

An additional complication in an Orthodox synagogue is that there are two different and important locations where speaking or chanting takes place. One is from the center bimah where the speaker faces the front of the room (the Ark) with his back to half the congregation.

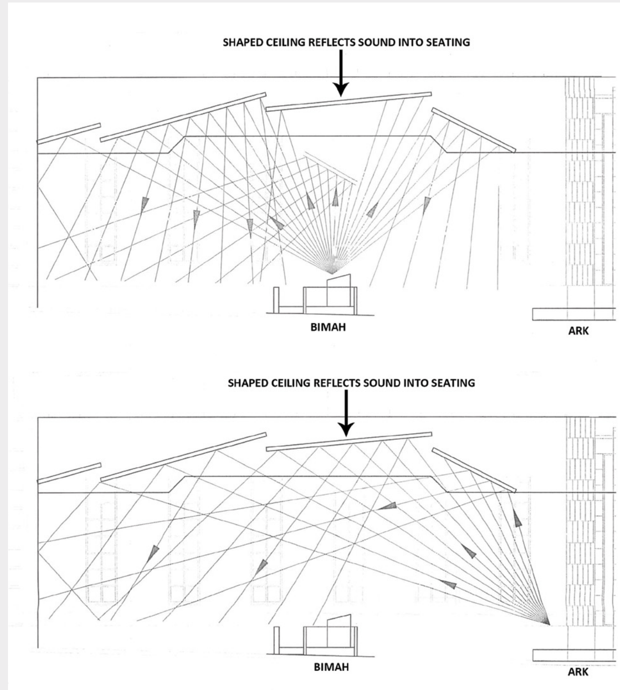


Figure 6. *Reflections for a sound source originating at the central bimah of a synagogue (**top**) and from the Ark (**bottom**).*

Figure 7. *Young Israel of Greater Cleveland Orthodox synagogue in Beachwood, Ohio, features ceiling shaping to support a person speaking at two critical locations.*

The second location is from the Ark facing the congregation; the room shaping must support strong early reflections to the entire congregational seating area for both speaking locations.

One example is Young Israel of Greater Cleveland in Beachwood, Ohio. The seating capacity of this Orthodox synagogue is unusually large. Providing excellent speech intelligibility for such a large congregation without the use of any electronic sound reinforcement was a formidable challenge. As is typical for Orthodox synagogues, there are two sound source locations that require natural reinforcement. The opportunity to improve natural reinforcement of speaking and chanting was limited to the ceiling design. **Figure 6** shows how the proposed ceiling design provides the needed reflections into the seating area from both sound production locations; **Figure 7** shows the built interior of the Young Israel of Greater Cleveland synagogue.

Acoustical Support of Congregational Participation in Worship

Some spaces have acoustical environments that encourage congregants to sing and participate in a worship service by reciting responsive prayers or by singing. Although, in general, more reverberant rooms provide better support of congregational participation than less reverberant rooms, the correlation between reverberation time and acoustical support of congregational singing is poor. Reverberation *level* correlates more strongly. The reverberation level is generally higher in smaller rooms than in larger rooms, whereas the reverberation *time* is generally higher in larger rooms than in smaller rooms. Consequently, smaller worship spaces generally provide better acoustical support of congregational participation than larger rooms.

As rooms get larger, the surface closest to the congregation (the floor) becomes the most important sound-reflecting surface to support congregational participation. Choir and music directors know from experience that carpeting is the worst thing to have on the floor to support congregational participation.

Acoustical support of congregational participation is a very dynamic phenomenon based on the known tendency of people to speak or sing more loudly to be heard as others around them do the same. In a worship space, if a congregant hears other congregants singing, he or she will feel comfortable singing more loudly. This encourages fellow congregants, in turn, to sing more loudly. This can result in a swell of energy that meets the goal of supporting congregational participation.

Conversely, in gathering spaces like restaurants, where the goal is to minimize the swell of energy to allow diners to communicate with a minimum of effort, carpeting is essential (see Roy and Siebein, 2019). Restaurants with sound-reflective floors, almost regardless of other wall and ceiling finishes, are often unpleasant spaces in which to have a meal due to the loudness of conversations at other tables. In other words, the acoustical goals for the design of a space to support congregational participation is exactly the opposite of the goal for the acoustical design of a restaurant.

Next to the floor finish, the ceiling is often the next closest surface to the congregation (compared with the walls) for a large majority of congregants. Therefore, in general, when sound absorption is required to control excessive reverberation in a worship space, it is best to incorporate sound absorption on the walls and not on the ceiling.

Some very large worship spaces use electronic enhancement (also called electronic architecture) systems to enhance acoustical support of congregational participation. These systems typically have arrays of ceiling-suspended loudspeakers that electronically add sound energy into the congregational seating area so that congregants hear themselves and other congregants more loudly, which encourages them to participate.

The Stonebriar Community Church north of Dallas, Texas, is one of several examples of churches that incorporated an electronic architecture system. These systems are rarely used in worship spaces but are frequently added to spaces for music performance that have compromised acoustics. Stonebriar's natural acoustics were designed to support their amplified praise band and, as a result, were not ideal for choral and orchestral music, styles used for their traditional services. Furthermore, congregational participation was a high priority for this church. To enhance their traditional service and to improve the acoustical support of congregational singing, Stonebriar added a separate electronic architecture system. In this arrangement, microphones hang both over the musicians' area and the congregation. That signal is processed and played back through an array of speakers that are suspended from the ceiling, pointing down toward the musicians' area and the congregation. The additional reverberant sound energy these speakers provide in the congregational area encourages people to participate in the worship service.

Conclusion

The acoustical design of worship spaces can be a far greater challenge than the acoustical design of a concert hall because the program of use is more varied and complex and there are inherent conflicts between the acoustical needs to support music versus speaking, both of which are fundamental requirements in almost all worship spaces. Furthermore, there are many more worship spaces likely to require acoustics design input than concert halls. My training and acoustics design experience in the design of concert halls was much greater than my design of worship spaces until the mid-1990s. In the last few decades, I have had the unique opportunity to lead the acoustics design of many worship spaces and to apply my experience in the design of concert halls to the design of these worship spaces; multiple examples have been discussed in this article. The examples chosen show the very wide breadth of design solutions, each informed by the unique worship style and prioritized program of use of each ministry.

It is hoped that these examples will serve as inspiration to other acoustics design specialists and their clients for more worship spaces of the future to provide better acoustical support of their unique worship style and, in so doing, enhance the experience of both the congregations and the clergy who lead these services.

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Why Was Your Hearing Tested: Two Centuries of Progress

Robert Ruben

Introduction

Today, almost every human being in the developed world and many in the rest of the world will have the opportunity to have their hearing tested from birth until old age. Testing, however, depends on interrelated factors including (1) the awareness of hearing loss; (2) the development of tools to test hearing; (3) knowledge of the causes of hearing loss; (4) the ability to intervene to restore or prevent further hearing loss; and (5) the development of devices to compensate for hearing loss.

Individuals undergo a hearing evaluation to determine whether a hearing loss is present and, if so, how great a loss; to determine the nature of the disease causing the hearing loss; and to provide a basis for determining whether there was further hearing loss due to environmental noise.

Although hearing loss has no doubt been ubiquitous in human populations, particularly with aging, testing for hearing loss and efforts to mitigate these losses are relatively recent. Indeed, the assessment of loss is only a few centuries old. The purpose of this article is to share some of the history of the evaluation of hearing loss, demonstrating that doing so is complex, but it has involved some of the leading "stars" among hearing researchers.

Before 1801: Qualitative and Subjective Assessments of Hearing Using the Human Voice

Anatomical and clinical writings that concerned the ear and hearing before the beginning of the nineteenth century did not address evaluating the hearing of most individuals. There was the awareness that hearing could come through bone conduction (the conduction of sound to the inner ear through the bones of the skull) that had been known since the sixteenth century as illustrated in the frontispiece of Bulwer's *Philocophus* (1648) (**Figure 1**). Bone conduction was observed in patients by Du Verney (1683), who noted that some hearing-impaired people would hear much better when the end of the vibrating instrument was held in the teeth and did not depend on hearing coming through the external auditory canal. He also diagnosed the blockage/closure of the external auditory canal as an anatomical site of the hearing loss.

As late as 1801, hearing ability was assessed by the subjective and qualitative perceptions of the patient and the physician as noted by Cooper in evaluating the results of his surgical intervention.

> "A woman about thirty-six years of age consulted me, in December last, respecting some disorder in her child. In attempting to converse with her, I found her so extremely deaf that it was with difficulty I could make her hear me... I immediately punctured the membrane of the left ear, being that in which the hearing was most defective. The operation was no sooner performed, than, to my great joy, and of course to hers, I found that, in that ear, she could hear what 1 said to her, without any particular exertion on my part to speak loud. She staid with me about half an hour; and, when she left me, was capable of hearing every thing that was said in the ordinary tone of conversation" (Cooper, 1801, p. 441).

1802 to 1921: Quantitative Measures of Hearing Ability Using the Human Voice and Physically Generated Sounds

Children

The earliest quantitative assessment of hearing was carried out in deaf children to determine if therapy improved their hearing. The first was by Wolke (1802), who developed an instrument to ascertain whether there was any improvement in the hearing of deaf children after they

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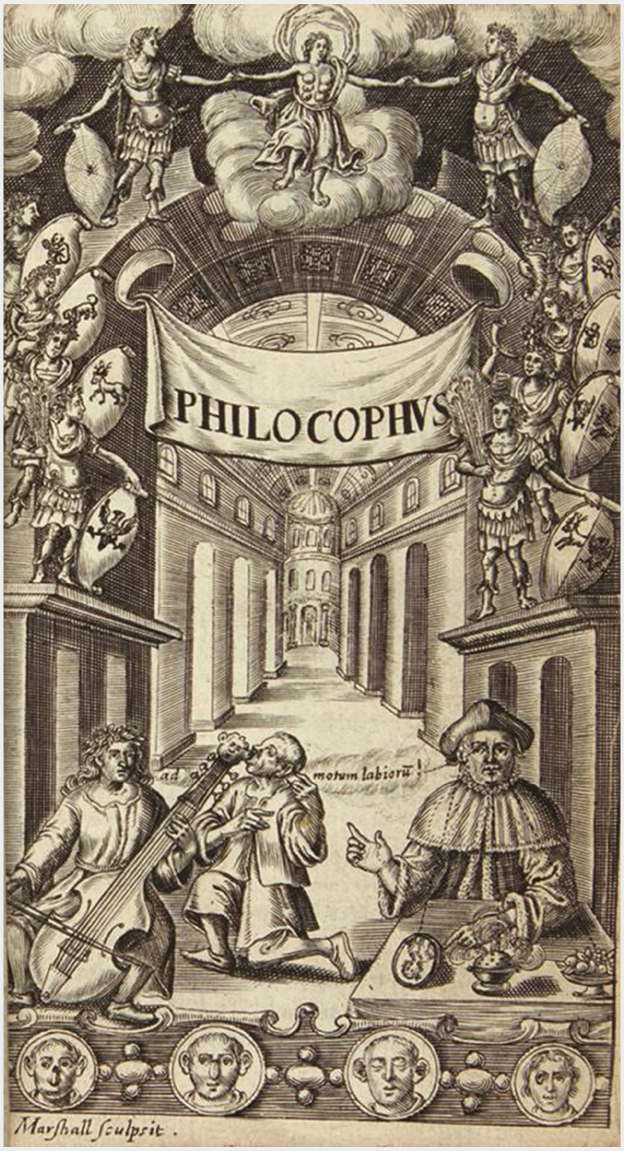


Figure 1. Philocophus *or* The deafe and dumbe mans friend *(Bulwer, 1648). This is the frontispiece of this work, which is the first known representation of bone conduction.* ***Middle left:*** *man next to the cello "listening" to the cello with his teeth to illustrate bone conduction.* ***Middle right:*** *effects of speech articulation by blowing smoke.* ***Bottom:*** *four faces (**left to right**): The first head shows a man with his mouth not in the normal position but located in the middle of the nose (smell), meaning that he can taste through his nose. The second man lacks a nose, and his mouth is shifted to the area of his nasal root, meaning that he can smell through his mouth (taste). The third man is blind; however, in each auricle an eye is engraved, thus he is able to see with his ears. The man on the right has no ears, but he hears with the right eye that is shown by an auricle replacing the eye (Pirsig and Stephens, 1994, p. 115). From the author's collection*

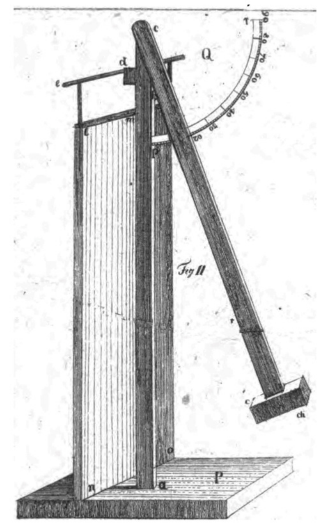


Figure 2. *Wolke's acoumeter was a wooden board (n, o, c, m,) placed upright. Attached to it was a drumstick (c, ch), which was dropped onto the board from various heights as measured by the protractor (Q) that determined the amplitude (Wolke, 1802).*

were exposed to electrical auditory stimulation. Wolke's work was based on the observations of Volta and many others (reviewed by Marchese-Ragona et al., 2019). Wolke's (1802) instrument, an acoumeter, was a wooden board placed upright, attached to which was a drumstick that could be dropped onto the board from various heights as determined by a protractor (**Figure 2**) that measured the amplitude of the sound. Itard (1821) described a similar instrument made of metal for ascertaining whether or not there was improvement in the hearing of deaf children after hearing exercises using voices.

School Screening

It was long recognized that school children with a hearing impairment would be at a disadvantage in learning and would often be considered mentally retarded. Blake (1876), a physician, recognized the need to determine which children had a hearing loss and created a screening program for school age children. Each child would have his/her hearing assessed by recording his/her ability to detect speech at a fixed distance from the teacher. The teacher spoke a proscribed series of test words based on the work of German investigator Wolf (1871) that were selected for the way in which they are affected by a hearing loss. If a child was found to have a hearing deficit, provision was made for the child to be positioned within the classroom so as to optimize his/her ability to hear what transpired. The child would also be seen by a competent medical person for care. This semiquantitative technique was only occasionally adopted during the next 45 years but was used for a time in Boston and New York City schools.

The need to identify the hearing-impaired school child was recognized in the United Kingdom in a report of the Chief Medical Officer to the Board of Education (1910) of London, UK The report noted that 3-8% of all the elementary school children in England and Wales had some form of defective hearing, noted the need for the testing of children, and stated that there was a lack of precise and consistent means to accomplish this. The report used a variety of different tests and felt that the best was the use of whispered speech for which there was no control of amplitude or content and consequently varied within and between tests.

Medical

During the first half the nineteenth century, children had their hearing assessed by asking them to listen to speech or the ticking of a watch. This was carried out primarily when the physician thought there could be occlusion of the external auditory canal by cerumen (ear wax) or foreign bodies or exudate (fluid) in the middle ear and then to determine the amount of hearing remaining in children who were considered "deaf and dumb" (Toynbee, 1860). The hearing assessment for occlusion of the external auditory canal was used to document the success of the intervention, that is, removal of the wax. One study of 411 children examined at the Deaf and Dumb Asylum found that three-fifths did not hear any sound, whereas the remaining children heard certain sounds such as repeating short words or the clapping of hands.

Tuning forks became part of the diagnostic pediatric armamentarium in the 1870s to differentiate between hearing loss from a conductive defect in the transmission of sound to the inner ear and a sensory hearing defect in the transduction of sound by the inner ear to the central nervous system. The knowledge of various tests for conductive and sensory hearing loss was well-known and extensively utilized by the beginning of the twentieth century.

Using tuning forks testing for children was challenging. Politzer (1902a) developed a very simple instrument called the acoumeter (**Figure 3**) that allowed for diagnosing a qualitative type of hearing loss as conductive or sensory loss and allowed for differentiation of diseases of the external or middle ear and, to a much lesser extent, of sensorineural loss. The testing allowed for the application of the then known effective medical or surgical interventions.

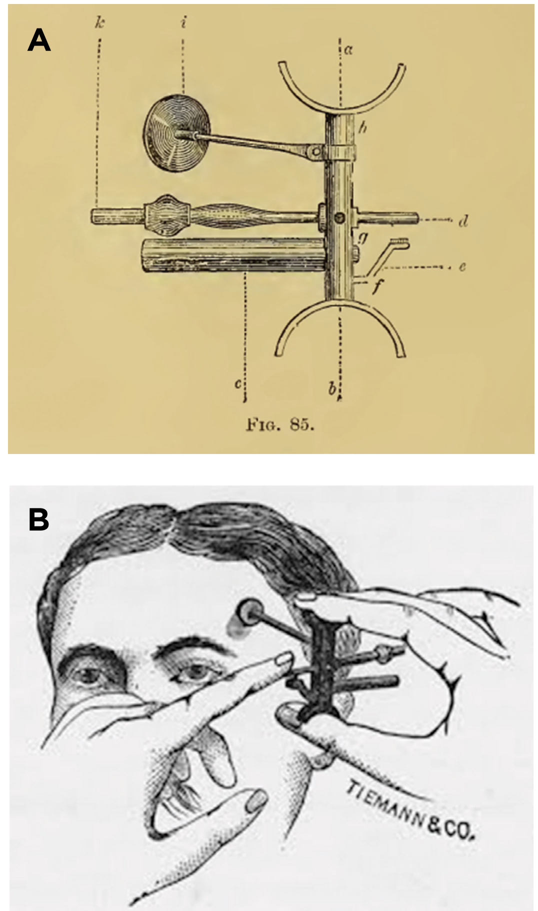


Figure 3. ***A:*** *Politzer acoumeter consisted of a horizontal steel cylinder (c) 28 mm long and 4.5 mm thick, connected with a perpendicular vulcanite column (h, f) by means of a tight screw. A percussion hammer (k, d) is attached above the place of attachment of the steel cylinder. This is movable on its long axis and produces the tone by falling on the steel cylinder. The device is rotated, h, so that the circular piece, i, is placed perpendicularly on the head and k, d is dropped against c which creates a sound that can be heard through air and bone conduction (Politzer et al., 1903). From the author's collection.* ***B:*** *application of the Politzer acoumeter in a subject (Winslow, 1882).*

Adults

Medical

Most of the otologic disease entities known in the twenty-first century had been defined during the nineteenth and early twentieth centuries. Parallel to this increase in knowledge was the advent of successful interventions, primarily surgical, for these various conditions. The knowledge of and the effective ways to care for ear diseases required an objective means of diagnosing and evaluating the outcomes of care.

During the nineteenth century, there was the significant development in the science of acoustics, most notably the work by Helmholtz (1863). The otological textbooks of this period emphasized that a requirement for evaluating the patient was to obtain a measure of the patient's hearing using speech as a qualitative measure. The more quantitative measures were through the use of tuning forks. Several standard utilizations of the tuning fork test were found in the texts then and now.

One such test was known as Weber's (1834) test. ln this, a 512-Hz tuning fork is placed on the forehead. The patient then reports in which ear the sound is louder. When the patient reports hearing the sound equally in both sides, it is considered normal. When one ear hears the tuning fork louder, this is the defective ear.

Rinne's (1855) test used a combined testing of air and bone conduction. The normal ear, therefore, hears the tone of the fork longer through the air better than through the cranial bones.

Screening

The first documented screening for hearing in an adult population was carried out by the German military in 1888. Individuals who were being considered for military service were classified so that those with normal hearing were sent to the front and the others served behind the lines (Dölger, 1927). Then, at the beginning of the twentieth century, hearing screening was established for military service in the United Kingdom and the United States.

At the beginning of the twentieth century, deafness of either ear constituted an absolute cause of rejection to serve in the United States Army. The testing criteria were qualitative.

> "As the distance at which the natural tone of voice may be heard in a closed room, when both ears are normal, is about 50 feet, the distance at which the applicant is to stand from the examiner must be as great as the apartments will allow, not to exceed 50 feet. The applicant will stand with his back to the examiner, who is to address him in a natural tone of voice. When the distance is less than 40 feet, it should be specified on the examination form, and the tone of voice will be lowered. Failure of the applicant to respond to the address of the examiner will demonstrate a defect" (Politzer, 1902b).

The earliest workplace hearing screening for civilian employees was conducted by railways. These were developed as a result of a series of accidents that appear to have occurred because the engineers, the drivers of the train, had a hearing loss. At the end of the nineteenth century, the European railways had established hearing screening for their employees that held positions in which good hearing was essential for safety. The railroad companies also acknowledged that rail service could cause hearing loss and therefore part of their program was to have periodic examinations of the hearing of the critical railroad workers. Politzer stated:

> "As many disturbances of hearing develop only during the time of service, such examination would seem of value, in the author's opinion, only if needed at regular fixed intervals. It may, however, be stated with satisfaction that most of the companies have given attention to this proposition" (Politzer, 1901).

Malingering

The increased attention to hearing ability by health workers, industry, and the military resulted in some individuals pretending, malingering, that they had a hearing loss. Some of these were individuals with psychiatric difficulties, others wanting to avoid perilous military service, and others wishing to be employed or remain employed.

As a consequence, a series of tests were developed to detect malingering. One method is the use of the Bárány noise machine. The noise is applied to the purported affected ear, and the patient is then required to read a passage. If the patient raises his/her voice with the noise, then one assumes that the ear being masked is functional because the patient can hear the noise. If there is no change in the volume of the reader's voice, it indicates that the ear subjected to the noise is hearing impaired (McKenzie, 1920).

Figure 4. *The Western Electric 1A audiometer. Available at acousticstoday.org/WE1aaudiometer. Accessed March 14, 2021 and April 15, 2021.*

1922 to the Present: Quantitative Measures of Hearing Ability Utilizing Psychophysics and Physiology

Beginning in the twentieth century, the development of electronics, primarily based on the vacuum tube, resulted in the creation of electronic-based instruments for testing hearing, the audiometer. These were originally reported in 1921 in Germany (Feldman, 1979). In 1922, the Western Electric Company (Fowler and Wegel, 1922) in the United States introduced the 1A audiometer that became the model for subsequent commercial instruments (**Figure 4**). The use of the audiometer to establish hearing ability in patients rapidly became the standard of practice throughout the world.

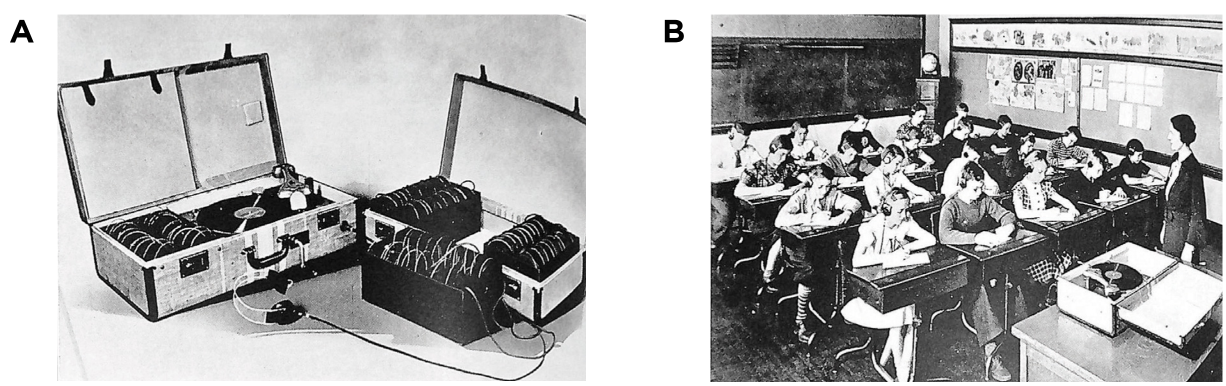
Children

The advances in electronics were applied to mass screening of children. **Figure 5B** shows a school class being tested with the equipment in **Figure 5A**. Several devices using a phonograph to control the stimulus that was distributed to a classroom of pupils through earphones was utilized through schools primarily throughout North America and Europe. **Figure 5A** shows the equipment used to test multiple children simultaneously. Fletcher (1929) stated that: “It is estimated that approximately 1 million have now been tested with this instrument...” By the 1940s, almost all schoolchildren in North America and Europe would have their hearing tested.

Screening for hearing loss in newborns was considered to be critical for the optimal development of the child. In 1944, British investigators Ewing and Ewing articulated the need for some means to test newborns, but with a comprehensive survey of the literature, they could not identify any way to carry this out. Fisch (1957), also in the United Kingdom, noted the need for a newborn/infant screening system and described what became to be known as a high-risk registry for identifying infants at risk for substantial hearing loss:

> “Screening of children with unknown possible cause of hearing loss their history is more practical... If

Figure 5. ***A:*** *4B phono audiometer complete with four receiving trays and carrying case.* ***B:*** *testing school children’s hearing using telephone headsets with the 4B audiometer (Fowler, 1947).*



there is a history of deafness in the family; if a child's mother had rubella or any other virus disease during a critical stage of pregnancy; if the child suffered from anoxia at birth of apraxia in a premature child, or the labor was unusually protracted, and the delivery was complicated; if a child had hemolytic disease of the newborn or was jaundice as result of premature birth mature birth or had kernicterus, in all these cases the offspring should be tested without exception at the appropriate time" (Fisch, 1957, pp. 233-234).

Hardy (1965) presented the details for a similar high-risk registry. During the next two decades, the high-risk registry was utilized but was only able to diagnose 50% of the affected children. These findings are summed up in the US National Institutes of Health Consensus Development Conference Statement (National Institutes of Health, 1993). By 1993, screening was dependent on the high-risk registry and some applications of the physiological tests: auditory-evoked potentials and otoacoustic emissions.

These objective quantitative assessments of hearing ability came about in the last half of the twentieth century through the application of physiological aspects of the auditory system to the diagnosing of hearing impairments in patients. These were the recording of the cochlear microphonic in humans (called electrocochleography) (Ruben et al., 1959), application of middle ear admittance to the diagnosis of middle ear pathology (Terkildsein and Thomsen, 1959), recording of auditory brainstem responses (Jewett and Williston, 1971), and the discovery of otoacoustic emissions (Kemp, 1978). These physiological assessments had a significant role in the establishment of hearing loss in patients who could not communicate whether they perceived sound. The most widespread use of these techniques was in the establishment of hearing loss in newborns and young children.

The application of the physiological advances, including measurements of the auditory brainstem response and evoked otoacoustic emissions, was first clinically applied to the testing of newborn infants and reported by Kennedy et al. (1991). A combination of physiological tests consisting of automated otoacoustic emissions and automated auditory brainstem response was utilized. In 1994, Hunter et al. reported on their two-stage universal screening test of 213 infants at a large district maternity hospital in the United Kingdom. They found that a two-stage screening protocol, first otoacoustic emissions and then, after the failure of otoacoustic emissions, an auditory brainstem response, to be the most effective.

White et al. (1993, 1994) reported their results of the two-stage screening program on infants born at Women and Infants Hospital of Rhode Island. They concluded:

> "Based on a relatively large sample of 1850 infants from a WBN [well-baby nursery] and a NICU [neonatal intensive care unit], this study provides evidence that (1) hearing impaired infants can be identified based on a TEOAE [transient evoked otoacoustic emissions] screening protocol and (2) many of those infants would not have been identified using the currently recommended approach of screening only high-risk children" (White et al., 1993).

White et al.'s results were confirmed in a New York State study carried out from 1995 to 1997 that included infants from diverse social, economic, and cultural backgrounds. There were 69,761 infants evaluated from 7 different regional perinatal centers (8 hospitals) representing various socioeconomic regions. All the hospitals utilized the two-tier system rescreening both in the well-baby nursery and in the neonatal intensive care units.

The two-step newborn infant hearing screening program is now a standard procedure for all newborn children in the United States (Centers for Disease Control and Prevention, 2019). The screening program has also been widely adopted in Europe. Throughout the world, it has been utilized by many but not all countries and modified in some to meet their economic, cultural, and geographic needs (Neumann et al., 2019).

Adults

Hearing loss as a consequence of exposure to noise in the workplace has been long recognized. The earliest reference to deafness resulting from exposure to noise in the workplace was published by Ramazini (1700, also see 1964) where he described hearing loss and workers in a flour mill. In his second edition in 1713, Ramazini describes the effect of ironworkers in the ghetto in Venice who, after working there for many years, became deaf.

> "From this quarter there rises such a terrible din that only these workers have shops and homes there but all others flee from the highly disagreeable locality... To begin with, ears are injured by that perpetual din,

> and in fact the whole head, inevitably, so that workers of this class become hard of hearing and, if they grow old at this work, completely deaf" (Ramazzini, 1713, 1964).

There was no compensation by industry for hearing loss until 1948 when the New York State Court of Appeals upheld the decision of the Workmen's Compensation Board to award Mr. Slawinski $1,661.25 for his hearing loss he worked for J. H. Williams and Company. The court stated that hearing loss due to industrial noise is an occupational disease and that there may be a compensable disability in an occupational disease even without any loss of earnings. This ruling was rapidly advanced throughout the United States, with multiple lawsuits resulting in compensation for industrial noise-induced hearing loss. This resulted in required standards of preemployment and employment hearing testing. The Occupational Noise Exposure Revised Criteria (National Institute for Occupational Safety and Health, 1998) for audiometric evaluations of employees required that a baseline audiogram be obtained at inception of employment, monitoring audiograms with retest audiograms conducted periodically during employment, and an exit audiogram taken at the termination of the worker's employment. The Occupational Safety and Health Administration (OSHA) has specified the length of time an employee can be exposed to sounds of various intensities, the details of programs for monitoring the hearing of employees, specifications for the equipment used for the monitoring of employees, and the use of protective gear and/or engineering controls (OSHA, 2021a). Now, many workers have multiple hearing evaluations while employed in industries with noise exposure, and the industries are required to have conservation of hearing programs (OSHA, 2021b).

Geriatric

The wide recognition of hearing loss in the aging population, presbycusis, has come about during the twentieth and twenty-first centuries. Concomitant with this has been the availability of accurate hearing testing, either in a facility or through the Internet. This quantitative documentation has allowed for the use of hearing aids. Hearing aid sales in the United States increased by approximately 750,000 in 1980 to more than 4,230,000 in 2019, a 5.6-fold increase (Hearing Review, 2021). This increase implies a similar increase in the number of hearing tests carried out. One could estimate that for each hearing aid, there was at least one, if not two or three, hearing tests carried out before the hearing aid was actually utilized by the patient.

Hearing loss in the elderly has been associated with psychiatric illness (Eastwood et al., 1985) and diminished quality of life (Carabellese et al., 1993). Other studies have shown a correlation of presbycusis with mortality (Lam et al., 2006). A small study of eight patients with Alzheimer's disease with hearing loss found that from one to four problem behaviors were significantly reduced for each patient after hearing aid treatment (Palmer et al., 1999). A study of depression in the elderly with hearing impairment showed that providing hearing aids had a significantly positive effect on the patients (Metselaar et al., 2009). These findings demonstrate the need for a geriatric hearing screening program.

Insofar as can be determined worldwide, no systematic hearing screening programs of the elderly are in place. The need for geriatric hearing screening will become even greater as the population ages. This history has yet to be written.

Conclusions

Three questions have been addressed in this article.

(1) Why would you have a hearing test? Since 1800 to the present, people were tested to determine if they had a hearing loss; to determine where the problem, the disease entity, was that caused the hearing loss; to determine the extent of their hearing loss; to determine an intervention to ameliorate their hearing loss; to establish their fitness to serve in a particular role in an occupation or military service; and to protect them from further hearing loss due to sound trauma in the workplace.

(2) Who had a hearing test? Everyone from the newborn to the aged was tested. The first hearing test was in the newborn intensive care unit or nursery. The last hearing test was when one is aged to provide for a hearing aid that would not only help in communication but also as a way of mitigating some of the cognitive deficiencies of aging.

(3) How was your hearing tested? This started out with a voice test that was qualitative; Then there was and still is the use of tuning forks that was qualitative but allowed for localization of the disease; advances

in electronics such as the audiometer that allowed for quantitative descriptions of hearing loss over frequencies; and, most recently, application of the physiology of acoustics for the objective measure of hearing ability of the patient.

Finally, in this article, I have tried to give the flavor of the history of hearing testing. Such testing has proven to be a substantial medical advance for humans from babies to the very old. In each case, the purpose has been to improve the quality of life that comes from being able to communicate effectively with sound. This gains upmost importance in the postindustrial era where most occupations in our communications-based economy require optimal communication, which is dependent on good hearing (Ruben, 2000; Bureau of Labor Statistics, 2021).

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"Thank You Dr. Green" - *Tim Tucker*

Oh, and thanks to Les and Ginny...

David M. Green and Psychoacoustics

William A. Yost, Roy D. Patterson, and Lawrence L. Feth

In July 2019, people from all over the world attended a symposium honoring a former Acoustical Society of America (ASA) president and Gold Medal recipient, David M. Green (**Figure 1**). Dave retired as professor emeritus from the University of Florida, Gainesville, in 1996, so one might wonder why he was being honored 23 years later and why so many people attended the symposium. Because we have known Dave a long time (the authors were in Dave's lab in 1970-1971 during Dave's tenure at the University of California, San Diego, La Jolla, from 1966 to 1973; see **Figure 2**), we would not be surprised if Dave's answer was something like, "Of course they showed up, I know these people and they all like a good party." The enjoyable symposium, "Greenfest," was sponsored by the Knowles Hearing Center at Northwestern University, Evanston, Illinois (the organizers were Bev Wright [Chair], Bob Lutfi, Jungmee Lee, Ann Eddins, David Eddins, and Beth Strickland).

Dave was being honored for several reasons. Foremost, for his many important, often pioneering, and still timely contributions to understanding hearing. In addition, he was being honored for his numerous contributions to the ASA and his service on national committees that addressed important societal topics. A recent *Acoustics Today* online article about Dave's tenure as ASA president describes several aspects of his career and accomplishments (available at bit.ly/2OPTqzK). Many people also attended Greenfest because they were one of the very large number of students, postdocs, and colleagues whom Dave has mentored over the years.

David Green's prolific theoretical and empirical contributions cover a very wide range of topics in the behavioral sciences, especially those related to psychoacoustical investigations of hearing. Dave is probably most well-known for his work on signal detection theory (SDT), which has had wide-ranging applications in the behavioral sciences and for many societal issues. He also developed and tested models of auditory detection, discrimination, and identification and made contributions to many other topics, including his work on what has become known as *profile analysis*.

Figure 1. *David M. Green at a previous home in Florida, 2007.*

Figure 2. *Green's Research Group (GRG), 1970-1971.* ***Back row (left-to-right)****: Sharon Able, Dave Green, Bill Yost, Roy Patterson, and Lynn Penner.* ***Front row (left-to-right)****: Neal Viemeister, Larry Feth, and Chuck Robinson. Photo was taken at Dave's home/pool in August 1970, by Elle Feth, Larry Feth's wife. David's swimming pool was more than a party local. It was the "lab" used in Norman et al. (1971, with assistance from the Roy Patterson study on hearing underwater.)*

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Dave's Contributions to the ASA, Society, and Acoustics

Dave has been a tireless contributor to his discipline and society. In addition to being an ASA president and Gold Medal recipient, he was, among other things, a former chair of the Psychological and Physiological Technical Committee, an associate editor of *The Journal of the Acoustical Society of America* (*JASA*), and an ASA Biennial and Silver Medal honoree. Dave also served on several committees of the National Academies of Sciences (NAS) and the National Research Council (NRC). Among his many honors, he was elected a NAS member in 1978.

These efforts produced important contributions concerning issues confronting society. In 1978, Dave led a team that participated in the "reenactment" of the not fully explained 1963 assassination of President John F. Kennedy in Dallas, Texas. Dave's team also reviewed the testimony of the 178 witnesses to the Kennedy assassination. The team consisted of Fred Wightman, now retired but then at Northwestern University, and Dennis McFadden, from the University of Texas at Austin, also retired. In Dave's Congressional testimony (available at bit.ly/3seyRdQ), he reported on witnesses' observations, on issues related to the possible location of the gunshots, and briefly at the end of his testimony, on the possible number of gunshots. Dave explained how the perception of the acoustics of a bullet fired from a high-powered rifle made it difficult to explain many of the witnesses' observations. He described his team's opinion that the location of the gunshots during the reenactment was relatively easy for them to determine for some locations and less so for others. Dave pointed out that the team knew that gunshots would be fired and were experts in perceiving sounds, including their source locations, whereas the gunshots would have been a surprise to the witnesses who were unlikely to have been skilled observers in perceiving sound. He also indicated that there was no sufficient scientific literature to address issues regarding the number of gunshots, but echoes and the acoustics of high-powered rifle shots probably led to some reports of multiple gunshots.

Then in 1994, Dave chaired a NRC committee dealing with issues related to acoustic thermometry of ocean climate (ATOC) and marine wildlife (see nap.edu/read/4557/chapter/1). The issues, as many ASA members might remember, were that the ATOC project would have produced high-intensity, low-frequency underwater sounds so that acoustic changes over long distances might provide estimates of global warming of a large area of the earth's surface (e.g., a lot of the Pacific Ocean); however, marine mammals (and fishes) are sensitive to these same sounds. The committee noted that not enough was known about marine mammal and fish auditory processing to adequately address the extent to which ATOC signals might adversely affect marine animals. The NRC committee made recommendations about what research might be undertaken and how regulatory requirements could be changed to assist in getting this research done.

Dave's Students, Postdocs, and Colleagues

Many who attended Greenfest and probably more than 60 others have studied and conducted research with Dave in his labs as students or postdocs or while on a sabbatical or another form of leave. These researchers have, in turn, passed on lessons learned from Dave to their students, postdocs, and colleagues. As John Swets pointed out in the Encomium for Dave's ASA Gold Medal in 1994: "Dave most visibly took on this unusually generous interest in the beginner's growth and recognition. He regards them all as having their stories to tell — and after a few years of his tutelage they really do" (acousticstoday.org/david-green-gold-medal-1994).

Dave and Signal Detection Theory

Dave's pioneering work on the SDT is contained in the highly cited book by Dave and Swets (1966; hereafter

Figure 3. *Dave Green (**left**) and John Swets (**right**) at Bolt, Beranek, and Newman in 1965, a year before Green and Swets (1966) was published. Thanks to Chris Conroy for providing this picture.*

referred to as *Green and Swets*; see **Figure 3**). The SDT was originally developed by the Electronic Defense Group (EDG) at the University of Michigan, Ann Arbor, in the 1950s. Wesley Peterson and Ted Birdsall at the EDG wrote mathematical papers about ideal signal detectors. Spike Tanner applied those ideas to psychophysical issues. At this time, Dave (a graduate student) and Swets (a starting assistant professor; see Swets' autobiography, 2010) helped advance the SDT in general, but over time, they extended Tanner's ideas and developed a general psychophysical theory of detection and discrimination of sensory stimuli, especially sound. One of the first auditory papers was a detailed technical report by Tanner, Swets, and Green in 1956 (available at bit.ly/2PSvLiG).

Although the SDT was developed mainly to deal with behavioral experimental design and results, it was also applied to other decision tasks (see Swets, 2010), such as decisions radar operators have to make. A radar operator must decide if a "blip" on a noisy radar screen is a "signal" representing a plane that may pose a danger ("Yes," there is a plane) or is merely "noise" not indicating any danger ("No," there is no plane).

Similarly, subjects in hearing experiments are often asked to decide (Yes or No) if a sound presented on a trial is one that contains a target signal mixed with noise (Signal plus Noise [SN]) or is only the noise (Noise Alone [NA]). In detection based on sonar stimuli and on sound in a hearing experiment, one has to "trust" the operator's/subject's response (Yes or No) regarding the occurrence of a signal. That is, to what extent does the response represent the observer's *sensitivity* to the signal (e.g., a radar blip representing a plane, a sound representing a particular tone)? If the detection response is not a reliable estimate of sensitivity, then an enemy plane may go undetected and responses indicating that a particular sound occurred may not provide useful information about auditory processing (e.g., a person's hearing loss may be missed). The SDT provides a theory for reliably estimating an observer's sensitivity in making detection decisions when a weak signal is presented in a noisy background.

Although Dave has not been "active" in the field since his retirement, Greenfest triggered a return to SDT. Dave published a Letter to the Editor of *JASA* (Green, 2020) in what he referred to as a "homily." Dave's "complaint" was, "I am somewhat disappointed about how SDT commonly is portrayed and taught." In his homily, Dave refers to the history of psychophysical measurements. The term psychophysics (psychoacoustics is the application of psychophysics to acoustics) was used by Gustave Fechner in his two-volume book *Elemente der Psychophysik* (1860) to define quantifiable functional relationships between objective measures of psychological sensations/perceptions and physical stimulus variables that might excite the senses. Fechner argued that there are procedures (psychophysical procedures, cataloged in his book) that allow for objective behavioral measures of sensations and perceptions that can be measured similarly to those of the physical objects themselves.

However, in Dave's words (Green, 2020), "The sensations produced by the stimuli were subjective; they were private or covert. The only objective fact was the observer's response on that particular trial." In detecting weak signals occurring in noisy backgrounds (i.e., differentiating between SN and NA), we might know, using a psychophysical procedure described by Fechner, that an observer says he/she detected the signal. The psychophysical procedures cataloged by Fechner (1860) provided ways to estimate correctly detecting the signal when it was presented (Hits), and Hits were used as a measure of sensitivity. However, what happens when the signal is not presented (when a response indicates that a signal was presented when it was not; a False Alarm)? Clearly, being able to avoid False Alarms would be important in obtaining an estimate of sensitivity. Fechner and many after him suggested ways to estimate observers' sensitivity in indicating that they detected a signal when it was presented (Hits) and when it was not (False Alarms). False Alarms were then used in various ways to "correct" Hits as a measure of sensitivity, although such "corrections" were only approximations.

SDT starts with the simple idea that combining Hits and False Alarms provides measures of sensitivity in a more reliable and objective manner than just measuring Hits, even if Hits are corrected by False Alarms. A stimulus-response table (**Figure 4**) describes the raw data from a detection task. The four cells indicate the four conditional probabilities (*P*; "Response"/Stimulus), indicating an observer's responses (Yes or No, a signal was presented) as a function of the stimulus (either SN or NA). Hit and Miss probabilities sum to one as do False Alarm and Correct Rejection probabilities, and, as a result, SDT only uses

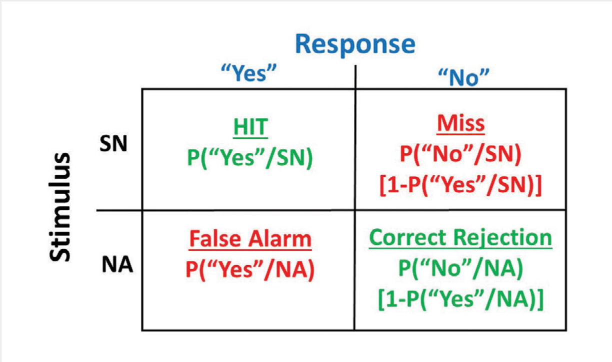


Figure 4. *Stimulus-response table indicating Hits, Misses, False Alarms, and Correct Rejections and their conditional probabilities, i.e.,* P *("Response"/Stimulus), in detecting ("Yes" or "No") whether a signal plus noise (SN) or noise alone (NA) was presented.*

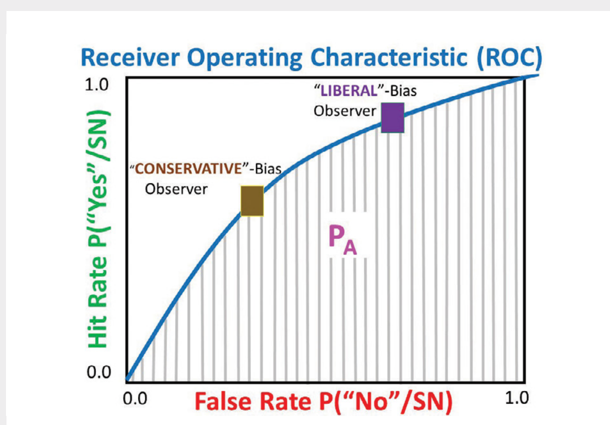
Hits and False Alarms. Clearly, if the Hit probability is high and the False Alarm probability is low, the observer had little difficulty correctly determining when the signal was and was not presented, and, thus, the observer was sensitive to the signal being presented.

However, consider a "conservative" observer who is reluctant to indicate the presence of a signal independent of his/her sensitivity versus a "liberal" observer who is very willing to indicate that a signal is present. Clearly, the observers have different response "*biases*" for indicating if a signal was or was not present. Assuming that the observers are equally *sensitive*, the conservative observer will have lower Hit and False Alarm probabilities than the liberal observer. Thus, Hits and False Alarms vary with changes in both sensitivity and response bias (they are independent measures of performance). How might Hit and False Alarm probabilities be combined to provide a single measure of how well the observer detected the signal (i.e., estimate sensitivity) independent of response bias?

Early in *Green and Swets* (1966, see Chap. 2) and in Dave's homily, a receiver operating characteristic (ROC; **Figure 5**) is defined, on which Hit proportion is plotted as a function of False Alarm proportion. A ROC contour is derived from a major assumption of the SDT that observers sample some aspect of the stimulus that forms a decision variable. A further assumption is that to maximize being as correct as possible in the long run in their decisions, observers use a particular value of the decision variable as a criterion for responding (C), so that if the sampled decision variable is greater than C, respond Yes the signal was present; if less than C, respond No; and if equal to C, guess. Thus, the conservative observer has a higher value of C than does an equally sensitive liberal observer. If only the noise is presented, the decision variable is distributed according to an underlining NA probability density function, and if the SN is presented, the decision variable is distributed according to an underlying SN probability density function. For any value of the decision variable, the SN distribution has higher probabilities than the NA distribution. The theory does not specify the kind of underlying distributions, only that the two distributions are overlapping probability density functions and that the decision variable is a monotonic function of the likelihood ratio formed from the probabilities of the two distributions.

The ROC contour in **Figure 5** shows the Hit proportion plotted as a function of the False Alarm proportion for arbitrary SN and NA distributions as C varies from –∞ (**Figure 5,** *bottom left corner*) to +∞ (**Figure 5,** *top right corner*), with the two points shown on the contour representing possible Hit and False Alarm proportions for a conservative and a liberal observer. Thus, C is represented by different Hit and False Alarm proportion combinations (different points)

Figure 5. *A receiver operating characteristic (ROC) contour showing Hit proportion as a function of False Alarm proportion (see* **Figure 4***). Combinations of Hit and False Alarm proportions for observers with different response biases (e.g., "Conservative" and "Liberal") are points on a ROC contour, whereas the area under the ROC curve* (P_A) *is a bias- and distribution-free measure of sensitivity.*



on a ROC contour, whereas the area under a ROC contour (P_A) can be used as a bias- and distribution-free measure of sensitivity (e.g., as the Hit proportion increases and the FA proportion decreases, P_A would increase independent of response bias, indicating an increase in sensitivity alone).

One way to test for the observer's sensitivity is the two-interval AB test. In this test, observers are presented two successive sounds: the signal occurs in either the first or the second interval (NA followed by SN or SN followed by NA, randomly determined), and observers indicate which interval contained the signal. One hundred percent correct responses indicate that an observer clearly detected the signal, whereas 50% correct responses indicate that the signal was inaudible. In Green and Swets (1966) and in Dave's homily (2020), Dave proves that the percentage of correct responses in the AB test is equal to the P_A.

This proof is nonparametric, that is, it is independent of any assumptions about the form of the NA and SN distributions. In many papers on SDT, a common first assumption is that the underlying distributions are both Gaussian and of equal variance (see Egan, 1975). If we assume that the observer has no bias to favor one interval or the other, the AB test becomes a second measure of the observer's sensitivity to the signal without having to make any assumptions about the form of the underlying NA and SN distributions. To paraphrase Green (2020), the moral of his homily is that although perceptual experiences are covert, percent correct and P_A both provide objective measures of the observer's sensitivity.

Dave often described SDT (e.g., Green, 1960, 1964) as "a combination of two distinct theoretical structures: *decision theory* and the theory of *ideal observers*." Some aspects of decision theory have been briefly described. Ideal observer theory (e.g., Green, 1960, 1964) "provides a collection of ideal mathematical models which relates the detectability of the signal to definite physical characteristics of the stimulus."

In considering a particular ideal observer (a particular mathematical model), a *detection model* can be developed. In such a model, the form of the NA and SN probability density functions (the "definite physical characteristics of the stimulus") is precisely defined. In many cases, Fourier series, bandlimited, white, Gaussian noise forms the NA distribution, and the SN distribution is this noise distribution plus a sinusoidal tone (see Green, 1960, 1964 for a detailed discussion of these assumptions). Using both the decision and ideal observer aspects of SDT, a detection model for describing the detection, discrimination, and identification of auditory signals presented in noisy backgrounds was developed, and Dave performed many psychoacoustic experiments testing the model (see Swets, 1964 for chapters describing some of these experiments, many authored by Dave). Papers published by Dave and many others established detection models as valuable for accounting for many aspects of human observers' detection, discrimination, and identification of a variety of auditory signals often masked by noise (e.g., Swets, 1964; Green and Swets, 1966).

SDT has also been used to evaluate the performance of humans and other animals in different sensory tasks, to measure decisions based on memory and attention, and to characterize how neural elements respond to stimulation (e.g., Swets, 1964; Green and Swets, 1966). In addition, SDT has been used in many nonlaboratory situations such as deciding when a radiological image may or may not indicate a tumor, when a jury may or may not decide that an innocent person is innocent, or when an alarm may or may not lead to a decision that there is a dangerous situation (e.g., see Swets, 2010). Thus, SDT is a powerful decision paradigm with wide application.

Dave and "Profile Analysis"

Although Dave published many experiments based on the SDT early in his career, he investigated a wide range of topics over the rest of his career. One of the many topics led to the publication of *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988). This book is about auditory intensity discrimination in general and when changes in intensity across a sound's spectrum can be discriminated, i.e., when there is a spectral "profile" that can be perceptually "analyzed." Most everyday sounds have complex spectra in which intensity varies as a function of frequency, and the perceptual differences between and among such sounds are often based on "spectral profiles."

Dave's interest in profile analysis was sparked by Murray Spiegel, a postdoc who received his PhD from Washington University in St. Louis, Missouri, working with Chuck Watson. Murray worked with Chuck on "10-tone pattern" perception (Watson, 2005). In an attempt to generate complex stimuli that had many properties of real-world sounds but whose acoustics could be carefully controlled, Chuck generated a temporal sequence of 10 brief (e.g., 40-ms), equal-amplitude tones presented sequentially, each with a different randomly determined frequency spaced far enough apart to be distinguishable. In one set of experiments, two 10-tone patterns were presented in succession, with the two patterns being the same or one pattern having the frequency of just one of the tones changed. The listeners determined whether the two patterns were the "same" or "different."

If highly trained listeners were presented the same 10-tone pattern (same frequency components fixed over time) over and over, they could, after considerable practice, distinguish a frequency difference for each tone in a pattern nearly as well as they could when the tones were presented alone rather than as part of a pattern. However, when the frequencies of the 10 tones were not fixed over time but varied randomly, the listeners were uncertain about the spectral changes that occurred. The more aspects of the patterns that were randomly varied, the greater the uncertainty and Watson (2005) showed that discrimination performance for 10-tone patterns depended on the amount of uncertainty. It did not take Murray long to get Dave interested in the role uncertainty played in these 10-tone pattern experiments.

Dave presented tones with different frequencies simultaneously rather than in a temporal sequence, and he asked the listeners to make an intensity rather than a frequency discrimination. Dave worked with several students and postdocs (Dave was at Harvard University and then the University of Florida at this time) in the development of the profile analysis paradigm (e.g., Chris Mason, Donna Neff, Tom Buell, Murray Spiegel, Bruce Berg, and, especially, Gerald Kidd). A basic spectral "profile" stimulus is shown in **Figure 6** in which the spectrum of 5 sinusoidal tones is plotted as decibel sound pressure level (SPL) as a function of tonal frequency plotted on a log scale. The tones are at equal log-frequency intervals, with a spectrally centered target tone.

Dave often used a two-interval task in which a profile of equal intensity tones ("flat" profile) was presented in one interval (randomly determined), and the other interval contained the same tones but with the target tone presented at a higher intensity ("target-incremented" profile). The intensity of the target tone required to discriminate one profile from the other was determined.

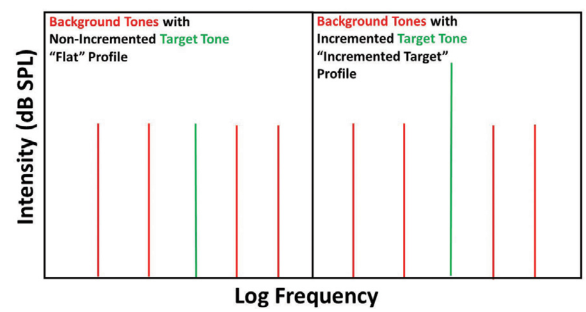


Figure 6. *Typical profile stimuli shown as spectra (intensity as a function of log frequency) of a 5-tone complex with a target tone (**green**) and background tones (**red**) spaced regularly on the log-frequency axis. **Left:** all tones are of equal intensity. **Right:** the target tone's intensity is increased relative to those of the background tones, forming a spectral profile. SPL, sound pressure level.*

However, if the stimuli were just like those shown in **Figure 6**, the interpretation of the results would be confounded because there are at least three "cues" that the listeners could use to make the discrimination. When the target tone's intensity is increased, the overall intensity of that profile is greater than the flat profile (this could be an appreciable difference for a small number of tonal components). Given that the tones were relatively far apart in frequency, the listeners could (after some practice) attend to the target tone and note that its intensity changed without regard to the intensity of the other tones. Alternatively, the listeners could note that the intensity of the target *relative* to that of the other tones was either the same or different. Dave's interest was the extent to which the listeners could make the relative level judgment across frequency for any one profile (i.e., are the listeners sensitive to the spectral profile generated by the increased target intensity?). To ensure that the listeners could use only a relative intensity cue to make their discrimination judgment, the overall intensity of the sounds was randomly roved by 20 dB or more. Such a random rove of overall stimulus intensity might produce the four profiles shown in **Figure 7**. With the random intensity rove, neither overall intensity nor the intensity of just the target tone could reliably indicate which profile had the incremented target intensity. Only by comparing the target intensity relative to the other component intensities within

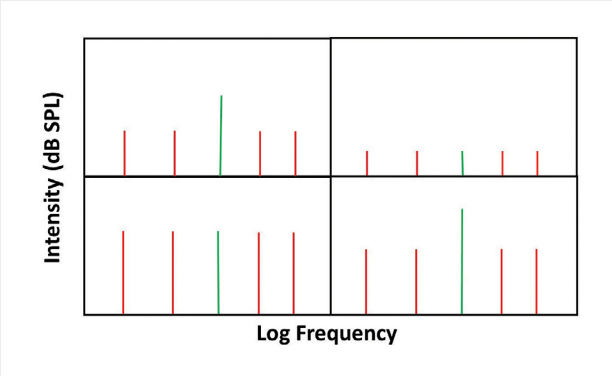


Figure 7. *Four spectral profiles (see **Figure 6**) are shown, each at a different overall intensity. Two are "flat" spectral profiles (**top right and bottom left**) and two are "target-incremented" spectral profiles. (**top left and bottom right**).*

a profile could that judgment be made. Dave showed in several experiments described in his book (Green, 1988) that trained listeners were sensitive to the relative intensity changes in a spectral profile.

In addition to spectral changes between two profiles, the time-domain waveform will also differ, and it could be a basis for distinguishing between profiles. To investigate this possibility, Green and Mason (1985) randomly varied the phases of the spectral components in several ways, which changes the time-domain waveforms but leaves the amplitude spectra unchanged. Phase variations made little difference in the trained listeners' ability to discriminate one profile from another. Thus, profile analysis is most likely due to differences in the stimuli's amplitude spectra as opposed to the time-domain waveforms.

Of all the aspects of profile stimuli that Dave studied, he was clearly impressed with one general finding: that when there were many background tones that were very different in frequency from the target tone, there was a large effect on profile discrimination performance. This is in contrast to what was often found in masking and discrimination experiments, where target detection or discrimination performance in these cases was affected mainly by spectral components close in frequency to the target component.

The general idea is that stimuli that are close together in frequency directly interact in the biomechanical inner ear transduction of sound into neural action potentials that flow to the brainstem via the auditory nerves. Each auditory nerve is tuned to a particular frequency range (each auditory nerve has a tuning curve) such that if stimuli have frequencies within that range, the nerve responds, but if components have frequencies outside the range, the nerve is unresponsive. A perceptual consequence of the tuning curve is the *critical band.* A critical band is a spectral region such that only components with frequencies within the critical band affect detection or discrimination performance of a target component. Thus, the profile analysis finding that components with frequencies well outside the target's critical band affected discrimination performance was not consistent with "traditional" critical-band accounts of detection and discrimination.

A conclusion of research on profile analysis is that auditory spectral processing is not necessarily limited by critical-band processing but can be "wideband." Although at the time of writing *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988) there were only a few examples of such wideband spectral processing in auditory detection and discrimination experiments, Dave did study the detection of tones of different frequencies in a noisy background early in his career (Green, 1958). In this study, he concluded that a wideband approach of integrating across critical bands could account for his results. In his profile analysis research, Dave pointed out that wideband processing is consistent with what must be required to perceive complex sounds such as speech and music, and profile analysis provides a means of investigating wideband perceptual processing of real-world sounds.

Shortly after the publication of *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988), several authors pointed out that the perceptual parsing of complex sounds is likely based on how sources produce sound, particularly when the sources produce nearly simultaneous sounds. Bregman's book "*Auditory Scene Analysis*" (1990) brought this view to the forefront. *Auditory Scene Analysis* describes the acoustic world as a scene of sound sources, and auditory perception involves determining the sound sources in such a scene. In Bregman's view, to do so requires not only an ability to process sounds produced by sources but also requires information gained from experience that has been stored in memory and then accessed through attentional processes. Perceiving sounds in an auditory scene often requires wideband processing, and profile analysis, along with several other paradigms that were subsequently developed, increased the understanding of the processes involved in auditory scene analysis.

End of an Era?

Dave continued to study profile analysis, spectral shape discrimination, and many other topics well after the publication of *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988). Dave retired as the field of psychological acoustics was changing. From the time of Fechner to the development of auditory scene analysis, a great deal of the study of psychological acoustics was strictly psychoacoustical, where studies focused on the direct functional relationship between acoustic variables and performance measures of detection, discrimination, and identification. SDT provided quantifiable performance measures (e.g., P_A), and ideal observer theory is a quantifiable means of obtaining psychophysical functional relationships between a performance measure and an acoustical variable.

Today, however, the questions often being asked in the field of psychological acoustics have moved beyond psychoacoustics as it was studied by Dave and his students, postdocs, and colleagues. For instance, many current psychological acoustic studies involve independent variables other than just acoustic parameters such as the age, gender, hearing ability, musical experience, species, or other characteristics of the subjects. In some sense, the strict study of psychoacoustics began with Fechner and began to end when Dave retired. There is much more to learn about auditory perception, but it is likely that the new knowledge will not be strictly psychoacoustical.

Throughout Dave's career, he worked with many students, postdocs, and colleagues. This ever-so-brief mention of just a few of Dave's numerous contributions probably indicates that his story may be longer and more consequential than most. However, to paraphrase Swets, many who passed through his lab had their own stories to tell, and after a few years of Dave's tutelage, they were in an excellent position to tell them.

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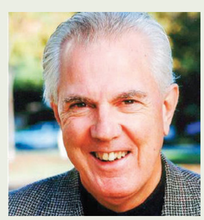

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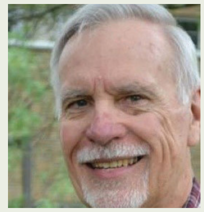

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The Physical Aspects of Vocal Health

Zhaoyan Zhang

For most people, not much conscious thought or effort is needed to produce a voice with the desired pitch, loudness, and voice quality. However, voice disorders are quite common. When disorders occur, the voice may require more effort to produce, be too weak to be heard, or have undesired quality changes that draw unwanted attention. Such changes can affect a speaker's personal identity and the ability to effectively communicate, thus limiting the ability to participate in educational, occupational, or social activities.

Most people have experienced difficulty with their voice after screaming at a sports event or after an upper respiratory infection such as the cold or flu. For teachers, singers, and other professional voice users, voice problems occur more often and the symptoms are often severe. For these people, the voice may get tired toward the end of the day. Sometimes the voice is no longer able to meet the higher expectations and greater demands of one's profession and those individuals have to make career changes.

This article focuses on voice disorders that are related to the production of sound by vocal fold vibration. Voice disorders are often grouped into three major categories based on their etiology. The first category includes organic voice disorders arising from structural changes to the larynx (e.g., inflammation due to an infection or voice overuse) that interfere with the vocal mechanisms.

The second category, neurogenic voice disorders, is related to neurological dysfunctions due to either paralysis, paresis, or neurological disease (e.g., Parkinson's disease) that impact neurological control of the vocal system.

The third category has been characterized in many ways, including as "functional" voice disorders. This category includes voice disorders with no known underlying organic or neurological origins that are presumably related to the improper use of vocal mechanisms and are thus "functional" in some aspect. A widely held assumption is that these disorders may have psychological origins, but more often they are adaptations to transient tissue changes (e.g., laryngitis) or compromised vocal mechanisms (e.g., paresis or paralysis).

The purpose of this article is not to discuss every voice disorder or category of disorders (but for more information, see Boone et al., 2010; Colton et al., 2011). Instead, it provides an updated review of the physical aspects of vocal health. The focus is on the physical components involved in healthy voice production, the major pathophysiology of voice disorders, and clinical care of common voice problems. The article ends by briefly discussing the existing knowledge gaps between current scientific understanding and the practice of clinical voice care.

Physiology of Voice Production

The human voice is produced in the larynx (**Figure 1A**), which houses the two opposing vocal folds. Each vocal fold consists of a soft membranous cover layer folded around an inner muscular layer. The vocal folds are connected together anteriorly but slightly separated posteriorly, forming a triangular-shaped airway (the glottis) (**Figure 1B**). At rest, the glottis remains open and allows airflow in and out of the lungs during breathing. During voice production (also known as phonation), the two vocal folds are brought together to close the glottis (**Figure 1C**). When the lung pressure is high enough (about 200 Pa), the vocal folds will be excited into a self-sustained vibration, which periodically opens and closes the glottis. This modulates airflow through the glottis and produces sound, which then propagates through the vocal tract and radiates from the mouth and nasal opening into the voice we hear.

An important feature of normal voice production is that the glottis remains closed for an extended duration within each cycle of vocal fold vibration (see **Multimedia 1** at acousticstoday.org/zzhangmedia), which interrupts the glottal flow. The rapid decline of the glottal flow

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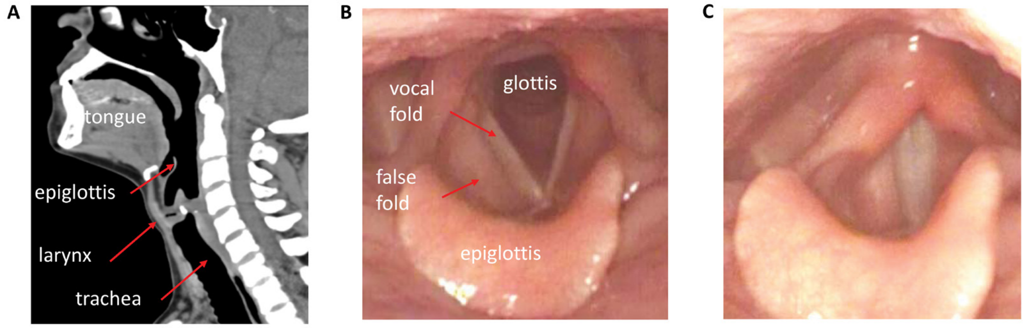


Figure 1. ***A:*** *computed tomography image of the head showing the airway and the larynx.* ***B:*** *top view of the larynx. The vocal folds are far apart at rest.* ***C:*** *vocal folds are brought together to close the glottis during phonation.*

during the glottal closing phase is the main mechanism for harmonic sound production, by which voices of different quality are produced and differentiated. An abrupt cessation of the glottal flow produces a voice with strong harmonic excitation at high frequencies and a bright voice quality that often carries well in a room or open space. On the other hand, a sinusoidal-like shape of the glottal flow with a gradual flow decline, often in the presence of an incomplete glottal closure, produces a voice with a limited number of higher order harmonics in the voice spectrum and a weak voice quality.

The glottal closure pattern during voice production is controlled by adductory laryngeal muscles that bring the two folds together (vocal fold approximation) to reduce the glottal gap. Indeed, phonation is impossible if the glottal gap is too large. Vocal folds that are insufficiently approximated tend to vibrate without complete glottal closure. This produces a breathy voice quality with weak excitation of harmonics and strong noise in the voice spectrum. Increasing approximation of the vocal folds leads to increased vocal fold contact and glottal closure, reducing air leakage through the glottis and increasing harmonic sound generation.

Activation of the adductory laryngeal muscles also modifies vocal fold shape and, particularly, the vertical thickness of the vocal fold medial surface. The medial surface vertical thickness plays an important role in regulating the duration of glottal closure and the produced voice quality. Increasing the vertical thickness allows the vocal folds to better maintain their position against the subglottal pressure. This is essential to achieve complete glottal closure at high lung pressure while producing a loud voice where vocal fold approximation alone is insufficient to ensure glottal closure during phonation (Zhang, 2016).

In general, thicker vocal folds tend to close the glottis for a longer duration during phonation than thinner vocal folds. Thus, changes in vertical thickness are essential to producing voice qualities ranging from breathy (see **Multimedia 2** at acousticstoday.org/zzhangmedia) to normal (see **Multimedia 3** at acousticstoday.org/zzhangmedia) to pressed (see **Multimedia 4** at acousticstoday.org/zzhangmedia). In the extreme case of very large vocal fold thickness due to strong vocal fold adduction, the folds often exhibit subharmonic or irregular vibration, producing a rough voice quality (Zhang, 2018), known as creak in the linguistic literature and more colloquially as vocal fry (see **Multimedia 5** at acousticstoday.org/zzhangmedia).

Pitch is controlled by elongating and shortening the vocal folds, which regulates the tension and stiffness of the vocal folds. This is possible because the cover layer of each vocal fold consists of collagen and elastin fibers aligned along the anterior-posterior (front-back) direction. These fibers are in a wavy, crimped state at rest but are gradually straightened with elongation and thus become load bearing. As more fibers are gradually straightened with vocal fold elongation, the vocal folds become increasingly stiff, thus increasing pitch.

Because the laryngeal muscles that control the vocal fold length also regulate the vocal fold vertical thickness, changes in pitch are often accompanied by changes in voice quality. For example, a pitch glide is often accompanied by changes in vocal registers. Vocal fry, produced often with increased vertical thickness and a long period of glottal closure, occurs at the lower end of the pitch range, whereas the voice at the high end of the pitch range is often in a falsetto register, produced with a reduced vertical thickness and a brief duration of glottal closure. The modal voice, which is used in conversational speech, is produced with an intermediate thickness of the vocal fold at the intermediate pitch range.

Vocal Fold Contact Pressure and Risk of Vocal Fold Injury

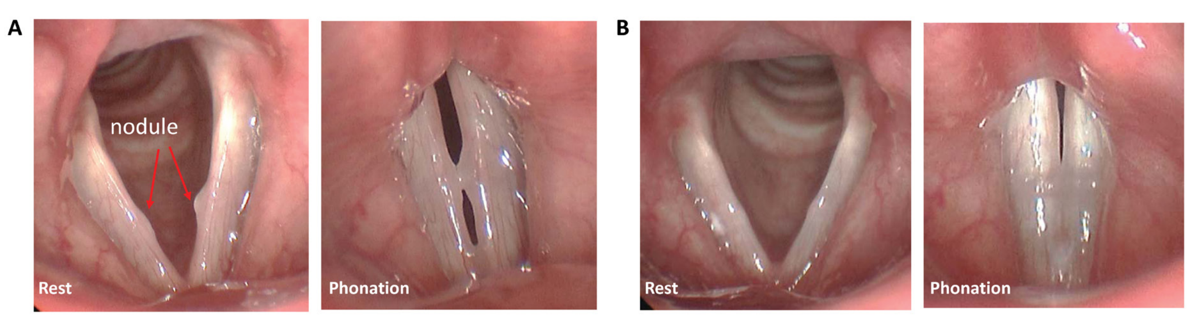
During voice production, the vocal folds experience repeated mechanical stress. In particular, the contact pressure sustained by the vocal folds during repeated collision poses the greatest risk of tissue damage because this pressure acts perpendicular to the load-bearing collagen and elastin fibers within the vocal folds (Titze, 1994). For a loud voice such as screaming, the contact pressure can be as high as 20 kPa locally for extreme voicing conditions as reported in recent numerical simulations (Zhang, 2020).

Although the vocal folds evolved to withstand the repeated contact pressure during phonation, when the contact pressure exceeds a certain level (e.g., due to talking loudly or screaming) or is sustained over an extended period (e,g., due to excessive talking or singing), it will cause injury to the vocal folds, triggering an initial inflammation response with fluid accumulation. This often results in degraded voice quality and difficulty in producing or modulating the voice. The threshold contact pressure triggering the inflammation response appears to vary individually depending on the daily vocal load, overall health condition of the speaker, and, possibly, the microstructural composition of the vocal fold tissues. If this hyperfunction behavior (loud voice for a prolonged period) persists, there may be permanent vocal fold lesions such as vocal fold nodules (**Figure 2**).

The magnitude of the peak contact pressure depends primarily on the subglottal pressure used to produce the voice and, to a lesser degree, the cover layer stiffness of the vocal folds (Zhang, 2020). Soft vocal folds subject to high subglottal pressure will vibrate with a large vibration amplitude and vocal fold speed at contact, and thus a high contact pressure is required to stop the vocal folds during collision. In general, thinner vocal folds (as, e.g., in a falsetto register) tend to produce lower vocal fold contact pressure (Zhang, 2020). Although the effect of the glottal gap on the contact pressure is generally small, the contact pressure becomes excessively high when the vocal folds are tightly compressed against each other (hyperadduction).

Because the subglottal pressure has a dominant effect on both vocal fold contact pressure and vocal intensity, the risk of vocal fold injury can be significantly reduced by lowering the vocal intensity or completely eliminated by vocal rest. However, vocal rest or reduced loudness is often not socially practical due to communication needs in everyday life. A more practical strategy is to adopt laryngeal and vocal tract adjustments to minimize the subglottal pressure required

Figure 2. ***A:*** *vocal hyperfunction can lead to vocal fold nodules on the medial edge of the vocal folds (**left**), which prevents complete glottal closure during phonation (**right**).* ***B:*** *vocal fold nodules almost disappear post-voice therapy (**left**), which significantly improves glottal closure during phonation (**right**).*



to produce voice of desired loudness, thus minimizing vocal fold contact pressure. At the laryngeal level, this can be achieved by adopting a barely abducted (with the vocal folds just touching each other), thin vocal fold configuration (Berry et al., 2001; Zhang, 2020). This barely abducted configuration is often targeted in voice therapy (e.g., the resonant voice therapy; Verdolini-Marston et al., 1995). In voice training, register balancing between thick and thin vocal folds in singing is often promoted to minimize subglottal pressure and purportedly laryngeal pathologies over time (e.g., the Bel Canto technique).

Vocal fold contact pressure can also be lowered by vocal tract adjustments. For example, when targeting a desired loudness, vocal fold contact pressure can be lowered by constricting the epilarynx (the part of the upper airway immediately above the vocal folds) or increasing the mouth opening whenever possible. Epilaryngeal narrowing often leads to clustering of vocal tract resonances in the 2- to 3-kHz range, which is known as the singer's formant, and amplifies voice harmonics in this frequency range. Increasing the mouth opening increases the efficiency of sound radiation from the mouth. Both adjustments reduce the subglottal pressure required to produce a desired loudness, thus reducing vocal fold contact pressure (Zhang, 2021).

Unfortunately, untrained speakers often increase vocal fold adduction when attempting to increase vocal intensity (Isshiki, 1964), especially in an emotional situation. This is particularly the case of speakers who habitually squeeze the larynx during talking. Hyperadduction of the vocal folds may also develop as an adaptive behavior in response to transient vocal fold tissue changes. Hyperadducted vocal folds are not vocally efficient, meaning that a higher subglottal pressure is required to produce a desired loudness than that needed for barely abducted vocal folds. Because hyperadduction is often accompanied by reduced stiffness and increased thickness in the cover layer, the risk of vocal fold injury is excessively high due to the combination of the high subglottal pressure required, tightly compressed vocal folds, and low cover layer stiffness. Tightly compressed vocal folds also have the tendency to exhibit irregular vocal fold vibration with large cycle-to-cycle variations, resulting in a rough voice quality. Whenever possible, this vocal fold configuration should be avoided in loud voice production by making the appropriate adjustments at the larynx and within the vocal tract.

Glottal Insufficiency and Adaptive Compensations

Although voice production with tightly compressed vocal folds is unhealthy, voice production with the vocal folds too far apart is also undesired. Whereas the latter vocal configuration requires the least laryngeal effort and poses the lowest risk to vocal fold injury at a low subglottal pressure, voice production is extremely inefficient due to the lack of glottal closure. Thus, attempting to talk loudly in this configuration would require excessively high subglottal pressures, resulting in a high respiratory effort and, potentially, a high vocal fold contact pressure. The produced voice is breathy in nature due to the large airflow escaping through the glottis. With the high lung volume expenditure, one may also feel short of breath and need to take another breath in the middle of an utterance, particularly when attempting to increase loudness. As a result, such a configuration is not ideal for conversational communication or loud voice production.

However, the ability to sufficiently adduct the vocal folds may be lost or weakened due to changes in vocal fold physiology, a condition known medically as glottal insufficiency. Such insufficiency may occur as a result of vocal fold paralysis or paresis due to trauma to the laryngeal nerves, vocal fold atrophy with aging, or changes in the membranous cover layer (e.g., vocal fold swelling or scarring). Under such conditions, one may develop adaptive vocal behaviors in an attempt to increase vocal efficiency and conserve air expenditure. This can be achieved by increasing activation of the adductory muscles to improve glottal closure if the neuromuscular mechanism is still intact. One may also adduct supraglottal structures such as the false folds and epiglottis (**Figure 3**), as often observed in muscle tension dysphonia. Although supraglottal adduction does not improve glottal closure, it may enhance source-tract interaction and thus increase vocal efficiency in addition to air conservation. Such adaptive behaviors often lead to increased laryngeal effort, vocal fatigue over time, and a strained voice quality. If such adaptation persists, it may lead to long-term voice disorders.

For example, vocal fold swelling often occurs after extensive shouting or screaming in a sports event or giving a lecture for a longer than the normal period. Extremely high subglottal pressures and, even more so, vocal fold hyperadduction in these situations readily lead to vocal

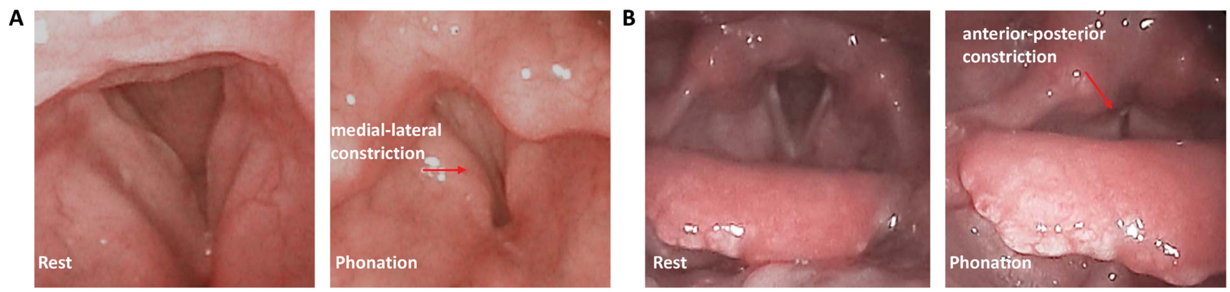


Figure 3. *Adduction of the supraglottal structures may lead to medial-lateral (**A: left to right**) or anterior-posterior (**B: front to back**) constriction of the airway immediately above the vocal folds, as often observed in muscle tension dysphonia.*

fold swelling. This swelling may also occur following an upper respiratory infection (such as the cold or flu), chemical exposure of the vocal folds due to laryngopharyngeal reflux (stomach acid reflux into the throat), or smoking. Vocal fold swelling makes it difficult to completely close the glottis along the length of the vocal folds, allowing air to escape through gaps around the swollen portion of the vocal folds. When vocal fold inflammation leads to an irregular medial edge of the vocal folds, irregular glottal closure may ensue, resulting in hoarse voice quality.

Vocal fold swelling is often transient and will resolve over time with vocal rest or when the underlying medical conditions have cleared. However, if one were to talk through these voice changes, one often has to increase lung pressure, tighten adduction of the vocal folds, and possibly adduct the false folds and epiglottis. This adaptation may lead to increased contact pressure between the vocal folds, further exacerbating the underlying vocal fold inflammation. If this adaptive behavior persists after the triggering conditions are resolved, the vocal fold inflammation may further develop into vocal fold lesions such as vocal fold nodules, polyps, and contact ulcers, with a more permanent change in voice quality (Hillman et al., 1989). For voice professionals, particularly singers, it is often recommended that they reduce voice use in the presence of vocal fold inflammation and avoid adaptive changes in vocal behavior.

Muscular Tension Around the Larynx

Voice disorders may also occur from increased tension in the perilaryngeal muscles that support the larynx (muscles connecting the larynx to other structures around the neck). This is often due to adaptive behaviors to compensate for glottal insufficiency but may also result from psychological stress (Dietrich and Verdolini Abbott, 2012).

Tension in the perilaryngeal muscles often raises the vertical position of the larynx. This results in increased adduction of the vocal folds and the squeezing of supraglottal structures such as the false vocal folds and epiglottis (**Figure 3**) (Vilkman et al., 1996), allowing a speaker to compensate for glottal insufficiency. However, in the absence of glottal insufficiency, such increased vocal fold adduction often leads to excessively high contact forces between the vocal folds and poses a high risk of vocal fold injury. Due to the high tension in the perilaryngeal muscles, the speaker often experiences vocal fatigue after an extended period of talking and may even feel pain around the neck.

Although voice production is primarily controlled by activities of the intrinsic laryngeal muscles (muscles with origin and insertion within the larynx), these muscles act on the laryngeal framework that is supported and stabilized by the perilaryngeal muscles. Excessive tension in the perilaryngeal muscles acting on the laryngeal cartilages makes it more difficult to adjust the relative position among the thyroid, cricoid, and arytenoid cartilages to which the vocal folds are attached. This may interfere with the delicate control of vocal fold geometry and mechanical properties by the intrinsic muscles and limit the range of vocal fold posturing. Tension in the perilaryngeal muscles may also lead to undesired relative positions between laryngeal cartilages, which often require compensation by increased activity of the intrinsic laryngeal muscles to maintain pitch or adductory positions. This may change the relative balance between the intrinsic laryngeal muscles, resulting in increased laryngeal effort.

Involvement of the Respiratory System

Adaptive behavior to tighten the larynx may also result from laryngeal-respiratory compensation. The respiratory system is responsible for providing and maintaining the subglottal pressure desired for speech production. In breathing at rest, the respiratory muscles are actively engaged during inspiration, whereas expiration often relies on a passive elastic recoil of the lungs and thorax, known as the relaxation pressure. The amount of relaxation pressure increases with the lung volume and is positive (i.e., pushes air out of the lungs) at a high lung volume and becomes negative (draws air into the lungs) at a very low lung volume. Speech production occurs during the expiration phase of breathing and takes advantage of the relaxation pressure in supplying and maintaining the desired subglottal pressure. By taking a breath to start speech at the appropriate lung volume, the desired subglottal pressure can be mostly supplied and maintained by the relaxation pressure for the entire breath group duration, without much extra respiratory muscle effort. In this sense, speech is often considered "effortless."

However, when starting speech at either too high or too low lung volumes, extra expiratory muscle effort would be required to either overcome or supplement the relaxation pressure. This additional muscle activation increases rapidly as the lung volume approaches the lower or upper end of the lung capacity. In the extreme case of starting speech at a very low lung volume, in addition to this extra expiratory muscle activation required to maintain the desired subglottal pressure, the level of vocal fold adduction must also be increased to conserve airflow and prevent running out of air before completing an utterance. Thus, speakers who habitually start their speech at a low lung volume often produce a voice with hyperadducted vocal folds and possibly adduction of supraglottal structures (Desjardins et al., 2021), leading to vocal fatigue and undesired voice changes.

A tight laryngeal configuration at a low lung volume may also result from a reduced tracheal pull effect. Tracheal pull is a downward force exerted by the trachea and the respiratory system on the larynx. This force applies to the cricoid cartilage and tends to reduce the degree of vocal fold adduction. Tracheal pull increases as the diaphragm descends. That is, the tracheal pull is strong when speaking at a high lung volume and decreases as the lung volume decreases (Sundberg, 1993). Thus, when speaking at a very low lung volume, vocal fold adduction may increase naturally due to reduced tracheal pull.

Hydration and Environmental Acoustic Support

Hydration is another important factor in maintaining vocal health. The vocal fold surface is lined by a mucous layer that functions as lubrication to reduce the contact pressure during vocal fold collision. When the speaker is dehydrated, the mucus becomes thick and sticky instead of thin and watery, a condition that deteriorates the lubrication effect in reducing vocal fold contact pressure (Colton et al., 2011). Dehydration may also increase vocal fold stiffness and viscosity, thus increasing the lung pressure required to produce voice. Thus, maintaining good systemic hydration is essential to voice professionals who use their voice extensively in their daily life.

Voice production is mediated through auditory feedback and thus is subject to changes in the speaker's acoustic environment. For example, with increasing background noise, we often increase vocal intensity to maintain the sufficient speech-to-noise ratio desired for communication. The increase in vocal intensity is often accompanied by a boost of high-frequency harmonic energy with respect to lower-frequency harmonic energy, indicating increased vocal fold adduction.

Similar voice changes are also observed when speaking in rooms with different reverberation characteristics. Speakers produce voice with a higher vocal intensity in rooms with a shorter reverberation time compared with rooms with a longer reverberation time in which acoustic reflections of their own voice provide strong auditory feedback and acoustic support (Brunskog et al., 2009). Thus, speaking for an extended period in a noisy environment or an acoustically "dead" environment with a very short reverberation time is likely to require an increased vocal effort and the speaker is prone to vocal fatigue and risk of vocal fold injury.

Clinical Voice Care

Clinical voice care attempts to restore the voice through medical, behavioral, and/or surgical interventions. When the voice disorder is triggered by an underlying medical condition, such as vocal fold swelling due to an upper respiratory infection, reflux, or smoking, medical treatment is necessary to clear the medical condition. Due to the delicate structure of the vocal folds, particularly within the membranous cover layer, the initial treatment is often behavioral or voice therapy, particularly for nonorganic voice disorders but also for some organic voice disorders such as vocal fold nodules (**Figure 2**). The goal of voice therapy is to restore the best voice possible, something that is often achieved through vocal health education and modification of vocal behavior using different vocal techniques and exercises. Even for patients who eventually require surgery, pre- and postoperative voice therapy is essential to achieve an optimal voice outcome and prevent recurrence of the voice disorder. For organic voice disorders or conditions of glottic insufficiency, surgical intervention is often more effective.

One of the most common voice disorders in the clinic is muscle tension dysphonia. It involves too extensive an effort in producing the voice, with excessive muscle force and a tight larynx configuration. Some patients may also present with vocal fold lesions such as nodules, due to the chronic exposure to excessively high vocal fold contact pressure. Voice therapy is often effective in improving voice in these patients. For example, external circumlaryngeal massage is often used to relax the larynx in patients with notable tension in the musculature around the neck. Some techniques take advantage of tasks such as yawning or sighing that are naturally produced with a reduced laryngeal muscle tension and a less adducted glottal configuration, often with a lowered vertical position of the larynx. By starting with such tasks and gradually transitioning into speech, the speaker can be trained to produce voice with the same relaxed laryngeal configuration, thus reducing vocal fold contact pressure and the risk of vocal fold injury.

Various vocal exercises are also used to train speakers to produce voice with a focus on vibratory sensations around the lips and cheek and along the alveolar ridge of the palate (e.g., resonant voice therapy), thus avoiding a tight sensation at the larynx. In some exercises, the speaker is instructed to perform pitch or loudness glides with a semi-occluded vocal tract configuration, producing either nasal sounds, trills, or phonating into a narrow tube such as a drinking straw. It is generally believed that by focusing on vibratory sensations in certain parts of the vocal tract, the speaker may adopt a vocal configuration that improves vocal efficiency and minimizes vocal fold contact pressure.

An important component of voice therapy is to reestablish the balance between respiration, phonation, and articulation. For example, for voice disorders resulting from weakened respiratory function or improper respiratory behavior, voice therapy often focuses on respiration strength training to improve respiratory function or training the speaker to begin speaking at an appropriate lung volume to ensure sufficient air supply required for speech (Desjardins et al., 2021).

For vocal fold mass lesions that are large in size, such as vocal fold polyps, cysts, and sometimes even nodules, voice therapy may have little effect and surgical removal is necessary. Because the membranous cover layer of the vocal folds is the vibrating component, it is critical that surgery remove as little tissue as possible and avoid significantly altering the delicate structure and mechanical properties of the vocal fold cover layer. Vocal fold scarring after surgery, particularly on the vocal fold medial surface where vocal fold vibration modulates airflow most effectively, often negatively impacts the patient's voice and vocal capabilities.

For patients who are unable to sufficiently adduct the vocal folds due to vocal fold paralysis, paresis, atrophy, or aging, vocal fold adduction can be improved through an office-based injection augmentation procedure in which fat or another material is injected into the vocal folds to displace the medial edge of the vocal folds toward the glottal midline. A more permanent solution is medialization laryngoplasty, in which an implant is inserted laterally to the vocal folds to permanently displace and reposition the vocal folds toward the glottal midline (Isshiki, 1989). These procedures are often able to significantly improve glottal closure and voice quality and reduce vocal effort.

In addition to adjusting the vocal fold position, vocal fold surgery also allows manipulation of vocal pitch. One way to achieve this is to adjust vocal fold tension by surgically modifying the relative positions between laryngeal cartilages. However, this often reduces the vocal range and the amount of pitch change is relatively small. In feminization voice surgery in which a large pitch increase is desired, surgery is often performed to not only adjust vocal fold length but also to reduce the vibrating length of the vocal folds by surgically merging the anterior portions of the two vocal folds or reducing vocal fold mass. Because pitch is only one of many aspects of gender perception, voice therapy is necessary in these patients to adjust other aspects of voice use such as vowel quality, stress, inflection, choice of words and conversational style.

Surgical intervention is also effective in treating some neurological voice disorders. For example, spasmodic dysphonia is a neurological voice disorder that results from involuntary spasms in laryngeal muscle activity, which interferes with normal vocal fold vibration and leads to intermittent voice breaks and strained or breathy voice quality. Current treatment aims to weaken the affected laryngeal muscles through botulinum toxin injection or surgically denervating the affected laryngeal nerves, both of which can significantly alleviate the symptoms.

Bridging the Gap Between Science and Clinical Practice

Current clinical voice care is often quite effective in at least partially improving voice production and quality. However, the voice outcome is often variable and relies heavily on the clinician's experience. Sometimes the voice still remains unsatisfactory after intervention, and the underlying reasons are often unclear. In this sense, clinical voice care is more art than science. The translation of findings from basic science voice research can play an important role in further improving clinical management of voice disorders and reducing variability in voice outcomes. For example, although vocal fold medial surface shape in the vertical dimension has been shown to be important to voice production (Zhang, 2016), it is often not monitored or targeted in current clinical voice examination and intervention, which focus on vocal fold position and glottal closure from a superior, endoscopic view. Targeting the medial surface shape in addition to other intervention goals may improve voice outcomes in patients whose voice remains unsatisfactory after intervention.

Many voice therapy techniques currently used in the clinic were modified from vocal training methods. Although many of them are effective, the underlying scientific principles often remain unclear. For example, semi-occluded vocal tract exercises are widely used in the clinic. Although some theoretical hypotheses have been put forward, they are not always consistent with the observed changes in the laryngeal and vocal tract configuration during such exercises (Vampola et al., 2011). Voice therapy and vocal training often emphasize vibratory sensations in certain parts of the airway. However, it remains unclear what laryngeal and vocal tract adjustments are elicited in patients by voice therapy and which of them are responsible for improvement in voice outcomes. A better understanding of the scientific rationale would allow clinicians to better monitor the progress of voice therapy or even adapt voice therapy toward patient-specific vocal behavior to further improve voice therapy outcomes.

Each individual voice is unique. Although some individuals are prone to vocal fold injury, others can talk loudly for an extended duration without experiencing vocal fatigue or noticeable voice changes. Little is known about the physiological and behavioral factors responsible for individual differences in vocal capabilities and vocal health. A mathematical model of voice production allowing manipulation of the voice in a physiologically realistic way would provide insights into why and how each individual voice is different (Wu and Zhang, 2019), which may lead to interesting applications both inside and outside the clinic.

Acknowledgments

I thank Maude Desjardins, Bruce Gerratt, Katherine Verdolini Abbott, Lisa Bolden, and Arthur Popper for their constructive comments on an earlier draft of this paper. I also acknowledge support from the National Institute on Deafness and Other Communication Disorders (NIDCD), National Institutes of Health (NIH), Bethesda, MD.

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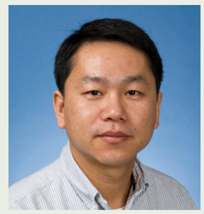

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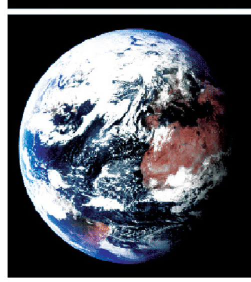

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ASA ACOUSTICAL SOCIETY OF AMERICA

Recent Acoustical Society of America Awards and Prizes

Acoustics Today is pleased to present the names of the recipients of the various awards and prizes given out by the Acoustical Society of America. After the recipients are approved by the Executive Council of the Society at each semiannual meeting, their names are published in the next issue of *Acoustics Today*.

Congratulations to the following recipients of Acoustical Society of America medals, awards, prizes, and fellowships, who will be formally recognized at the Fall 2021 Plenary Session at the meeting in Seattle, Washington. For more information on the accolades, please see acousticstoday.org/asa-awards, acousticalsociety.org/prizes, and acousticstoday.org/fellowships.

Silver Medal in Animal Bioacoustics
Peter M. Narins
(University of California, Los Angeles)

Silver Medal in Biomedical Acoustics
William D. O'Brien, Jr.
(University of Illinois, Urbana-Champaign)

Silver Medal in Noise
Paul D. Schomer
(Schomer & Associates, Champaign, IL)

Silver Medal in Psychological and Physiological Acoustics
Ruth Y. Litovsky
(University of Wisconsin, Madison)

Silver Medal in Signal Processing in Acoustics
William S. Hodgkiss, Jr.
(University of California, San Diego, La Jolla)

Silver Medal in Speech Communication
Joanne L. Miller
(Northeastern University, Boston, MA)

Pioneers of Underwater Acoustics Medal
Finn B. Jensen
(SACLANT Undersea Research Centre, La Spezia, Italy)

Congratulations also to the following members who were elected Fellows in the Acoustical Society of America in the Fall 2021.

- **Kyle M. Becker** (Office of Naval Research, Arlington, VA) for leadership in ocean acoustics
- **Mark A. Bee** (University of Minnesota, Minneapolis) for contributions to understanding amphibian bioacoustics
- **Matthew J. Goupell** (University of Maryland, College Park) for advancing understanding of binaural processing in electric and acoustic hearing
- **Brian T. Hefner** (University of Washington, Seattle) for contributions to scattering and reverberation in underwater acoustics
- **Brent Hoffmeister** (Rhodes College, Memphis, TN) for contributions to the ultrasound characterization of bone
- **Adrian K. C. Lee** (University of Washington, Seattle) for contributions to our understanding of auditory attention
- **Subha Maruvada** (US Food and Drug Administration, Silver Spring, MD) for contributions to ultrasound metrology
- **D. Benjamin Reeder** (Naval Postgraduate School, Monterey, CA) for advancements in underwater acoustic propagation and scattering
- **Bradley E. Treeby** (University College London, UK) for contributions to computational modeling in biomedical ultrasound
- **Richard A. Wright** (University of Washington, Seattle) for contributions to understanding how phonetic variability impacts communication
- **Pavel Zahorik** (University of Louisville, KY) for contributions to understanding auditory perception in natural environments
- **Pei Zhong** (Duke University, Durham, NC) for contributions to shock wave lithotripsy

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Ask an Acoustician: Kathleen J. Vigness-Raposa

Kathleen J. Vigness-Raposa
and Micheal L. Dent

Meet Kathleen J. Vigness-Raposa

This "Ask an Acoustician" essay features Kathleen J. (Kathy) Vigness-Raposa, a principal scientist at INSPIRE Environmental. Kathy received her BS from Miami University, Oxford, Ohio, and her MS in biological oceanography and PhD in environmental sciences from the University of Rhode Island (URI), Kingston. In addition to her position at INSPIRE, she has served on and off as a faculty member at the URI since 2014. Kathy's work on the educational website "Discovery of Sound in the Sea" (see dosits.org) won the Acoustical Society of America Science Writing Award for Media other than Articles in 2007. This website still serves as an important educational tool for many. Kathy served on the technical committee for the Providence meeting and is an associate editor for *The Journal of the Acoustical Society of America*. I will let Kathy tell you the rest.

Tell us about your work.

My work has focused on assessing the impacts of underwater sound on marine mammals, sea turtles, and fishes and translating complex acoustic concepts for broader audiences. I have been part of a number of different projects, from environmental compliance studies and permitting documentation to passive acoustic monitoring for marine mammals during active acoustics projects to predicting marine mammal distributions and abundances based on environmental covariates. Most recently, I have been part of a team that is focused on the sounds from the construction and operation of offshore wind farms and on the potential exposure to underwater sound and electromagnetic fields from those developments.

Twenty years ago this fall, URI Principal Investigator Gail Scowcroft, other URI colleagues, and I launched the DOSITS project. The DOSITS project synthesizes peer-reviewed science related to underwater sound, including content on sound sources, potential impacts on marine life, and how animals and people use sound underwater. DOSITS has been a great collaboration among acousticians and experts at digesting science content for a variety of audiences, but also is ground-breaking in that all DOSITS content is peer-reviewed by a panel of scientific experts that currently includes Arthur N. Popper, Darlene R. Ketten, James H. Miller, and Aaron M. Thode. It has been so awesome to be part of this project that is increasing the understanding and awareness of the science related to underwater sound.

Describe your career path.

I became interested in acoustics as a high school student participating in a National Science Foundation (NSF) summer program at St. Olaf College in Northfield, Minnesota, and I have always loved the ocean. However, I wasn't sure how someone from Wisconsin would get a job doing marine biology, so I got an undergraduate degree in secondary science education. This was fortuitous because it provided me with an incredibly diverse background in biology, chemistry, geology, and physics.

I then went to the Graduate School of Oceanography at the URI to work with Howard Winn on the vocalizations of minke whales. Unfortunately, Dr. Winn passed away

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unexpectedly after my first year of graduate work, but at the same time James H. Miller came to the URI Ocean Engineering Department. I took Miller's signal-processing course that fall and was looking for guidance on how to continue moving forward with my MS research. I ended up convincing H. Thomas Rossby that tracking his SOund Fixing And Ranging (RAFOS) floats (RAFOS is SOFAR spelled backward; they are floats that listen for signals and are used to map ocean currents well below the surface) was just like tracking vocalizing whales, and I completed a modeling sensitivity study of the critical parameters for passive acoustics tracking of marine mammals for my thesis.

In the meantime, I needed funding and Miller connected me with William T. Ellison at Marine Acoustics, Inc. (MAI). MAI is a scientific and engineering company that provides environmental consulting, research and development, and naval technology and training services to a diverse set of government, corporate, and international clients. I started working part-time for MAI as part of a research team studying the potential effects of the US Navy's Surveillance Towed Array Sensor System (SURTASS) Low Frequency Active (LFA) acoustics system. This work transitioned into a full-time job, first in the Washington, DC, area, then in Newport, Rhode Island, where I helped to develop research methods and modeling tools to determine the sensitivity of marine animals to anthropogenic activities and to estimate their exposure in specific scenarios. MAI has developed the Acoustic Integration Model (AIM) that models the four-dimensional acoustic field (three-dimensional space + time) into which simulated animals ("animats") are distributed and through which they move, acting as dosimeters to estimate their acoustic exposure.

To better inform the animal distribution and abundance inputs to AIM, I went back to school to complete my PhD, focusing on using environmental covariates in geospatial models to predict distribution and abundance. While at MAI, I worked my way up from staff scientist to senior scientist to Vice President of Environmental Projects, focusing more on project management and proposal writing in later years. In 2020, I shifted to INSPIRE Environmental, where I am a principal scientist, focusing on offshore wind activities and using more of my geospatial skills as part of an integrated team studying seafloor health, benthic habitats, and fisheries interactions.

What is a typical day for you?

I get up around 4:45 a.m. and go for a run; this is my meditation time when I get my best ideas and get myself organized for the day. When I get home, I walk our two dogs and get my 12-year-old daughter, Brierley, off to school at 7:00 a.m., then turn to work. The vast majority of my job is computer analyses, writing reports and proposals, and coordinating with colleagues. I don't really have a "typical" day; I need to address which priority is most urgent at the time while also keeping others moving forward and being productive on our projects. I don't often take a lunch break because I tend to graze throughout the day. I have been working at home since March 13, 2020, because of COVID-19, so now I try to take a break around 2:00 p.m. when my daughter gets home from school. We will play a little basketball or ping pong or take the dogs for a walk, then she sits down to homework and I continue with my tasks. I wrap up around 5:00 p.m. (or would be home by then if working in the office) and shift to evening activities and dinner preparation. I am the president of our town's land trust and the president of a local Montessori school's board of directors, so the juggling act continues!

How do you feel when experiments/projects do not work out the way you expected them to?

I am disappointed, obviously, but then I try to tease out the individual steps within the project to identify factors that I may not have considered properly or points at which errors may have occurred. I do a lot of modeling so having empirical data and/or a general sense of what the outcome should be is very helpful at retracing steps and ferreting out mistakes.

Do you feel like you have solved the work-life balance problem? Was it always this way?

Some days are better than others, but I definitely struggle with the work-life balance. My husband, Kenneth B. Raposa, is the research coordinator for the Narragansett Bay Research Reserve, so it is tough to juggle both of our jobs and all of our and our daughter's activities. Working from home during COVID has been both a blessing and a curse in that I am able to support our daughter and dogs, but I find it hard to turn off the demands when my office is just steps away, whereas my commute used to provide a degree of separation and decompression that I haven't been able to achieve at home.

What makes you a good acoustician?

I am a good acoustician because I have a solid foundation in physics and mathematics that allows me to dissect complex problems into fundamental principles. I worry that various coding applications make it too easy to implement a function without truly understanding its assumptions and structure. This also makes it more difficult to detect errant outputs and develop an intuitive sense of accuracy. I think it is particularly important for bioacousticians to develop their math and physics foundation to understand the acoustics.

How do you handle rejection?

I am definitely a glass is half-full kind of person so I try to take rejection as constructive criticism and spin out the positive from the negative. What was good? What was bad? How could I improve? What might be the underlying drivers that resulted in this decision? I also like to talk through the process with others, be they colleagues that were part of the original project or outside mentors that might be able to provide a second opinion. Then I work to develop an alternate strategy that gets me to the same end game.

What are you proudest of in your career?

I am most proud of the work I have done with the DOSITS project. It is a passion of mine to explain complex scientific topics and make them digestible by the general public. I think this is a critical skill that all scientists need to learn: what are you doing and why is it important. And I am incredibly proud that DOSITS has been funded for over 20 years at this point. It is a reminder that you can break projects into incremental pieces to meet funding allotments and those increments may become extensive pieces of work over time. Don't feel that you need to tackle everything all at once but prioritize for greatest impact with what you can do.

What is the biggest mistake you've ever made?

Not sticking up for myself soon enough. I am very good at facilitating conversations from an outside perspective and I am usually more forthright once I know the individuals with whom I am working, but I tend to struggle when I am in a group of individuals that I don't know well. I want to keep the group moving forward and find a conciliatory position that will please the greatest number of people. I am a big picture person and can identify the needs to keep the group moving forward, so I tend to volunteer to fill those voids at my own expense, often with a greater time commitment than I would like.

What advice do you have for budding acousticians?

Don't give up and be flexible. A work ethic is 90% of the fight, and the path is never straight and narrow. If you continue to improve your skills and keep up with the literature, you will find a niche for yourself.

Have you ever experienced imposter syndrome? How did you deal with that if so?

I'm not sure it is imposter syndrome so much as time warp syndrome. I feel like just yesterday I was working on my Master's thesis, but then when I think about all that I have done and accomplished over the years, I feel like I am 250 years old! I think it is important to continue to be true to yourself, know your strengths and weaknesses, and define goals that keep you moving forward.

What do you want to accomplish within the next 10 years or before retirement?

At INSPIRE, I am most proud of our work to mentor younger scientists and conduct science outreach to diverse communities. As the offshore wind industry takes off on the US East Coast, I am excited to continue the work that I am doing and continue to focus on opportunities to facilitate the general public's understanding of and interest in science.

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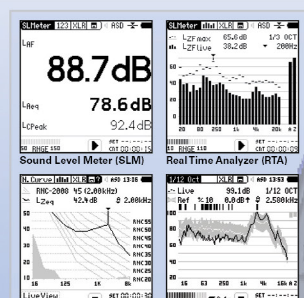

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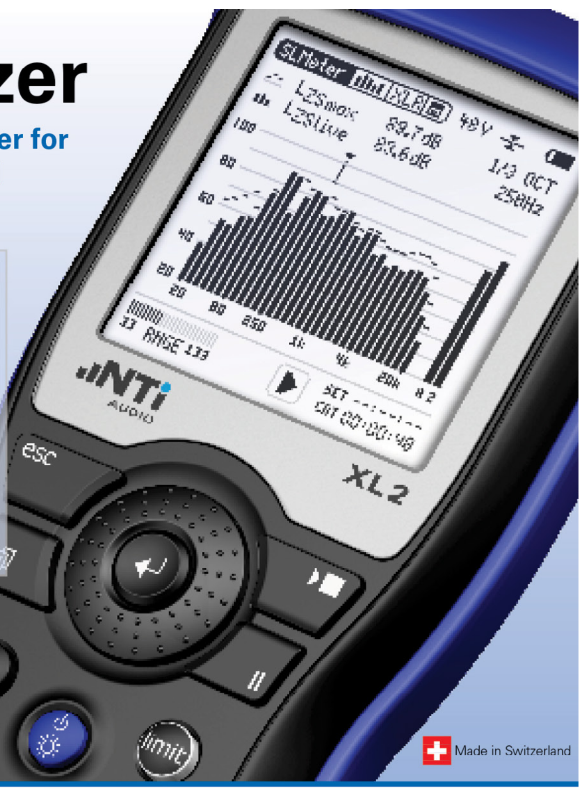

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The ASA at the International Science and Engineering Fair

Laurie Heller

Figure 1. ***Top:*** *Wanjia Fu.* ***Center, left to right:*** *Eugene Choi, Irfan Nafi, and Raffu Khondaker,* ***Bottom, left to right:*** *Govardhan Poondi, John Rho, and Chinmayi Ramasubramanian.*

The International Science and Engineering Fair (ISEF; see bit.ly/3ykRalG) is a program of the Society for Science and the Public and is the world's largest international precollege science competition. This year, the Regeneron-sponsored ISEF took place virtually from May 3 to May 20, 2021. As a Special Award Organization (SAO), the Acoustical Society of America (ASA) recognizes and awards acoustics-related projects. The ASA judging team was led by Laurie Heller (Carnegie Mellon University, Pittsburgh, Pennsylvania) and included Inder Makin (A. T. Still University, Mesa, Arizona), Xin Luo (Arizona State University, Tempe, Arizona), and Thomas Kaufman (Otojoy, Scottsdale, Arizona). For more information about ISEF and the role of the ASA, please see the essay by Makin [*Acoustics Today* 14(4), 66-68; available at ow.ly/fLFg50ujsrC).].

The judges selected the 35 top projects with acoustics relevance from the 1,800 total submissions. Based on reading the students' poster boards and documentation, the judges selected 13 projects for student interviews. Interviews were conducted virtually; the judges deliberated to narrow it down to four awardees. In addition to cash prizes, these awardees were also invited to attend Acoustics in Focus.

The First Award of $1,500 in cash (plus $200 for the school and $500 for the mentor) went to Wanjia Fu (Shanghai Foreign Language School, Shanghai, China) for research into the acoustics and perception of unwanted noise when playing the Erhu, a challenging Chinese musical instrument. The Second Award of $1,000 (plus $100 for the school and $250 for the mentor) went to Eugene Choi, Irfan Nafi, and Raffu Khondaker (Thomas Jefferson High School for Science and Technology, Alexandria, Virginia) for their sensory substitution prototype that integrated acoustics, beamforming, vibration, and sound classification. The Third Award of $600 (plus $150 for the mentor) went to John Rho and Govardhan Poondi (Plano West Senior High School, Plano, Texas) for a device that utilizes EEG signals to select and enhance an attended speech stream. Honorable Mention went to Chinmayi Ramasubramanian [Sri Kumaran Children's Home (CBSE), Bangalore, India] for classifying the severity of Covid-19 via breath sounds with machine learning. To read the Awardee's abstracts, please visit the Explore Sound website at exploresound.org/isef-asa-winners. See **Figure 1** for a picture of the winners.

The judges look forward to seeing future accomplishments from the many talented youth who participated in the Regeneron ISEF!

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Disability Invisibility in Academia: How to Support Disabled People in Research and Beyond

Ira Kraemer and Elizabeth Kolberg

Imagine that you have found the ideal new member for your lab with the perfect skills and background to contribute. Best of all, the individual has accepted your offer to join the lab! After you share the offer letter, the Office of Disability Services contacts you about the new lab member. Do you have any idea what accommodations this person might need? Have you fostered a spirit of inclusion, leading to this person disclosing their disability to you?

What qualifies as a disability? The United States Americans with Disabilities Act (ADA) defines disability as "a person who has a physical or mental impairment that substantially limits one or more major life activity." However, because this definition is a matter of United States law, it means that the definition is a legal one that includes individuals with any record of a disability and individuals who do not openly identify as having a disability even if they meet these criteria.

Many disabled individuals feel that there is a stigma associated with identifying as disabled. Throughout most of their lifetime, disabled people are implicitly and explicitly told by society that having a disability is a bad thing. Society tells children not to stare and not to ask about differences. Disabled people are called "differently abled" or "people with special needs" instead of people with disabilities (Poe, 2018). This is often due to the stigma of having a disability.

Aside from people with very noticeable physical disabilities, disability has been a relatively unacknowledged identity until recently. Within diversity initiatives at most universities, disability is not considered an important part of a diverse academic system or important to academia. There are many disabled scientists working in academia who are leaders and contribute to highly important findings within their field. However, many disabled people hide their disability out of fear of judgment and stigma. In this essay, we explain why fostering an accessible environment can make a huge difference in the lives of any disabled person in academia. And, although this article focuses on the academic setting, many of the issues discussed are also relevant to settings outside of the academic world. Indeed, accessibility in general is important for creating a welcoming environment for disabled people in any profession. Specific accessibility needs and solutions will differ, but there is a universal need to be accommodating to anyone with a disability.

How to Support Disabled Individuals in Academia

Disability is rarely considered by funding agencies or within demographic surveys in academia and rarely analyzed with intersectional identities such as race, class, religion, gender identity, and sexual orientation. Individuals who openly identify as having a disability are often underrepresented in academia (Brown and Leigh, 2018; Swenor et al., 2020). Ableism (discrimination against disabled individuals), stigmas (cultural biases), and inaccessibility in academia may be several reasons that students, staff, and faculty often choose to hide their disabilities (Brown and Leigh, 2018; Marks and Bayer, 2019; Ramírez, 2019). Abled people (people without disabilities) need to consider how inaccessibility, lack of understanding, perpetuation of ableist language in research, and lack of openly disabled representation can harbor an unwelcoming and even hostile environment to anyone in academia with a disability.

To create a welcoming environment for disabled people, abled people need to be willing to learn from people with disabilities themselves, acknowledge when they are uninformed about a topic, and reach out for resources about how to implement accessibility at their university or other workplace (Burgstahler, 2012).

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Here are some of the questions that each person needs to ask. Do you know how to get accommodations at your university or workplace? Do you know who to contact, and what you would have to do? Do you know what accommodations are offered? Is your course, lab, and/or building accessible to those with disabilities already and if not, can it be made accessible?

Types of Accommodations

Accommodations for people with disabilities can look drastically different depending on the person and their needs. These are just a handful of potential accommodations for disabled people: (1) flexible work hours; (2) later start times for a sleep disorder; (3) physical lab accessibility for sitting down/mobility aids; (4) a standing desk for back pain; (5) ergonomic lab equipment for fine motor disabilities; (6) captions in Zoom meetings and recorded lectures; (7) providing screen reader accessible material and alt-text in images; (8) moving a desk to a different part of the room due to light sensitivity; (9) adding dampers to the side of a door that slams for hyperacusis; and (10) installing flashing alarms for people who are deaf or hard of hearing (Adler et al., 2019) (for more examples, see askjan.org/a-to-z.cfm). Many people in academia may have multiple disabilities, and sometimes, even conflicting accommodation needs exist within the same person, leading to changing accommodations based on fluctuating needs for dynamic disabilities.

Most disability services do not focus on making research accessible but rather on classrooms. And even this can be hard for disabled students to acquire without confusion or judgment from professors. The issues mentioned may contribute to disabled students, faculty, and staff getting left behind, dropping out, or deciding once they graduate to leave academia completely (Marks and Bayer, 2019). There are systemic barriers to being a disabled person in academia, and these often go unacknowledged. However, by becoming aware of accessibility issues and including disabled people in these conversations, everyone can be part of a large positive change and foster better inclusion within the scientific community.

How to Implement Accessibility

What Does Physical Disability "Look" Like?

People who have physical disabilities may use a wheelchair, crutches, a cane, braces, or orthotics or not use any mobility aids at all. Some people may use some mobility aids or none depending on the day, as most disabled people have dynamic disabilities.

IK: "I am a relatively 'young' looking person who often does not use mobility aids but still needs to take the elevator due to my physical/pain disabilities and cannot walk long distances. People almost never assume I have a physical disability unless I use a mobility aid, which they then assume is a temporary injury, and people stop me to ask me invasive questions such as 'What happened?' while I just want to go about my day."

ERK: "Most people are surprised to learn that I receive disability accommodations because I have a doctorate in audiology. This could suggest that those who have disabilities are not able to successfully achieve such pursuits, which is inaccurate and why I think it is important to advocate for those who have disabilities."

The point of the first quote is that some people use the elevator instead of taking the stairs because they have physical disabilities that cause fatigue, pain, or limited motion without using mobility aids, and many people will not disclose this need to others. Taking the elevator may be seen as "lazy" to people who are not aware of that person's disability. It is important not to assume that everyone you meet does not have a disability. Assumptions of ability often occur based on biases such as age, race, and gender. Think about the times you have made a judgment about someone else. Could those judgments be related to a person's disability?

Physical Accessibility

Unfortunately, most labs even today are not created with accessibility in mind. Accessibility in research specifically has rarely been explored, especially in regard to diversity efforts. It is important, especially for people in leadership in academia, to consider that a student, staff, or faculty member may have a disability and to plan accordingly, regardless of whether someone has disclosed or not.

It's important for nondisabled administrators, faculty, and even students to understand that there are many barriers for disabled people in the academic environment. Often, these barriers begin with not being able to physically enter and maneuver a space, whether it is a building, research lab, or field research site, such as a ship. A graduate student can only perform research in labs that they can access.

General Mobility Accessibility

As a faculty member, when building a new lab, it is important to design in a universally accessible way, especially for wheelchair users. This accessibility provides many more benefits than just for that one potential future person who uses a wheelchair. Anyone can acquire a physical disability at any age, and that person might be doing research in this particular lab now or in the future.

Having an accommodating environment is inclusive of anyone who needs access to a lab, including collaborators, lab assistants, or any staff or student who needs access to the space or tools within your lab space and yes, even for the faculty member. Many academics today do research even into their 80s. Many older people develop disabilities as part of the aging process, whether this means arthritis, eyesight disabilities, or needing to sit due to an inability to stand for extended periods of time.

Having to maneuver through an inaccessible lab space as a disabled person can be painful and even lead to acquiring more disabilities by extending the limits of one's body. By designing every lab space with accessibility in mind, disabled people will be able to access this space and be included in research without being in pain or sacrificing more of their long-term physical health.

By ensuring that a lab is physically accessible, especially for wheelchair users, it is important to include bench space at chair height, with leg room underneath wide enough for a wheelchair, leg room under the fume hood rather than safety cabinets below, a lowered sink with leg room for washing labware, a separate lower handle for the emergency shower, and an extension pipe for the eyewash to incorporate leg room (Duerstock, 2014). It is also important to design the space with the width of a wheelchair in mind, so that the wheelchair users can maneuver easily through the lab (Duerstock, 2014). Providing physical accessibility will also help anyone who needs to sit in a chair rather than stand when doing lab work and/or anyone who uses a cane, crutches, or rollator to move around.

Physical Accessibility Outside the Lab

Physical accessibility extends outside the lab as well. Here are some questions to consider when assessing the physical accessibility of a research lab or classroom. Is there an automated door to the bathroom on the lab floor? Is the accessible stall in the bathroom actually large enough for a wheelchair user to turn around and close the door? Can a wheelchair user reach the soap dispenser and sink? Would a wheelchair user be able to get to the lab in your building and through the doors? Are there any stairs or steps within your lab space? Are all emergency exits accessible to individuals who use other types of mobility aids (e.g., use of windows and ladders for underground rooms)?

IK: "As someone who has invisible disabilities, I often notice when people are unaware of accessibility. Does the graduate program have a walking tour for incoming students and is that walking tour accessible? Are there accommodations or alternate routes available for tours? Does the lab pride itself on taking a hike every week, although this activity is not something in which every disabled person can participate?"

Although many abled people may consider these things to be a minor inconvenience, these are warning signs to disabled people that they have not been considered during the recruiting process and that they will likely face more barriers to accessibility in the future in that program.

Classrooms, Learning, and Accessibility

Most disability services in academia focus on classrooms. However, even accommodations in classrooms can be hard for disabled students to acquire without confusion or judgment from professors. Professors should not ask a student to disclose their disability when meeting about accommodations because this can make a student feel like they have to "prove" their disability.

Accessibility for Teaching

Another barrier to accessibility includes lack of captions for Zoom meetings. Software and course materials should be checked for accessibility with screen readers for people who are blind or have low vision. For people who have difficulty speaking due to anxiety, stuttering, or another disability, text answers should be accepted as part of participation. Consider a person's communication preferences such as e-mailing, meeting by Zoom, in-person appointments, or phoning. It is important to remember that not everyone will disclose their disability to you, and what you may assume are preferences may actually be someone else's accessibility needs.

If a faculty member is unsure on how to make a course the accessible, it is important to seek out accessibility training from your university's accessibility resource center and/or get help from an IT department to help make the course accessible (Burgstahler, 2012). There are also many resources outside the university written by disabled people themselves that provide helpful information on how to mentor disabled students.

Conclusion

In conclusion, accessibility in research, classrooms, field sites (Healey et al., 2015), and many more is crucial to the participation of students, staff, and faculty with disabilities. Disabled people have the knowledge, passion, and creativity to thrive in academia (Marks and Bayer, 2019). However, inaccessibility and the stigma of disability in society even today is a large barrier to being able to do so. Please consider openly welcoming disabled people, advocating for them, accommodating them, and believing in their needs and talents. When in doubt, ask the disabled person directly about what accommodations they need. It's never too late to be more inclusive.

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ASA WEBINARS

The Acoustical Society of America has established a Webinar Series with the goal to provide ongoing learning opportunities and engagement in acoustics by ASA members and nonmembers throughout the year, as a supplement to content presented at bi-annual ASA meetings.

ASA Webinars will be scheduled monthly and will include speakers on topics of interest to the general ASA membership and the broader acoustics community, including acoustical sciences, applications of acoustics, and careers in acoustics.

Find a schedule of upcoming webinars and videos of past webinars at **acousticalsociety.org/asa-webinar-series**

Administrative Committee Report: Committee on Medals and Awards

Brenda L. Lonsbury-Martin

The Committee on Medals and Awards is charged with recommending to the Executive Council candidates and citations for the awards of the Society, with the exception of the ASA Science Communication Awards and certain other awards as may, from time to time, be assigned by the Executive Council to the Committee on Prizes and Special Fellowships. The recipients of each of these awards and the award citations shall be determined by the Executive Council. The Committee is further charged with recommending to the Executive Council nominees and citations for the A.B. Wood Medal, and where appropriate for awards by other organizations, and with forwarding information on non-Society awards to the appropriate Technical Committee Chairs for possible action or advice.

The Committee on Medals and Awards, unofficially known as the MAC, is a standing committee of the Acoustical Society of America (ASA). The MAC is composed of a chair and as many other members as there are Technical Committees (TCs) of the Society, all of whom are ASA Fellows. The current membership consists of 13 members and the chair (who does not represent a TC). The terms of the chair and MAC members are limited as noted on the ASA website (see acousticalsociety.org/procedures#awards). It is important to appreciate that these positions are not appointed forever and turn over regularly. The chair's major responsibilities are coordinating MAC activities; making certain that all work is completed on time and in good order; communicating with ASA Melville Office, which provides support to the Committee's work; and reporting the Committee's recommendations to the Executive Council (EC).

Each regular member of the Committee is an ex officio member of the TC represented by its member. MAC members have two important roles in that they are responsible for representing their own fields by suggesting candidates for awards and for assisting TC subcommittees in preparing nomination dossiers. However, when voting, MAC members are responsible for reviewing all nominations and supporting the best candidates regardless of the technical field involved. Additional responsibilities are that members are expected to attend both Spring and Fall ASA meetings and to spend a significant amount of time related to the nomination and dossier preparations of their TC.

Annually, the Society recognizes outstanding achievements in acoustics with several honors, which are reviewed on ASA website (see bit.ly/3m1eK1e). Here are noted details concerning the purpose of each award or honor, the eligibility requirements, and a record of prior recipients. The presentations of these awards are divided between meetings so that at the Fall meetings, nominations for the Gold Medal, the R. Bruce Lindsay Award, and the Helmholtz-Rayleigh Interdisciplinary Silver Medal are reviewed. The last medal is a cross-specialty award that requires each nomination be supported by two or more TCs. Nominations for the Technical Area Awards, including named awards and Silver Medals, are evaluated at the Spring meetings.

The Technical Area Awards recognize individuals, who can be nonmembers, for their contributions to the advancement of science, engineering, or human welfare through the application of acoustic principles or through research accomplishments in acoustics. The eligibility of a TC to award a Silver Medal is determined each year based on the size of the TC, represented by the number of ASA members who choose the TC as their primary interest in acoustics.

Furthermore, the MAC reviews other nominations for ASA awards, including the Distinguished Service Citation that is awarded to a present or former member of the Society in recognition of outstanding service to the ASA and the Honorary Fellowship for a member or nonmember who has attained eminence in acoustics or who has rendered outstanding service to acoustics. The MAC also recommends

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US or Canadian ASA nominees, whose work is associated with the sea, for the United Kingdom Institute of Acoustics (IOA) A. B. Wood Medal, which is awarded for "distinguished contributions to the application of underwater acoustics." Occasionally, the MAC recommends the preparation of nominations for other non-ASA awards such as the US President's National Medal of Science.

Nominating procedures vary for different awards. For some honors such as the Gold Medal, R. Bruce Lindsay Award, and A. B. Wood Medal, MAC members have the sole responsibility for generating lists of candidates. In contrast, nominees for the Technical Area Awards are proposed by the pertinent TCs, many of which have appointed subcommittees to assume responsibility for this task. For the Distinguished Service Citation and the Honorary Fellowship, any member or Fellow of the Society may nominate candidates on forms available from the ASA Melville Office (see asa@acousticalsociety.org). A guideline for preparing the forms and documents for nominating and seconding letters for any award of the Society, along with deadlines, is available from the ASA Melville Office.

ASA members who are interested in suggesting candidates for any Society award should contact the chair or the appropriate member of the MAC for information on how to prepare and submit their recommendations. It is important that specific guidelines be followed because dossiers are the bases on which the MAC conducts its voting. If all the dossiers are arranged similarly and address similar topics, fair and equal treatment of all the candidates is facilitated. Voting on nominees, which is conducted in secret, utilizes a ranking procedure, and this ranking of candidates is reported to the EC, which typically bestows an award on the candidate who received the top ranking by the Committee. Although voting deliberations can be intense, they are always interesting and scholarly. Hopefully, the information presented here on MAC operations and procedures will encourage ASA members to seek out relevant information that will assist them in nominating their deserving colleagues for the many awards and honors of the Society.

One only needs to examine the list of ASA award recipients to appreciate the important contributions made by acousticians to humanity (see bit.ly/3m1eK1e). The early awardees included pioneers from every area of acoustics. These were followed by acoustical scientists and practitioners who crafted the acoustics of some of the world's outstanding concert halls, contributed to the development of cochlear implants, devices, and methods for the treatment of tumors and diseases, devised a microphone that is a component in cell phones and other devices, and made significant advancements in virtually every area in the acoustics field. It is easy to understand why MAC members have consistently expressed the sentiment that they find their service in identifying individuals who are deserving of the Society's medals and awards personally gratifying.

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Vantage: A Report on the Acoustical Society Foundation Fund

James H. Miller

This is the second annual "Vantage" report in which we hope to provide Acoustical Society of America (ASA) members with an overall view of where the Acoustical Society Foundation Fund (hereinafter referred to as the Fund) has been and also where the Fund is headed (see bit.ly/3we52wg}. The feedback on last year's report (see bit.ly/3u4jjdz) was positive, and I hope this report will also be well received.

I am providing information about the Acoustical Society Foundation Board (hereinafter referred to as the Board), the financial performance of the Fund, expenditures, the support provided to the new Summer Undergraduate Research or Internship Experience in Acoustics (SUREIA), the impact of the Covid-19 pandemic on the Fund, and a discussion on how members can support the Fund's mission. I conclude with a brief description of how to donate to the Fund.

The Acoustical Society Foundation Board

The Board supports the mission of the ASA by developing financial resources for strategic initiatives and special purposes. With the generosity of its many donors, the Fund provides awards, prizes, fellowships, and scholarships and supports other types of programs. The Board is made up of dedicated, hardworking volunteers, currently including Anthony Atchley, Freddie Bell-Berti, David Feit, Ron Freiheit, John Hildebrand, Ed Okorn, Rich Peppin, ASA Treasurer Judy Dubno as an ex officio member, and me as Board chair.

The Board makes recommendations to the ASA Executive Council about award levels for each activity the Fund supports. These activities are listed in **Table 1**. The Board also solicits funds across and outside the ASA and works with donors who wish to set up new programs and make contributions to existing ones.

Financial Performance in 2020

Contributions in 2020 to the Fund from members and friends of the ASA totaled $70,770. In addition, gains from investments, interest, and dividends totaled $1,363,223. Expenses for the Fund were $286,323, which mostly included the awards, prizes, fellowships, and scholarships, and the details of these expenses are covered **Fund Expenditures in 2020 in Support of the ASA**. Net assets in the Fund at the end of 2020 were $11,424,510 compared with $10,462,143 at the end of 2019, an increase of 11%.

Fund Expenditures in 2020 in Support of the ASA

In 2020, the Fund was very active in supporting the many activities of the Society. Awards, prizes, fellowships, and scholarships shown in **Table 1** were supported by the Fund in the amount of $240,945. You can find details of each of these activities at bit.ly/3we52wg. And, as an aside, after reviewing these activities, think about any for which you or your students might apply.

The support for student travel to ASA meetings through the Student Transportation Fund is one of the most important activities of the Fund. The experience and

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Table 1. *Awards, prizes, fellowships and scholarships supported by the Fund*

Acoustical Oceanography Student Travel Award
ASA Early Career Leadership Fellowship
Frank and Virginia Winker Memorial Scholarship for Graduate Study in Acoustics
Frederick V. Hunt Postdoctoral Research Fellowship in Acoustics
James E. West Minority Fellowship
Leo and Gabriella Beranek Scholarship in Architectural Acoustics and Noise Control
Medwin Prize in Acoustical Oceanography
Pioneers in Underwater Acoustics Medal
R. Bruce Lindsay Award
Raymond H. Stetson Scholarship in Phonetics and Speech Science
Robert Bradford Newman Student Award
Robert J. Urick Prize for Best *JASA* Article by a Student in Ocean Acoustics
Robert W. Young Award for Undergraduate Student Research in Acoustics
Rossing Prize in Acoustics Education
Royster Student Scholarship Award
Student Transportation Awards
Theodore John Schultz Grant for Advancement of Acoustical Education
Trent-Crede Medal
von Békésy Medal
Wallace Clement Sabine Medal
Wenger Prize for the Student Design Competitions
William and Christine Hartmann Prize in Auditory Neuroscience

connections made by students with each other and with more senior members can change lives. The future of the Society is our students, and this investment in their careers will pay off for decades. With ASA meetings converted to virtual events, no awards from the Student Transportation Fund were made in 2020 but will resume with the Fall 2021 meeting in Seattle, Washington.

The Fund has two distinct types of accounts: those with donor restrictions (41%) and those without donor restrictions (59%). As the names imply, these categories inform us how the ASA can spend the monies along with spending rules approved by the Executive Council. As an example, one of the accounts with donor restrictions is the Frank and Virginia Winker Fund, which was created by ASA member Doug Winker to establish and support the Frank and Virginia Winker Memorial Scholarship for Graduate Study in Acoustics. One of the Funds without donor restrictions is the Operating Fund, which supports many activities and all administrative expenses and had $2,969,356 at the end of 2020 compared with $2,685,843 at the end of 2019, an increase of 10.6%.

Summer Undergraduate Research or Internship Experience in Acoustics

The ASA has established a plan to enhance diversity, equity, and inclusion in the field of acoustics (see the *Acoustic Today* essay by Porter; available at bit.ly/3fvx2F7). As part of this plan, the ASA has created a 12-week paid, summer undergraduate research program for underrepresented minority students interested in acoustics from around the country. This new program will emphasize training, mentoring, research, and preparing students for graduate studies and careers in acoustics. The Fund supported SURIEA with $30,000 in addition to support from the ASA; American Institute of Physics; National Council of Acoustical Consultants; Threshold Acoustics, LLC; and other donors. As I write this report, SURIEA received 170 applications for support for research in 2021, but funds were available to fully support a maximum of 12 internships. Unrestricted donations to the Fund will help assure that SURIEA extends beyond 2021 and allows the ASA to increase the number of supported students underrepresented in acoustics.

Covid-19 Impact on the Foundation Fund

As I write this report, the world is still dealing with the Covid-19 pandemic. However, with the excellent leadership of the ASA Investments Committee chaired by Dave Adams (which is charged with reviewing the financial investments of the ASA including those of the Fund) and with advice from the Society's investment advisors, the financial impact of the pandemic has been mitigated. The emphasis on long-term growth has allowed the Fund to weather several storms of the last decades, and we are looking forward to continued gains over the next months and years.

What Do You Want the Fund to Do?

The Fund does a lot of good in supporting the ASA mission. But we can do more. If you have an idea about where the Fund can make a difference, let's start a conversation. For example,

- Do you feel strongly about acoustics education?
- Do you want to make a difference for early-career acousticians?
- Do want to support the ASA commitment to increase racial diversity, equity, and inclusivity in acoustics?
- Do you think emerging research in one of our technical areas needs a kick start?
- Are you excited about standards?
- Do you want to recognize a pioneer in acoustics or an outstanding teacher/mentor by creating a fund and naming it in their honor?

Reach out to me at miller@uri.edu. I would enjoy hearing your ideas and discussing how we might implement them.

Ways to Give

Donors have a number of options for giving to the Fund and they include

- Outright gifts of cash,
- Publicly traded securities,
- Real estate,
- Tangible personal property,
- Life insurance,
- Bequests,
- Pooled income fund,
- Charitable trusts, and
- Charitable annuities.

For more information on these giving options, see bit.ly/3wcViCG.

One of the options listed is a charitable trust. In my 2020 report, I discussed charitable remainder trusts. This year, I focus on revocable trusts. A revocable trust is a trust in which provisions can be changed or canceled by the grantor or the originator of the trust. During the life of the trust, income earned is received by the grantor, and only after death do the assets transfer to the beneficiaries of the trust (in this case, the ASA). There are a number of advantages to revocable trusts that include continuity of management during disability, flexibility, avoidance of probate, and immediate availability of funds.

Let me know if you would like to learn more about using one of these options to donate to the Fund. Or just visit the Fund's website (available at bit.ly/3we52wg) and click Donate at the bottom. This will take you to the Fund's web page where you can use a credit card (or other means) to donate to the Campaign for Early Career Leadership, the Student Transportation Fund, or make an unrestricted donation to the Fund (all are tax deductible).

Thanks for taking the time to read Vantage, our annual summary of the Acoustical Society Foundation Fund.

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ASA Publications now has a podcast!

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My Acoustics Library

Neil A. Shaw

Some people collect hubcaps. Some people collect porcelain. From the time of my college days to the present, I have collected books, and how I started collecting is serendipity. For some reason, I held onto the texts (and notebooks) from my days at Cooper Union, New York, NY, and the University of California, Los Angeles (UCLA), and would, occasionally, acquire a new or used book for the collection. One day in the early 1980s, I was taking care of Mark R. Gander's house, VP of Marketing for JBL Professional at the time. I noticed he had a couple of shelves filled with acoustics and audio books. I took a yellow pad and started to write down some of the titles; after noting about eight or nine titles, I wrote "All of them." After this revelation, trips to used bookstores became routine.

Now, the time to find a new home for my library is nigh, so I contacted *Acoustic Today* (*AT*) to place a classified ad. To make it interesting, the ad was in "web" Latin in the Spring 2021 issue (available at bit.ly/32ejMOR).

At its peak, my library had over 1,600 books from the 1820s to the present. After placing the *AT* advertisement, Arthur Popper, the editor of *AT*, said he thought that members of the Acoustical Society of America (ASA), and perhaps an institution, would be interested in knowing about the content of the library because there are so many historic and classic books on acoustics and related topics. He asked if I would write an essay about the library and how there came to be so many texts: what I collected, why, some stories of a few, and a picture or two (see **Figure 1**) that shows a portion of the library (note that all but the top shelves are doubled stacked).

Figure 1. *Part of the library discussed in this essay.*

So, this informal essay is an attempt to address the editor's curiosity. Throughout my career, I traveled quite a bit, and a nice way to spend some time while on the road was to check out the used bookstores in the various and sundry cities and towns that I visited. With my interests in acoustics, audio, perception, mathematics, physics, and more, used bookstores offered an education, in a sometimes-musty environment. The 1980s were a time when many engineers and academics who practiced during the Second World War and during the Cold War were retiring and "de-acquiring" their book collections, and I was able to add quite a few classic books to my own library during that time.

During the trips, I would go to Brattle Books in Boston, Massachusetts (see brattlebookshop.com) and The Strand in New York City (see strandbooks.com) as well as to stores in many other cities. I found my first copy of Wallace Clement Sabine's *Collected Papers on Acoustics* (1922) at Book City in Burbank, California (a review by Egan [1988] of the Peninsula Publishing reprint edition can be found at bit.ly/3ey1W01); Alfred Ghirardi's copy of Greenlees' *The Amplification and Distribution of Sound* (1939; see his brief discussion of the delicate matter of how to tell people they do not know how to use a microphone on p. 194; some things never change!) from Stevens Book Shop in Raleigh, North Carolina (via mail); one book by Dayton Clarence Miller from Philip Morse's library was found at Brattle Books; and another of Miller's books was acquired due to my being the ASA Los Angeles Chapter representative. There were other finds and surprises, but, sadly, these serendipitous moments are mostly gone.

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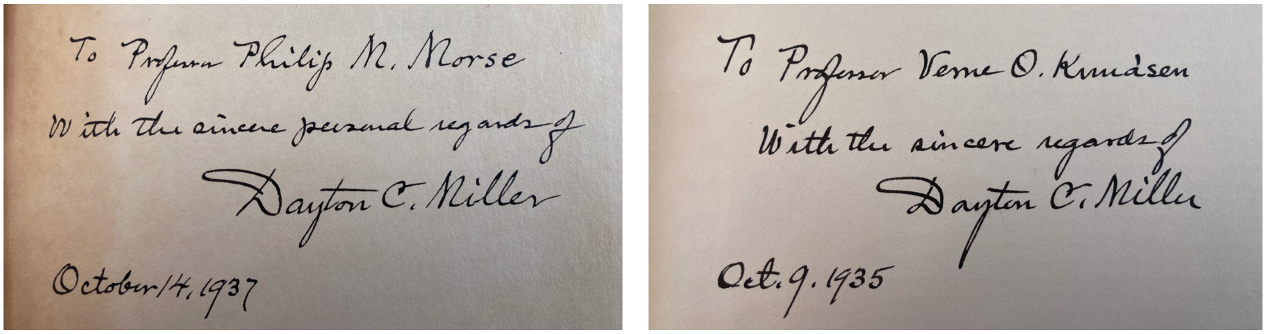

Figure 2. *Dedications in two books (see text for details).*

Mark, Jesse Klapholz (a friend in Philadelphia, Pennsylvania, who also had a large collection), and I were always on the hunt for the Holy Grail (at least for electroacousticians): Harry Olson's *Acoustical Engineering* (1957). I obtained my first copy from Stevens Book Shop. We also jointly prepared a paper about acoustics and books (Shaw et al., 1994).

Some of the texts from my library are often cited in contemporary papers and to find and read them (not always from cover to cover) was illuminating, instructional, and, yes, sometimes inspirational, especially when I later met and got to know the authors at ASA and Audio Engineering Society (AES) meetings and in more informal settings. Many works in the collection are by colleagues too numerous to name due to space constraints.

Among some others I got to "know," I have several editions of *Fundamentals of Acoustics* by Kinsler and Frey (1962), the textbook I used in Richard Stern's UCLA Engineering Acoustics 153A class; *Noise and Vibration Control* by Beranek (1971), the textbook for William C. Meecham's (a founder of the Institute of Noise Control Engineering) Acoustics 153C class; and *Theoretical Acoustics* by Morse and Ingard (1968), the text for Meecham's Acoustics 253A class; and books by Lamb (1965) and Knudsen (Knudsen, 1932; Knudsen and Harris, 1954).

The D. Van Nostrand Bell Telephone Laboratories series in my library includes texts by Bode (1945), Mason (1942), and Schelkunoff (1943), all of whom are authors whose work and texts are foundational. These communication theory texts are seminal works in their field and even include acoustics. There is Fletcher's *Speech and Hearing* (1929) and *Speech and Hearing in Communication* (1953). McGraw Hill had its own collection that included seminal texts in electrical engineering and acoustics (including one by Beranek, 1954).

In electroacoustics, my library includes works by Hunt (1954), Olson (1957), Leach (1998), Rossi (1988), Kleiner (2013), and Eargle (1981, 1 of his 10 books; more at bit.ly/3uA2etb).

My interest in acoustics books led to some work for *The Journal of the Acoustical Society of America* (*JASA*) and the *Journal of the Audio Engineering Society* (*JAES*), including book reviews (Shaw, 2001), some time with the Books+ Committee of the ASA, and presently as the *JAES* associate editor for book reviews. My 35 years as a book reviewer added many texts to the library.

Beranek was the author of many books that I was introduced to in some acoustics courses at UCLA. I met Beranek at ASA meetings and had a collegial relationship with him and was honored to present an invited paper about his books for the special session honoring him at the Spring 2004 ASA meeting (Shaw, 2004).

On a 1986 visit to Brattle Books, I noticed a thin volume, *Sound Waves: Their Shape and Speed* (Miller, 1937). When I opened it, I saw an inscription (see **Figure 2**, *left*). Well, this was astounding! I knew that Morse (1976) was alive and I wrote to him, noting that the text may have been "borrowed." He affirmed it was, and I returned the book to him. A short time later, I received a signed copy of the ASA reprint of *Vibration and Sound* (Morse, 1936). I wrote to Morse again in late August to thank him and to let him know that I was going to be in Boston. I received a letter from his attorney informing me that Morse had passed away. So when I was in Boston, I visited the attorney and told her the tale of *Sound*

Waves: Their Shape and Speed. In February 1987, I received a package with *Sound Waves: Their Shape and Speed* and a letter noting that Morse's daughter had searched the last of the unopened boxes of books "and has found the enclosed book which we gladly return to you."

In 2004, I received a call from James Knudsen, one of Knudsen's grandchildren, who found me on the ASA Regional Chapter web page, informing me that the family was donating Knudsen's home to UCLA. He assumed I did not know his grandfather. I replied that not only did I know of his grandfather but had also taken classes in the building named after him. So I went over to the house and found many boxes of personal papers, bibles, awards, medals, letters, and files from his time at UCLA as well as some boxes of books. A report of this can be found in *Acoustics Today* (Shaw, 2011). Anyway, the upshot is that the UCLA Archives accepted all material except the books. These resided in my wine cellar for many years until Steven Garrett from Penn State University, University Park, came to visit; we were graduate students together at UCLA and have kept in touch over the years. He suggested that Knudsen's books come to Penn State and join those of Harris (1979), the coauthor of *Acoustical Designing in Architecture* (Knudsen and Harris 1954). I informed the family of this; they agreed and added that I could select one book to keep. I selected a thin volume, *Anecdotal History of the Science of Sound* (Miller, 1935). The inscription is seen in **Figure 2**, *right*.

I could go on about how the library and reviews led to my proofreading a contemporary text on electroacoustics (I learned a lot of things that I thought I knew) and the preface to a reprint edition of a classic two-volume room acoustics text, my commemorating a mentor's books at his memorial, and "live" presentations as well as more tales from musty places, but I have more than run out of space. And, yes, the library has found a home; the university will be announcing details later this year.

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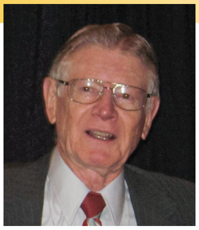
Obituary
David Theobald Blackstock, 1930–2021



David Theobald Blackstock died on April 30, 2021, in Austin, Texas, where he was born, raised, and spent most of his life. During his lifetime, he became known internationally as an eminent scholar in acoustics, a mentor to both junior and senior acousticians, and an extraordinarily kind man.

After receiving BS and MS degrees in physics from the University of Texas at Austin (UT), David served two years in the US Air Force, then joined F. V. Hunt's group at Harvard University, Cambridge, Massachusetts, and earned a PhD in applied physics in 1960. After three years at General Dynamics and seven years as an associate professor of electrical engineering at the University of Rochester, Rochester, New York, David returned permanently to UT in 1970 to join its Applied Research Laboratories, and in 1987, he became professor of mechanical engineering.

David's most important contributions were in nonlinear acoustics, which involves sound so intense that waveforms distort as they propagate, such as sonic booms. Seminal work by David in the 1960s, and independently by R. V. Khokhlov in the former Soviet Union, established a foundation for nonlinear acoustics that is still employed today. Among other fundamental contributions, David developed a general solution revealing a limit for the amplitude of a sound wave no matter how powerful the source is.

Subsequently, David, along with his graduate students, performed research that combined theoretical, experimental, and computational approaches to a range of problems in acoustics. Applications included underwater sonar, jet noise, sonic booms, mitigation of road noise, and biomedical ultrasound. Since the late 1990s, one of David's greatest pleasures was acting as a scientific advisor for a National Institutes of Health grant for breaking kidney stones with shock waves. Their program review in January 2020 was the last conference David attended.

David's teaching and graduate student supervision are legendary. He could succinctly and lucidly describe complex phenomena to students having a range of abilities. He was especially known for precise grading, and he would correct grammar even on homework assignments. The seemingly unending corrections in his signature green ink were a crucial element of how he taught students to both think logically about problems and present solutions clearly. He also had a keen drive to build a sense of community, which could be as simple as playing lunchtime soccer with students or as formal as organizing lunch dates for students to meet with senior researchers at acoustics meetings.

David's professional home was the Acoustical Society of America (ASA). He served as its vice president and president and was a recipient of its Gold Medal, Silver Medal in Physical Acoustics, and Rossing Prize in Acoustics Education. He was also chair of the International Commission for Acoustics, essentially a "united nations" for acoustical societies. In 1992, he was elected to the National Academy of Engineering.

Despite all the international recognition David received, he felt most honored by the ASA Student Council renaming its mentoring award after him in 2019, now called the Student Council David T. Blackstock Mentor Award. His reaction spoke volumes for his humility and the importance he placed on helping young acousticians achieve their dreams.

David was preceded in death by his wife, Marjorie, in December 2019. They are survived by their four children, Silas, Susan, Stephen, and Peter; six grandchildren; and five great-grandchildren.

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Obituary
Irwin Pollack, 1925–2021

Irwin Pollack, professor emeritus of psychology at the University of Michigan, died in Ann Arbor, Michigan, on January 23, 2021. During a career spanning more than 50 years, first as a civilian researcher in the US Air Force from 1949 to 1963 and then as a professor of psychology at Michigan from 1963 until his retirement in 1995, Irwin was a creative and highly productive research scientist who worked on a wide range of problems in sensory psychology, hearing, speech perception, and human information processing.

Irwin was born in Bridgeport, Connecticut, on April 10, 1925. He graduated from the University of Florida, Gainesville, in 1945 and completed his PhD degree in experimental psychology at Harvard University, Cambridge, Massachusetts, in 1949. Irwin was a Fellow of the Acoustical Society of America (ASA) and was internationally known for his pioneering work on hearing, loudness, pitch, and speech intelligibility.

Irwin initially worked on applied problems related to auditory information processing, especially hearing in noise and speech intelligibility under adverse listening conditions. Much of the research he did in the Air Force was published in *The Journal of the Acoustical Society of America* (*JASA*) in the 1950s and is considered to contain seminal findings in speech and hearing sciences and human factors. Several studies were ahead of the field, anticipating future applications in everyday, real-world environments. For example, Sumby and Pollack (1954) demonstrated that seeing the face of the talker provides an improvement in the signal-to-noise ratio (SNR) equivalent to a 15 dB gain in speech intelligibility in noise. For many hearing-impaired listeners, dynamic optical information in the face plays a significant complementary role in supporting robust speech understanding, even under compromised listening conditions with hearing aids or cochlear implants.

After Irwin moved to Michigan, he began a second highly productive phase of his career, studying more basic fundamental issues of human information processing involving the detection, discrimination, and recognition of complex auditory and visual sequential patterns. In addition to his empirical work, he also contributed several highly influential papers on the application of signal detection theory and receiver operating characteristic (ROC) analyses to the problems of recognition memory. Irwin was a strong advocate of what was then considered to be the "new look" in perception and cognition. He was dedicated to developing more precise methods to study hearing and speech communication based on developments in statistical decision theory and sensory processing, motivated by the theory of signal detection that provided novel methods for separating sensory processing from decision making.

His wife of almost 72 years, Marcille Kaufman Pollack, passed away a few weeks after his death on March 9, 2021. He is survived by his three children Sharron, Phyllis, and Stanley; five grandchildren; and one great-grandson. Irwin leaves a wonderful legacy of generosity, wise guidance, kindness, and love with his family, colleagues, and students.

Selected Publications of Irwin Pollack

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Letters to the Editor

Acoustics Today welcomes "Letters to the Editor." Letters (maximum 150 words) can be on any topic related to acoustics or any comments on material in recent issues of *Acoustics Today*. Letters will be published on a space-available basis. Letters should be sent to apopper@umd.edu.

The Least Useful Equation in Acoustics?

It is always disconcerting to see the inflated importance that acousticians assign to the wave equation, as well as their failure to comprehend its meaning. Dr. Eastland's fine article in the Spring 2021 issue of *Acoustics Today* (https://bit.ly/3ukKcKK) provides a clear example of this problem. He correctly states that "The [wave] equation relates the temporal and spatial changes to these variables," but the previous sentence incorrectly claims that the "[wave] equation provides the mathematical relationships between the variables of interest in acoustics, often the acoustic pressure or particle velocity and the speed of the wave."

Three first-order differential equations that determine "the mathematical relationships between the variables of interest." Pressure and density are related by the equation of state, pressure and velocity are related by the momentum equation (e.g., the non-dissipative Euler equation), and density and velocity are related by the continuity equation. That content of those *local* relations is obliterated when they are combined to form the *global* second-order wave equation.

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Letter to the Editor

The article Computational Methods and Techniques Across Acoustics by G. C. Eastland in the Spring 2021 issue of *Acoustics Today* (https://bit.ly/3ukKcKK) talked about the role of computers in acoustics. Analysis concepts based on energy principles developed by W. P. Mason might also be added to the list due to their importance in entire industries, including the entire sound reproduction industry, every ultrasonic device employing piezo electric material, and every active or passive sonar device. The technique allowed a designer to re-configure an acoustic device into an electrical circuit analogue and from there develop its acoustic and electrical properties.

Dr. Mason was the president of the Acoustical Society of America (ASA) in 1956, was an ASA Gold Medalist, and the author or co-author of numerous publications.

Bruce Keller
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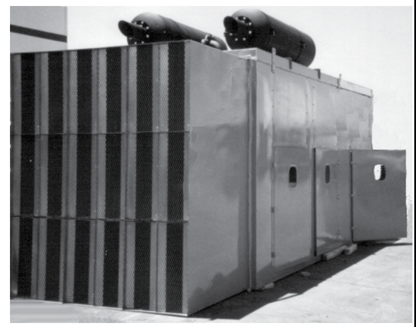

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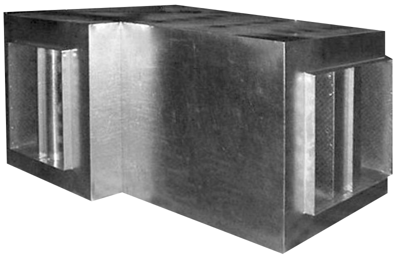

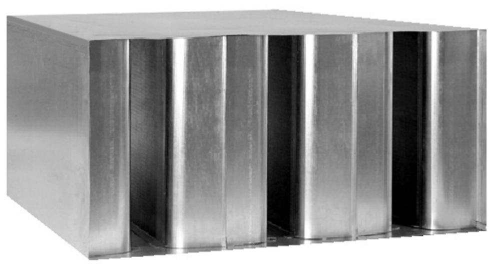

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