Acoustics Today

Winter 2023 Volume 19, Issue 4

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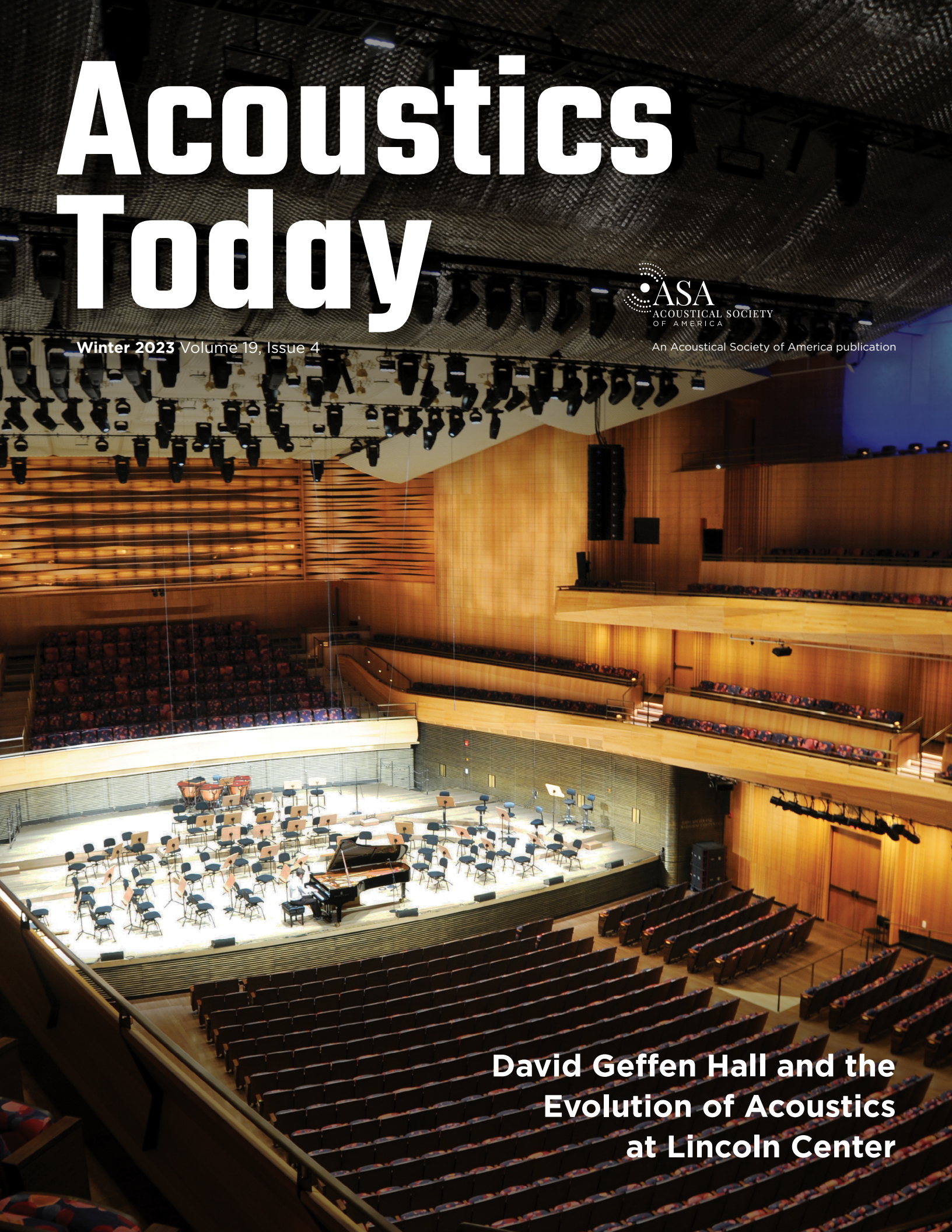

David Geffen Hall and the Evolution of Acoustics at Lincoln Center

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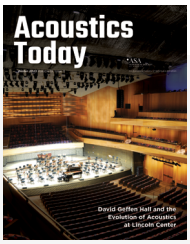

About the Cover

Photo of the David Geffen Hall at Lincoln Center in New York, NY. © 2023 Paul H. Scarbrough. Read Scarbrough's related article, "David Geffen Hall and the Evolution of Acoustics at Lincoln Center" on page 41.

ASA ACOUSTICAL SOCIETY OF AMERICA

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Acoustical Society of America

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www.acousticalsociety.org

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From the Editor

Arthur N. Popper

I start this column by pointing out two items in this issue of *Acoustics Today* (*AT*) that I think may be of particular interest to all Acoustical Society of America (ASA) members. First, although I normally do not point members to the "From the President" column, I am doing so for this column since ASA President Stan Dosso (see page 10) presents very important, interesting, and useful information about the ASA budget that every member might want to read.

Second, with three scholarly journals and a magazine, it can be hard to keep up with the many things going on with ASA publications! To help readers "navigate" this plethora of useful information, *AT* is now providing a "guide" (see page 12) for finding out about new articles in ASA journals, activities of ASA authors and editors, and other information for and about the acoustics community. And, as web offerings from ASA publications increase and change, we will provide updates both in the magazine pages and on the *AT* website (acousticstoday.org/asa-publications).

This issue of *AT* includes articles on several "themes" that have "evolved" since I assumed editorship of *AT*. I have not wanted special issues on one topic because I want readers to always be able to find at least a few articles in every issue that would interest them. In fact, the only single-topic issue was one to honor Leo Beranek, one of the great giants of our Society, on his 100th birthday (see bit.ly/3F76eZ2). And because of the amazing diversity of Leo's life, I suspect that almost everyone found some article in that issue that was engaging.

But, over the many issues that I have edited, I have tried to incorporate informal themes, and these are exemplified in our online feature "*AT* Collections" (see bit.ly/AT-Collections) where we group articles from the 19 years of *AT* into various topics.

One of the topics that I have thought as the most interesting has been on the acoustics of musical instruments. As a nonmusician, I have found the diversity in instruments, how they work, and their acoustics quite fascinating. To date, we have probably covered most groups of Western instruments. But we broaden a bit in this issue when Jonas Braasch and James P. Cottingham discuss both Western and Asian reed instruments. Jonas and Jim teach us a good deal about the similarities and differences of the instruments and their reeds, and they delve into the evolution of these instruments.

Our second article is by Joseph Haxel, Christopher Bassett, Brian Polagye, Kaustubha Raghukumar, and Cailene Gunn. I first met Joe Haxel several years ago when we collaborated on a project that led to a recent article in *The Journal of the Acoustical Society of America* (see doi.org/10.1121/10.0020150). The topic of this *AT* article is likely to be very new to many members, offshore energy sources that are not wind farms or oil and gas platforms. It turns out that many interesting devices are being developed to capture energy from the movements of the oceans, and Joe and his colleagues give a broad and interesting overview of many of these new technologies and their acoustics.

The third article switches to how computers understand speech. In his article, Douglas O'Shaughnessy first talks about how humans understand speech but then takes on interesting questions about how our devices, using things like Siri and Alexa, understand what we say. Of course, with the tremendous rise in interest in artificial intelligence (AI), the issues Doug raises become even more timely, and he provides insight into very important issues for all of us.

Another topic that we have covered a good deal in *AT* is architectural acoustics (see bit.ly/3Q57qlT). This issue has two such articles, and by chance, they are very complementary in the discussion of concert halls.

The fourth article is by Paul H. Scarbrough who shares a fascinating story of the acoustics of what is now known as David Geffen Hall at Lincoln Center in New York, New York. At its beginning, the hall, originally named Philharmonic Hall, had, as Paul shares, very substantial acoustic issues. But over the decades and with the help of a great

deal of work (and money), the hall has evolved to have what critics are saying is outstanding acoustics. Paul was one of those most involved in the design of the acoustics of the latest iteration, and so he brings a very personal perspective to the story.

The related article, the fifth in this issue, is by E. K. Ellington Scott. Ellington also discusses the acoustics of concert halls but from the perspective of the musician. This is rather personal for Ellington because besides being a new PhD in architectural acoustics, he is an accomplished jazz musician (bit.ly/AT-Scott). Thus he "views" the acoustics not only from his perspective in the design of spaces but also from working in those very spaces.

As usual, we have several "Sound Perspectives" (SP) essays. The first SP is part of our "Conversation with a Colleague" series (see bit.ly/ATC-CWC), edited by Micheal Dent. This essay is a conversation with Andrew Piacsek. Andy has a diverse interest in physics and in education, and he marries these interests in very interesting ways that are definitely worth reading and thinking about.

In the next SP, James H. Miller provides his annual report about the ASA Foundation (see bit.ly/ATC-Foundation). The Foundation is a very important part of ASA, and it makes substantial contributions to many of our activities and members. I hope everyone will read Jim's informative column and perhaps consider donating to the Foundation.

Another very important part of the ASA is the Women in Acoustics (WIA; see bit.ly/AT-WIA) Committee. In this essay, WIA members Tracianne B. Neilsen, Kathleen E. Wage, Arezoo Talebzadeh, and Anna Diedesch introduce us to two amazing woman leaders of the ASA and then talk about leadership. In particular, I want to point out that this piece and its focus on leadership is something that should be read by every ASA member because it provides insights that not only benefit individuals during their careers but also in some of the ways they can contribute to the ASA.

The final SP is by ASA member Gail Scowcroft. I invited Gail to share her career with us because she has made unique and very important contributions to acoustics that involve ASA members from many technical committees. In particular, Gail is cofounder of the Discovery of Sound in the Sea website (see www.dosits.org), and she has led this group for over two decades (see bit.ly/ATC-DOSITS for more information about DOSITS). DOSITS does an amazing job in science education for everyone, from students to journalists to educators to regulators, and it is used by individuals from around the world, getting over 12 million hits a year.

Finally, please remember that the SPs are essays that have the goal of sharing interesting and useful information about the ASA, its members, special ASA projects, and most anything else about acoustics. The essays in this issue reflect that diversity of information and ideas.

My intent in mentioning this is to remind readers that if any ASA member or group has ideas or information they think would be of broad interest to ASA members and they would like to share it in an SP, please contact me (apopper@umd.edu) and we can discuss the idea. The lead time for essays is far shorter than for articles, and the essays themselves are substantially shorter. I would particularly like to invite ASA technical committees (see bit.ly/AT-TC) and ASA committees (see bit.ly/ATC-Committees) to consider updating members about activities since their essays were published quite a while ago.

From the President

Stan Dosso

ASA Finances: Where Are We At and Where Are We Going?

In my second President's column, I discuss what I see as perhaps the most important issue facing the Acoustical Society of America (ASA) in the long term: our finances. I'm sure many ASA members are struggling these days with postpandemic inflation and the challenge of balancing their personal and/or work budgets each month. Likewise, the ASA is experiencing its own financial challenges, although these predate Covid-19.

To illustrate the historical trends, **Figure 1** shows the record of total revenue and total expenses from 2005 to 2022 (**Figure 1**, *top*) and the net difference (revenue minus expenses) over the same period (**Figure 1**, *bottom*). What jumps off the page here is the observation that annual surpluses of typically a few $100K up until 2012 transition to annual deficits of as much as $1M thereafter, although the deficits seem to have plateaued at about $300K to $400K for 4 of the last 5 years.

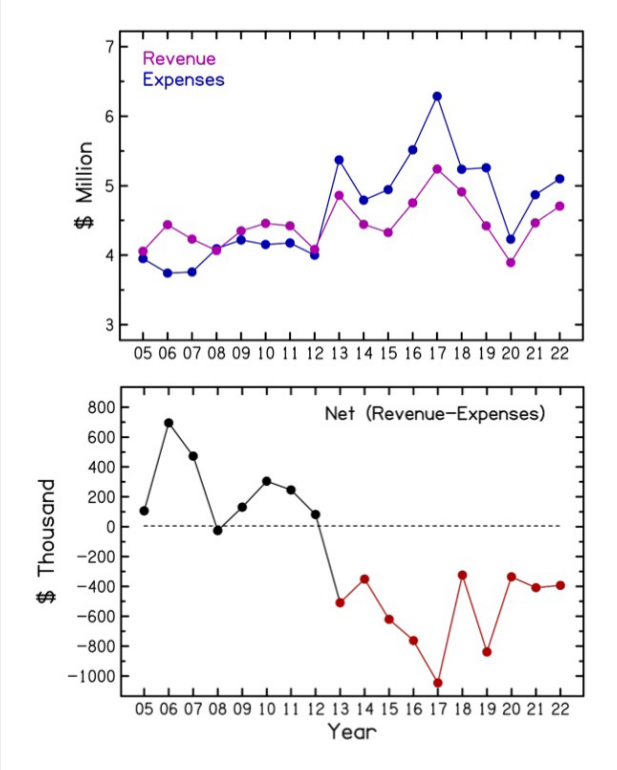

Figure 1. ***Top:*** *total revenue (purple) and expenses (blue) from 2005 to 2022.* ***Bottom:*** *net revenue minus expenses for the same years. Figure courtesy of Judy Dubno.*

Although these deficits are a big concern, I should hasten to say "Don't panic!" Due to the ASA's substantial reserve funds, saved and invested during the decades of plenty, we've been able to pay our expenses and could continue to survive deficits for a number of years to come; we're not going broke any time soon. The situation is not disastrous, and drastic actions that severely curtail or degrade our programs are not required.

However, these deficits are not sustainable in the long term, and the ASA needs to come to grips, much sooner rather than later, with balancing our budget so that the Society can continue to carry out its mission for many decades to come. In fact, the ASA Executive Council (EC) started taking a hard look at finances and reducing expenses a few years ago, which may explain the partial recovery from the worst deficits over the last few years (**Figure 1**). Nevertheless, much more needs to be done to get back on solid financial footing. Explaining this situation, which is serious but not desperate, to the ASA membership and seeking your buy-in as we consider and make changes is the purpose of this column. I should also add that times are tough all around these days for academic/professional societies; the ASA is not alone in addressing budgetary woes.

In the big picture, the ASA earns its largest revenues through subscriptions to our flagship publication, *The Journal of the Acoustical Society of America* (*JASA*). Annual membership dues, meeting registration fees, and standards also bring in significant revenues, together with a few more-minor revenue sources. Significant expenses are spread over several cost centers, with the largest generally being publications (including *JASA*, *JASA Express Letters*, *Acoustics Today*, and *Proceedings of Meetings on Acoustics*); Member Services; Meetings (two per year);

Outreach; and Standards. If some cost centers are unfamiliar, Member Services includes administrative support of the ASA, its members, and its governance; Outreach includes all activities of the ASA administrative and technical committees, acoustics educational programs, and student programs.

ASA publications consistently provides the only net surplus; all other cost centers run at a deficit. However, it's important to note that some cost centers, such as Outreach and arguably Member Services, shouldn't be expected to make money or break even. It's our goal to support/subsidize some programs that support ASA's mission without charging extra fees, although costs should be scrutinized. But it is reasonable to consider whether other programs, such as Standards and Meetings, should consistently run at a significant deficit. For instance, if our two meetings in 2022 had broken even, the ASA would have realized a small overall surplus for the year rather than a $400K deficit (**Figure 1**). However, our meetings almost always run significant deficits (whereas some other societies manage to run meetings at a profit).

Three years ago, an ad hoc subcommittee of the ASA Finance Committee was tasked to carry out an analysis of the ASA's historical budget and spending, and they reported to the EC in October 2020. Among their findings

- There is no single cause for the deficit. Expenses have risen over time in all cost centers without compensating increases in revenue. Simply put, the ASA is spending more than it is making;
- The number of programs supported by the Society has grown, whereas few, if any, have been ended. As a rule, programs do not generate offsetting revenue;
- *JASA* continues to be the ASA's predominant source of revenue as well as a principal means of accomplishing the Society's purpose; and
- The ASA is very fortunate to have a large balance in its reserves that can be used as a financial backstop. However, the ability to provide a backstop is limited and has been severely taxed recently. Furthermore, large draws on the reserves means that they cannot be used for strategically important investments in the Society's future.

I've already alluded to the last two points, but the first two are also telling: expenses have increased faster than revenues virtually everywhere (similar to the inflationary pressures we feel in our personal or work budgets), and the ASA tends to add more programs than it ends, with most programs adding to the deficit. One takeaway here is that although we clearly must reduce expenses, we also need to increase revenues. We won't be able to cost cut continually to offset inflation while also maintaining our current programs, and we've already fallen behind in that regard. In particular, the modest increases in meeting registration fees and membership dues over recent years have not kept up with rising expenses (particularly meeting expenses, which increased by 30% across the board in 2022 alone). So further increases will likely be forthcoming in the years ahead; please be understanding. Another takeaway is that we need to consider sunsetting or pausing programs. In fact, apart from budgetary reasons, evaluating and streamlining or ending programs is needed on an ongoing basis to avoid becoming overprogrammed and stale, so this can be a positive, not negative, process.

The Finance Subcommittee concluded that "returning ASA to a sustainable financial footing is going to be a complex, long-term process, with no easy answers" and made a number of recommendations and suggestions. Some of these have already been implemented, including

- eliminating meeting travel support for EC and Technical Council (TC) members and
- eliminating meeting travel support and stipends for associate editors.

Other ongoing savings were instigated by the pandemic, including

- replacing twice yearly in-person Officers and Managers Meetings with virtual meetings, eliminating travel, accommodation, and meeting costs and
- reducing ASA headquarters office space because staff mostly work remotely now.

Other recommendations from the subcommittee and from the Meetings Reimagined Committee are in the process of being implemented, including

- turning the ASA Books Program over to the American Institute of Physics Publishing at no loss and with potential shared profits;
- assessing the return on investment of each of the ASA's publications, taking into consideration fiscal returns as well as quality, reputation, and benefits to members;

- reducing the Accompanying Persons Program at ASA meetings, reconfiguring the Women in Acoustics event, and eliminating the Society luncheon, short courses, tutorial, and one of two buffet socials, to be replaced with a Wednesday afternoon/evening social focus comprising a keynote speaker, Plenary Meeting and Awards Ceremony, gala social, and jam session.

The latter point on ASA meeting revisions, which are underway, was discussed in my last column (see bit.ly/3PG8hrP) and is an example of how making changes in long-standing activities can represent an opportunity to streamline and refresh programming.

There's more that could be said and much more that needs to be done in addressing the ASA's finances. But I hope this column is helpful in providing information on where the ASA is at and where we need to go financially. I'd like to thank ASA Treasurer Judy Dubno, Executive Director Susan Fox, and Past President Peggy Nelson for their invaluable input here. As always, I welcome your feedback (sdosso@uvic.ca).

Find out the latest from ASA Publications

With three scholarly journals and a magazine, it can be hard to keep up with everything going on with Acoustical Society of America (ASA) Publications! To help readers "navigate" this plethora of information, we have a variety of options for finding out about new articles in ASA journals, activities of ASA authors and editors, and other information for and about the acoustics community. Here are our current offerings:

Across Acoustics (Podcast): Twice monthly audio interviews with authors of popular *JASA*, *JASA-EL*, *POMA*, and *AT* articles about their research. Episodes range from 10 minutes to an hour, and you can listen to them on your favorite podcast platform! acrossacoustics.buzzsprout.com

Propagations (Blog): Weekly updates about the latest news from ASA Publications, including articles featured on *JASA* and *JASA Express Letters* covers or in *JASA*'s quarterly Technical Area Picks, meeting-related content, trending content from social media, and more! acoustics.org/propagations

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See **acousticstoday.org/asa-publications** for the latest version of this list!

ASA School 2024

Living in the Acoustic Environment

11-12 May 2024
Ottawa, Ontario, Canada

ASA School 2024 is an Acoustical Society of America event for graduate students and early career acousticians in all areas of acoustics to learn about and discuss a wide variety of topics related to the interdisciplinary theme *Living in the Acoustic Environment*. ASA School 2024 follows on the success of five previous ASA Schools starting in 2012, and will provide opportunities for meeting instructors and fellow attendees, mentoring, discussing research topics, and developing collaborations and professional relationships within acoustics.

Program and Costs

ASA School 2024 will take place at the Westin Ottawa Hotel, which is the ASA meeting hotel. Lectures and demonstrations followed by discussions will be given by distinguished acousticians in a two-day program covering topics in *acoustical oceanography, animal bioacoustics, computational acoustics, musical acoustics, physical acoustics, signal processing in acoustics, structural acoustics and vibration, and underwater acoustics*. Although ASA School 2024 will focus primarily on these 8 technical areas, graduate students and early career professionals in all areas of acoustics are encouraged to attend to achieve a broader understanding of the diverse field of acoustics.

The registration fee is $50. Hotel rooms at the Westin Ottawa Hotel for two nights (double occupancy) and meals will be provided by ASA. Participants are responsible for their own travel costs and arrangements including transportation to the Westin Ottawa Hotel.

Participants and Requirements

ASA School 2024 is targeted to graduate students and early career acousticians (within 3 years of terminal degree) in all areas of acoustics. Attendance is limited to 60 participants who are expected to attend all School events and the ASA meeting immediately following on 13-17 May 2024. ASA School attendees are required to be an author or co-author on an abstract for presentation at the ASA Ottawa meeting.

Application and Deadlines

The application form and preliminary program will be available online in December 2023, at www.AcousticalSociety.org.

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Free Reeds: An Intertwined Tale of Asian and Western Musical Instruments

Jonas Braasch and James P. Cottingham

Introduction

Free reed instruments are a class of reed-based wind instruments where a reed swings freely through an open frame to generate a sound. The harmonica and the accordion are two popular free-reed instruments in the Western world, and the mouth organs sho (see youtu.be/yUpr1F1dZt0) and sheng are two prominent Asian examples (**Figure 1**). The free-reed mechanism provides a distinctive sound for musical instruments and demonstrates some extraordinary acoustic phenomena that are discussed in this article. Given that classical orchestras usually lack free-reed instruments, it is the wind instrument type that readers are probably least familiar with, even though they are widespread in traditional Asian music and popular Western music.

To understand free reeds in the larger context of wind instruments, one can look to the von Hornbostel and Sachs (1914) classification of musical instruments, which is still used today. For example, in terms of the article classification system used by *The Journal of the Acoustical Society of America*, von Hornbostel and Sachs primarily categorized instruments based on their tone generators, the part of the instruments that essentially produces the sound. The top categories in the classification system for music divide instruments into wind (aerophones), percussion, and strings. Wind instruments are then defined by their sound-generating mechanisms. Most wind instruments use the players' lungs to create an overpressure by blowing, whereas in a few instruments like the harmonica, a sound can also be created while inhaling (drawing), thus forming an underpressure reservoir.

Figure 1. *Examples of two popular free-reed instruments, the Chinese sheng (**left**) and the European accordion (**right**). Accordion image by Henry Doktorski, used under CC BY-SA 3.0 license.*

Figure 2 shows how reed and flute instruments evolved over time in these categories. All available evidence points to Southeast Asia as the region of genesis for musical free-reed instruments. Without a doubt, the invention of the earliest wind instruments was a combination of ease of build and a chance for discovery. Early wind instruments were often built from objects found at home, such as bird bones, animal horns, and hollow wood and reeds. Unfortunately, some materials are not well-preserved over time like others, so we know of bone flutes that are about 50,000 years old (Atema, 2014) and other early instruments from animal bones, but not of similar old instruments made, for example, from wood.

Unfortunately, the wood used to make the early prototypes of wooden free-reed instruments rotted in Southeast Asia's tropical climate, leaving some of the history up to conjecture. The feili of the ethnic Yi group in Yunnan, China, is one of the, if not the earliest, free-reed instruments (Lam, 2003/2004). It is a straw-made free-reed instrument with

https://doi.org/10.1121/AT.2023.19.4.14

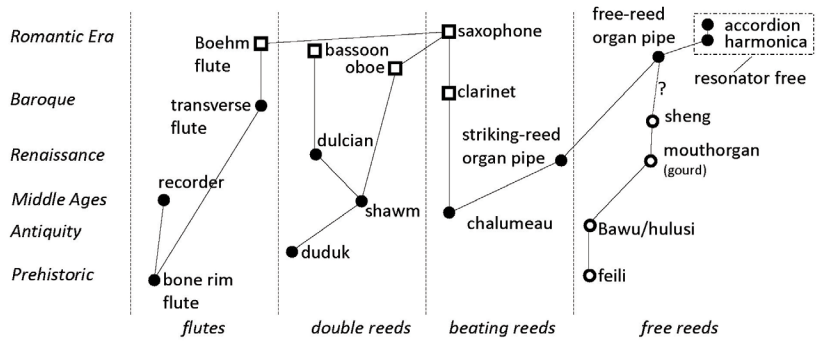


Figure 2. *Development of musical wind instruments over time for different music periods from Prehistoric to the Romantic Era. Instrument families are grouped according to the instrument classification type: flutes, double reeds, beating reeds, and free reeds (von Hornbostel and Sachs, 1914).* ***Solid lines:*** *evolutionary connections;* ***open boxes:*** *current orchestral instruments;* ***circles:*** *Asian free-reed instruments.* ***Question mark*** *indicates the still-debated question of whether European free reeds were copied from Asian free reeds.*

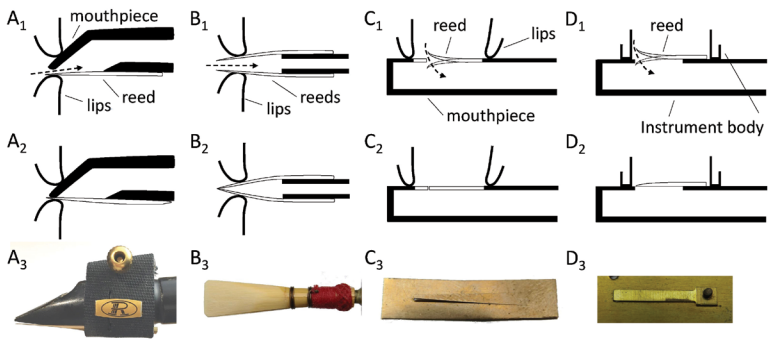


Figure 3. *Functional schematics (**side views**) and pictures of common reed mechanisms.* ***A1:*** *striking reed mechanism of a saxophone mouthpiece. The reed acts as a periodically opening valve, and air will flow when it is open in the direction of the **dashed arrow**.* ***A2:*** *airflow will stop when the reed is closed, and the periodically moving airflow will create the sound.* ***A3:*** *actual saxophone mouthpiece (**side view**).* ***B1-2:*** *periodic airflow for a double reed where two reeds vibrate against each other to enable and stop the airflow periodically.* ***B3:*** *actual bassoon double reed (**top view**).* ***C1-2:*** *airflow for an Asian free reed. In this case, the reed can swing freely through the frame.* ***C1:*** *"open door" state, with each reed above the frame.* ***Dashed line:*** *alternative open state below the frame.* ***C2:*** *"closed door" state.* ***C3:*** *Asian bawu free reed (**top view**). In this example, the reed and the frame are made from the same metal piece and are simply separated by two narrow cuts.* ***D1-2:*** *function of the European-type free reed that simply differs from the Asian-type free reed by mounting the reed above the frame and not within frame. It is mounted outside the reed plate or frame in such a way that the reed only sounds with one direction of airflow. In contrast, the Asian free reed is in plane with the frame (**C1-3**).* ***D3:*** *actual harmonica free reed that is riveted onto the frame. The reed is, therefore, slightly elevated from the frame.*

three finger holes that is very simple to make. An incision is made in the upper end to produce the free reed. In accordance with the Yi's oral tradition, a girl who was mute discovered the feili, and it became her voice. A sheng, a Chinese mouth organ with free reeds, is the earliest known example of a free-reed instrument, dating from 430 BC (von Falkenhausen, 1993).

Acoustics of Free Reeds

Free and Beating Reeds

Figure 3C shows that a free reed is a vibrating tongue constructed or mounted in a way that allows it to vibrate back and forth through its reed plate or frame, much like a swinging door. It depicts the "open door" state, with each reed above the frame and the alternative open state

below the frame, and the "closed door" state. Also shown is an Asian free reed. In this example, the reed and the frame are made from the same metal piece and are simply separated by two narrow cuts.

In contrast, **Figure 3A** shows that the mechanism of a beating (or striking) reed in an instrument such as the saxophone is slightly wider than the opening over which it is mounted. In double-reed instruments (**Figure 3B**), two reeds oscillate against each other, and the mechanism does not require a frame like beating- and free-reed instruments.

Asian and European Free Reeds

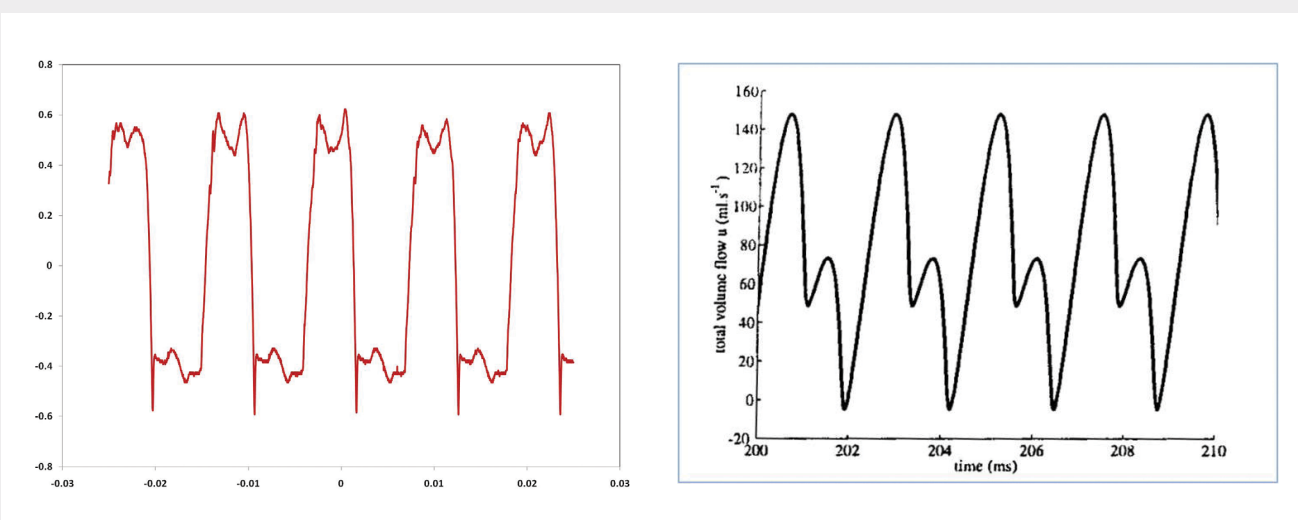
The principal acoustical difference between the Western and Asian free-reed instruments is in the design of the reeds (**Figure 3**). The Western instruments employ reeds that are separately constructed from the frame and mounted on top of the latter. The reed is, therefore, slightly elevated from the frame and is mounted outside the reed plate or frame in such a way that the reed only sounds with one direction of airflow (**Figure 3D**). In contrast, the Asian free reed is in plane with the frame (**Figure 3C**). This small constructional difference has very important acoustic consequences: The Western free reed can sound on its own, whereas the Asian free reed needs a resonator like a pipe to sound. We discuss this effect in **Asian Free Reeds**.

At a simple level of analysis, the sound production of a free reed is like that of a siren. As noted by Helmholtz (1954, p. 95), "The passage for the air being alternately closed and opened, its stream is separated into a series of individual pulses. This is affected on the siren…by means of a rotating disc pierced with holes." For the free-reed instrument, the airstream is interrupted by the oscillating reed tongue.

Normally, a reed of a Western wind instrument behaves like a so-called blown-closed reed, that is, a reed where a musician's initial attack tends to decrease the distance between the reed and the frame. A clarinet reed mounted in its mouthpiece is an example of a blown-closed beating reed. Several theorists have developed models for the oscillation of the air-driven free reed (e.g., St. Hilaire et al., 1971).

When a free-reed instrument is played, it is reasonably common for the tip of the reed to oscillate about its equilibrium position, with an amplitude of 15% of the reed length. Furthermore, the design of the free reed ensures that when the reed tongue moves outside its reed plate, it presents a large opening. Thus, if the reed is oscillating due to a pressure difference between its two sides, the average volume airflow rate through the instrument will be large. Indeed, the rate has been measured for various instruments and calculated in theoretical models. For example, for a harmonica chamber housing a relatively small reed, the average flow rate is typically hundreds of milliliters per second, comparable to that for a clarinet, which has a much larger reed.

Figure 4. ***Left:*** *relative pressure waveform of a blown accordion reed.* ***Right:*** *calculated airflow rate of the reed after Millot and Baumann (2007). Adapted from Cottingham (2011).*



Waveform of Free Reeds

Figure 4, *left*, shows the pressure waveform as measured by a microphone close to a blown accordion reed in a laboratory wind chamber. The waveform approximates a square wave similar to that of a siren. **Figure 4**, *right,* depicts the reed's volume airflow of a similar reed as calculated by Millot and Baumann (2007). As expected, the airflow rate occurs in two large puffs per cycle, each puff corresponding to the reed opening on one or the other side of the reed plate. The smaller puffs occur when the reed passes below the plate.

The von Hornbostel-Sachs classification (1914) further differentiates if musical instruments use a resonator that changes the pitch of the tone generator or if they are resonator free. All orchestral wind instruments use a resonator that can be effectively changed in length through finger holes (woodwind instruments), slides (trombones), or valves (for most brass instruments; see Moore, 2016) to change the pitch of the instrument to play melodies. Nearly all Western free-reed instruments like the harmonica and the accordion, however, are resonator free, so they must use a set of reeds, one for each tone (see **Figure 2**). In the Western free-reed design, a resonator will usually not affect the pitch of the reed by much, and instruments require a separate reed for each tone. In Western pipe organs (Angster et al., 2017) and in Asia, free-reed instruments with resonators are very common, for example, in the form of the bawu (see youtu.be/UG8D1zyqYFU) and hulusi (see youtu.be/pPvJa6TYjqU). Here, the dimensions of the resonator, the length in particular, determine the sounding fundamental frequency of the reed.

A note played on the accordion or harmonica has an easily identified tone quality. An objective way to characterize this one quality is to observe that the sound spectrum has abundant higher harmonics, as the approximate square waveform would suggest. Some listeners would describe the tone as rich; others would call it harsh; the choice depends on the context and individual taste. In any event, the sound quality can be modified by the presence of a resonator.

Free Reed Characteristics

Free reeds have a characteristic sound that allows musicians to identify the free-reed instruments' sound as a distinct group (like an average person can clearly hear the different vowels /a/, /e/, /i/, /o/, and /u/). This means that

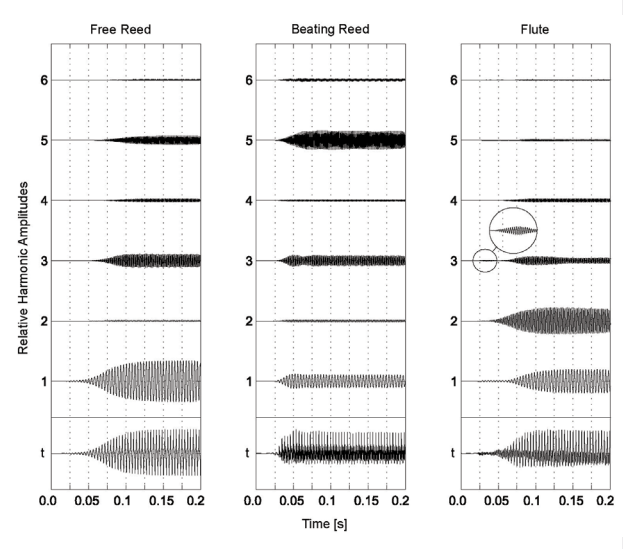


Figure 5. *Onset sounds of a free reed compared with a beating reed and flute. Each graph shows the total sound (**bottom**) and the first six partial tones with rising frequencies (**top**). The initial sound starts at the third partial tone, has a very low amplitude (**small circle**), and has been magnified to make it visible (**large circle**). Adapted from Braasch and Ahrens (1999).*

a trained musician hears a free-reed instrument out from beating or double-reed instruments just by the sound-producing mechanism (listen to an accordion sound example at youtu.be/CJFQTP2RXo4). Free reeds have a unique common onset behavior that can be used by the listener to perceptually separate the free-reed sound from other musical instruments (Braasch and Ahrens, 2000). Compared with a beating reed, the onset duration (the time needed to reach the full amplitude of a tone after its initial beginning) for a free reed is fairly long.

Moreover, the free-reed onset phase occurs with a delayed progression toward the higher harmonics, meaning that the fundamental frequency sounds first and then the higher harmonics start to appear with increasing frequency (**Figure 5**, *left*). The onset phase of beating reeds is usually much shorter, and all harmonics appear simultaneously because the reed starts to beat against the frame right away (**Figure 5**, *middle*).

Flutes can also have a long onset phase, but their sound typically starts as a noise signal produced by the jet stream formed against an edge that is then converted to a harmonic signal through the resonator. In the case

shown **Figure 5**, *right*, the sound starts at the third partial tone. In addition to what can be seen in **Figure 5**, free reeds also have a unique upward shift in fundamental frequency during the onset phase, often in the ascending order of semitones that stretches over several dozen milliseconds. This sound effect gives free-reed instruments their characteristic sound in both Eastern and Western cultures.

Asian Free Reeds

Asian instruments employ free reeds in which the reed and its frame are cut from a single piece of material (**Figure 3C**). Nowadays, metal is the usual choice, but other possibilities include bamboo or similar plant material (Miller, 1981). The reed tongue is positioned so that, absent any pressure difference, it is in the closed position. Any initial pressure difference on the two sides of the reed will cause its opening to increase.

Hence, reeds in Asian instruments are the blown-open type. In many instruments, including the khaen, a single reed functions with both directions of airflow (see youtu.be/9_u5w5d2xiQ). Because of their structure, the Eastern reeds must generally be coupled to a resonator, usually a long round pipe with a constant diameter. For some very simple single-reed instruments, however, the player's vocal tract serves as a resonator. Theory predicts and experiments verify that for the Eastern instruments, the sounding frequency of the reed-pipe combination is greater than both the natural frequency of the reed and the resonance frequency of the pipe (Hikichi et al., 2003).

Figure 6. *Asian free-reed instruments.* ***A:*** *bawu;* ***B:*** *hulusi;* ***C:*** *khaen;* ***D:*** *detail of reed found in each bamboo pipe element of the khaen. Each reed pipe in the khaen sounds when blown or drawn.*

Free Reeds with Resonators and Finger Holes

Many Asian free-reed instruments, such as the bawu (see youtu.be/UG8D1zyqYFU), use a cylindrical bamboo resonator with finger holes to change the pitch (see **Figure 6A** and **B**) in a way similar to the way the clarinet is played by pressing tone holes. The bawu is a diatonic musical instrument, which means it has only defined notes for one scale, for example, C major. Other scales can only be played with extraordinary finger combinations, like opening a finger hole halfway. In contrast, modern Western orchestral instruments use complex key or valve mechanisms, so that the instrument can be played throughout all musical keys with a similar balanced tone quality.

The construction of the bawu is unique because it combines a diatonic body with a free-reed generator. Although nearly every culture uses wind instruments in the form of flutes and double-reed and beating-reed instruments in conjunction with a diatonic resonator, but the use of a free reed with a diatonic resonator is unique to Southeast Asia. The hulusi is a similar instrument that has one or two additional reed-resonator systems to produce drone sounds to accompany melodies. For these instruments, it is typically not possible to oscillate the reed into an upper register, and the range is, therefore, limited to a major ninth.

However, in contrast to Western woodwind instruments that only produce additional notes above the fundamental register, the reed of the hulusi can be blown in a way that produces two additional sounds with frequencies below the natural register of the instrument.

Mouth Organs

Multipipe mouth organs are unique to Asia and exist in various forms used in folk and official court ensembles. For every offered pitch, the Asian mouth organ uses a distinct reed that is coupled to a resonator with a single

finger hole (see **Figure 6C** and **D**; also **Figure 1**, *left*). Only when closing the finger hole of a pipe will the reed sound. This is because the open finger hole will cause an impedance mismatch that prevents the reed from oscillating; recall that the Asian free reeds are blown-open types and that these require a resonator to sound. Acoustically speaking, opening the finger holes takes the resonator away, and the reed can no longer sound.

Mouth organs were originally built around a gourd as the main body, but the modern sheng in China and sho in Japan consist of metal bodies with bamboo pipes. In general, mouth organs are polyphonic, producing harmonic clusters outside the Western major/minor chord tradition. The clusters can be varied dynamically to create complex textures because the free reeds are very stable with changing wind pressure.

Western Free Reeds

The exact origin of the Western free-reed type is still unclear, with two competing theories (which is why we placed the *question mark* in **Figure 2**). The first theory assumes that the Western free reed was copied from Asian instruments. Indeed, it has been documented that individual instruments were imported to Europe as curiosities, although there is no indication that they were played or that their mechanisms have been understood. The alternative theory assumes that Western free reeds were invented independently from their Asian counterpart. European free reeds are not only built in a uniquely different way from the Asian free reed, but the standard European free-reed construction is also more complicated.

The earliest known European free-reed instrument was a speaking machine by Christian Gottlieb Kratzenstein to produce vowel sounds. The device was based on musical instrument technologies of pipe organs and won him a prize in 1780. In his elaborate treatise, Kratzenstein does not mention the Asian free reed with a single word, even though there is speculation he might have seen an Asian mouth organ in Copenhagen, Denmark. Instead, Kratzenstein argues that he redesigned the striking reed of an organ to swing freely through the frame to avoid the harshness that is found for a striking reed when hitting the frame every cycle, a sound very uncharacteristic of the human voice (Ahrens and Braasch, 2003). One needs to keep in mind, though, that science at the time was a European-centric endeavor, and it might have been then considered ethical to omit naming outside sources.

Free-Reed Pipe Organ Stops, Physharmonica, and Reed Organs

The first musical European free-reed instruments were organ pipes that evolved shortly after Kratzenstein's invention (for a general acoustical introduction to pipe organs, see Angster et al., 2017). Free-reed organ pipes soon reached their final form when the tuning mechanism was added (Strohmann, 1811). Early on, free-reed pipe organ stops became popular in Germany, France, and other central European countries.

One of the earliest successful freed-reed instruments in Europe was the physharmonica (see en.wikipedia.org/wiki/Physharmonica), an instrument without resonators. These instruments existed before free reeds were manufactured industrially and were an early attempt to build expressive pipe organs. By quickly changing wind pressure through a foot-controlled pressure-variable bellow system, they can be played quieter or louder. In this context, it is important that only free reeds maintain their pitch under wind pressure variation. In contrast, traditional flute and striking reed stops demonstrate an audible increase in pitch with increasing wind pressure, an effect also experienced by students when learning the recorder. The success of the physharmonica was rather short-lived after it became apparent that the tuning stability was a real problem because the frequency-stable reeds detuned relative to the widely common flute and striking-reed pipes with the changing temperature in churches.

The reed organ, the harmonica, and the accordion all evolved from the physharmonica, and the latter two instruments are still the most frequently used free-reed instruments in the Western world. Although the basic acoustical principles of operation apply to all three, they differ in the design of the air supply. The reed organ uses a keyboard-operated set (or sets) of reeds, all sounding on the same direction of airflow (Cottingham, 2002). This is affected by mounting the reeds on a suitable wind chest. This can be done with either an overpressure in the chest (a "pressure" instrument) or an underpressure (a "suction" instrument). The accordion family of instruments uses a hand-operated bellow that provides airflow in either direction through the reed chambers and hence

requires a separate reed for each direction of airflow. The modern mouth-blown harmonica also uses two reeds in each wind chamber.

Harmonica

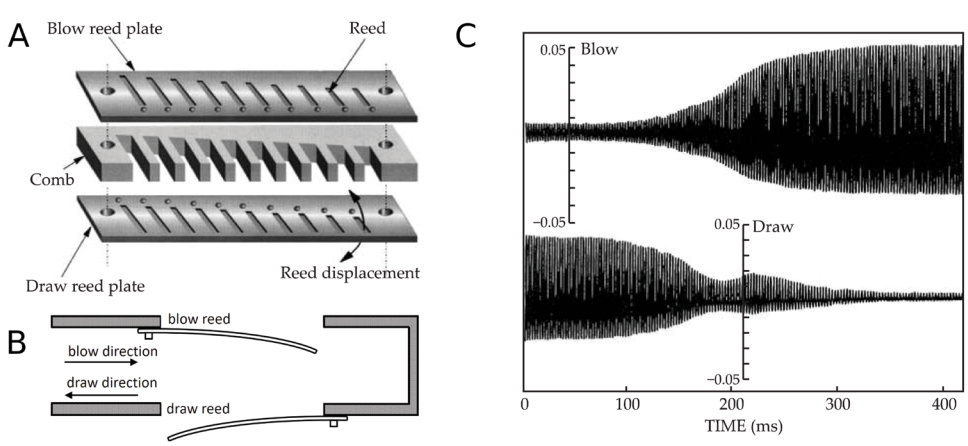
The harmonica is arguably the simplest European free-reed instrument, but its design provides unique, complex acoustic features that are discussed at the end of this section. The comb-shaped frame of the harmonica contains chambers with free reeds, covered by top and bottom plates that can be blown directly using the lips (and tongue) to channel the air to the desired slot or group of slots for playing single tones and chords (see **Figure 7A**). The exact course of invention remains unclear, although the first prototype appeared sometime in the first quarter of the nineteenth century.

Joseph Richter invented the current diatonic harmonica design around 1825. His harmonicas have two reeds per slot, where one is activated by blowing and the other by drawing air (see **Figure 7B**). When blowing the harmonica, the blow reed closes initially inside the blow plate while opening the draw-reed plate. The blow reed then oscillates inside and outside the plate. **Figure 7** shows a snapshot of the inside state. It is more active than the draw reed and determines the pitch of the sound, but the latter is moving as well. The opposite effect occurs when drawing air. Then the draw reed has the primary motion. Adjacent blown reeds are tuned in thirds, and the corresponding drawn reeds are a (semi)tone off according to a diatonic scale. Diatonic harmonicas, which have 7 tones in each octave (2:1 frequency ratio) can be played chromatically by tone-bending individual reeds to complete all 12 tone steps in an octave like on a piano keyboard. Tone bending is an extended technique mastered by Howard Levy and others (see youtu.be/Pz2jPAxUuss).

Free reeds soon lent themselves for industrial mass production, making instruments cheaply available during the middle of the nineteenth century and leading to a popularization, especially in the amateur world. Already in 1827, the Austrian Chamber of Commerce reported 500,000 sold instruments in Vienna alone.

When playing the harmonica with straight blowing or drawing, the principal sounding reed is a blown-closed one coupled to the musician's vocal tract, which acts as a resonator. Johnston's (1987) groundbreaking research looked at the volume of the mouth cavity as well as the connection between the two reeds that share a chamber. He made two important observations. First, the notes that can be bent are those for which the primary reed plays a note higher in frequency than the secondary reed. Second, these notes can be bent downward to pitches between the two reeds. **Figure 7C** depicts the evolution of the amplitudes of the primary and secondary reeds when

Figure 7. ***A:*** *enlarged view schematic of a 10-hole diatonic harmonica with reed plates and comb that isolate the reed pairs into the chamber. The two-reed plate covers that are below the top and bottom of the reed plates are not shown.* ***B:*** *functional side view of the harmonica.* ***C:*** *relative acoustical sound pressure measurement of the harmonica pitch-bending effect. Adapted from Bahnson et al. (1998).*



a harmonica player performs a draw bend. When the player draws air, the depicted draw reed starts to sound in G. By adjusting the shape of the vocal tract and tongue position after the sound has started (while continuing drawing), the blow reed in F-sharp takes over and the sounding pitch increases. This effect is called a draw bend.

Skilled players can further extend the pitch-bending range through overblowing and overdrawing to sound the harmonica beyond the frequencies of the chamber reeds by shaping their vocal tract. In this case, only one reed is used primarily. The technique entails more than just blowing or drawing more forcefully than normal. Bahnson et al. (1998) were able to show that the shape of the vocal tract, rather than its volume, enables this technique.

Accordion

An early accordion prototype was patented by Cyrill Demian together with his sons Karl and Guido in 1829, giving the instrument its name. Demian's instrument had buttons to activate free reeds for one hand only while the other hand operated the bellow for the wind supply. Nowadays, both hands operate buttons or keys to play bass and treble sounds at the same time. Demian used two reeds for each key, mounted in opposite directions. Like the harmonica, one reed sounded when the bellow is squeezed, and the other when the bellow is drawn. This feature is unique to European free-reed instruments, given the instrument's characteristic sound of chord progression in popular music.

Today's accordions commonly use the right hand for the treble keys or buttons and the left-hand buttons for the bass and chords. Because keyed free-reed instruments do not have a dynamic key system like the piano, the bellows operation is a crucial part of dynamics and expression, using the benefit of the tuning stability of free reeds with changing wind pressures that were already key for expression devices in pipe organs.

Recent Developments

Although most known free-reed instruments matured into their final design decades ago, several new instrument developments with free reeds have been conceived. Missin (2011) reports a key mechanism to extend the tonal range of the bawu by Li Song (see patmissin.com/history/bawu.html). Tonon (1998) invented and patented an accordion in which the player can simulate the ability of the harmonica player to bend pitches. In his accordion construction, he can lower the pitch of a note by gradually coupling the reed to an interior pipe resonator.

Finally, Braasch (2019) retrofitted a soprano saxophone with numerous tone generators, including an enlarged bawu reed providing a similar tonal range to the original bawu. This way, the saxophone can be played in the lower register without the need to control the lip muscles. It becomes very easy to play for beginners who have not trained their lip muscles yet. The effect of how different tone generators sound with the same saxophone resonator can be heard at youtu.be/hz8jsEN4QjA.

Concluding Remarks

Soon after their (re)invention, free reeds became the sound generators of choice for inexpensive and even toy-like musical instruments in the West and then the whole world. Industrial manufacturing techniques allowed the mass fabrication of harmonicas, accordions, and reed organs. The association of the characteristic free-reed sound with these popular musical instruments became a challenge for free-reed instruments for classical music, like the reed organ and free-reed pipe organ stops. The mass fabrication of free-reed instruments declined rapidly after the invention of the transistor and integrated circuits because they allowed even cheaper mass-produced instruments. Free-reed instruments prevailed wherever their characteristic sound or expressive possibilities were sought, for example, the blues harmonica, the Tango bandoneon, and the mellow bawu tone for traditional Chinese music.

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Listening to the Beat of New Ocean Technologies for Harvesting Marine Energy

Joseph Haxel, Christopher Bassett, Brian Polagye, Kaustubha Raghukumar, and Cailene Gunn

When we hear about offshore energy in the news media and other popular information sources, images of oil platforms and, more recently, wind farms flash across our screens. However, there is a new, rarely known sector of offshore energy under development that is focused on harnessing the renewable power contained in ocean waves and currents and converting it to electricity. These new technologies termed marine energy converters (MECs) are the topic of this article. They not only have the potential to make a significant contribution to our energy needs but may also generate new sources of anthropogenic sounds in the oceans that require measurement and characterization to ensure that there are no harmful effects to marine life.

Although many of these new technologies produce sound during their operations, making actual acoustic measurements of these devices in the high-energy ocean waves and tidal currents necessary for generating meaningful amounts of electrical power is anything but trivial. This type of energy conversion, known as marine energy, is an emerging renewable resource that is now in its testing and development phase. Because MECs contain multiple moving parts as well as electrical generation equipment, they can produce underwater noise audible to marine life, such as the whales, fishes, and sea turtles commonly observed around marine energy sites. Therefore, the sounds generated by these new technologies are of high interest to researchers, regulators, and industry developers. Whenever a new MEC is installed for testing, researchers deploy hydrophones to understand the characteristics of the sounds it generates. In turn, they inform regulators about what to expect from these new technologies while helping the technology developers understand what they might do to make them quieter during their next round of testing. However, placing a hydrophone in a tidal stream or near a surf zone is not only logistically challenging for the safe deployment, recovery, and survivability of the sensors but is often equally as tough for the scientists and engineers making those measurements in the pitching and rolling waves and strong currents.

Marine Energy: The Next Frontier of Renewable Energy

Globally, offshore renewable energy research is an emerging contributor to a more diversified and sustainable energy portfolio that can meet collective climate goals. Although land-based renewable energy solutions like solar and wind have gained momentum for decades and offshore wind has recently begun to be deployed at large scale, the lesser known sector of ocean energy technologies, collectively known as "marine energy," also has a significant potential to contribute. MECs come in many shapes and sizes and are used to harness the powerful movement of waves and currents to generate electricity. Private companies and research institutions have developed many innovative designs for capturing these renewable resources, which range from turbines spinning in tidal currents to bobbing, tethered buoys that capture and convert the mechanical energy from the rise and fall of surface waves. Yet, the diversity of MEC designs has raised permitting and regulatory stakeholder concerns about the potential environmental impacts of introducing these novel devices into marine ecosystems. Reducing the knowledge gap regarding sounds produced by MECs and the potential biological impacts remains a priority.

In this article, we introduce a range of MEC technologies, share the current state of knowledge around MEC sound emissions, and describe some of the tools that have been

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developed for the acoustic characterization of MECs with a look toward the future.

New Technologies, New Uncertainties

According to a recent study by the National Renewable Energy Laboratory, Golden, Colorado (see nrel.gov), "utilizing just one-tenth of the technically available marine energy resources in the 50 states would equate to 5.7% of our nation's current electricity generation, enough energy to power 22 million homes" (Kilcher et al., 2021). Although it may seem implausible for these technologies to contribute to electricity generation away from the coasts, underwater turbines similar to those used to harness the power of tidal currents can operate in rivers and constructed channels (e.g., irrigation systems).

Although relatively nascent when compared with established renewables like wind and solar, the adolescent marine energy industry is evolving and expanding rapidly. However, it remains some distance from coalescing on a single set of basic designs that are the most effective and economical. For example, although terrestrial and offshore wind projects ubiquitously employ three-bladed, horizontal-axis turbine designs, horizontal-axis tidal turbines employ a range of blade counts. Some turbines rotate on a different axis or depart entirely from wind, employing oscillating foils or "kites." For now, developers conceive, design, build, and test a wide range of progressive technologies for electricity production in a range of coastal and riverine environments from remote waterways to highly urbanized estuaries.

Although much of the emphasis in the industry has focused on relatively large, commercial-scale power generation, there is also a broad interest in the development of small-scale devices to power maritime operations, industries, and research applications that can take advantage of the greater availability of electrical power at sea (Geerlofs, 2021). Regardless of scale, the marine energy industry has significant potential to make meaningful contributions toward clean energy goals and coastal and maritime markets (Copping et al., 2020).

Meanwhile, consideration and mitigation of the potential environmental risks associated with the transition to renewable energy resources is also critical for the success of the marine energy industry. Given the youthful state of the marine energy sector, reducing carbon emissions and driving down energy costs are key factors for technology development, but ensuring a "do no harm" approach is also an important priority.

Marine Energy Converters 101

Wave, tidal, and current energy converters may operate differently from one another, but all translate the kinetic and/or potential energy associated with water motion to the mechanical motion of MEC components and ultimately to electrical power. As these devices operate, several systems components including generators, gearboxes, structure components, and supporting infrastructure like chains and anchors may produce sound (Polagye, 2017).

The marine energy industry has many players at different stages of technological development. As acousticians, our role in this emerging industry is to perform high-quality measurements of sound radiated from devices and to minimize the incorrect attribution of confounding sounds in the environment to the devices. Our collective experience is that this is often more difficult than one might anticipate and that doing so requires establishing reasonable a priori expectations for what sounds the MECs might produce. This also requires some background in the design and operation of the devices. We now provide some background to familiarize the reader with the operating principles and basic device designs that provide context for the types of sounds that MECs produce.

Wave Energy

Wave energy converters (WECs) transform the potential and kinetic energy of waves into electrical power through a variety of approaches. Some device developers focus on deeper water (>50 m) for their WECs to take advantage of the more intense wave energy resources in open water environments. Other designs target relatively shallow areas to capture the energy from shoaling waves that are slowed, shortened, and steepened as they approach the coastline and interact with the seafloor (**Figure 1**). In both cases, although we often conceive of waves as a periodic rise and fall of the water surface, this is only, on average, half of the energy contained in wave motion. The other half is kinetic energy in rotating "wave orbitals" that are strongest near the sea surface and decrease exponentially with depth. Although waves can be generated by wind shear across any body of water, consistently

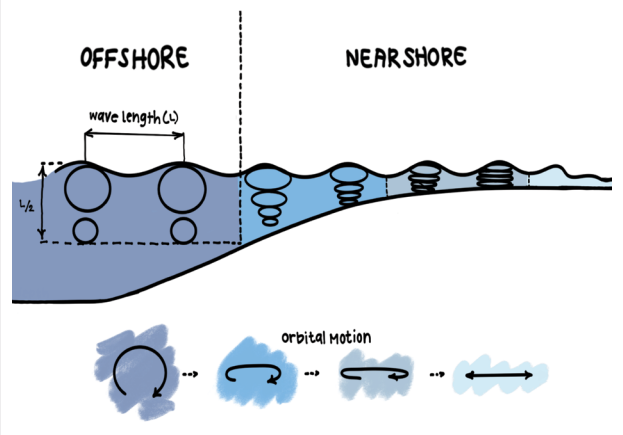


Figure 1. *Ocean waves propagating toward shore interact with the seafloor and change shape, becoming steeper and shorter. The orbital motion of the wave energy is altered from circular in deep water to largely horizontal as the depth becomes shallower.*

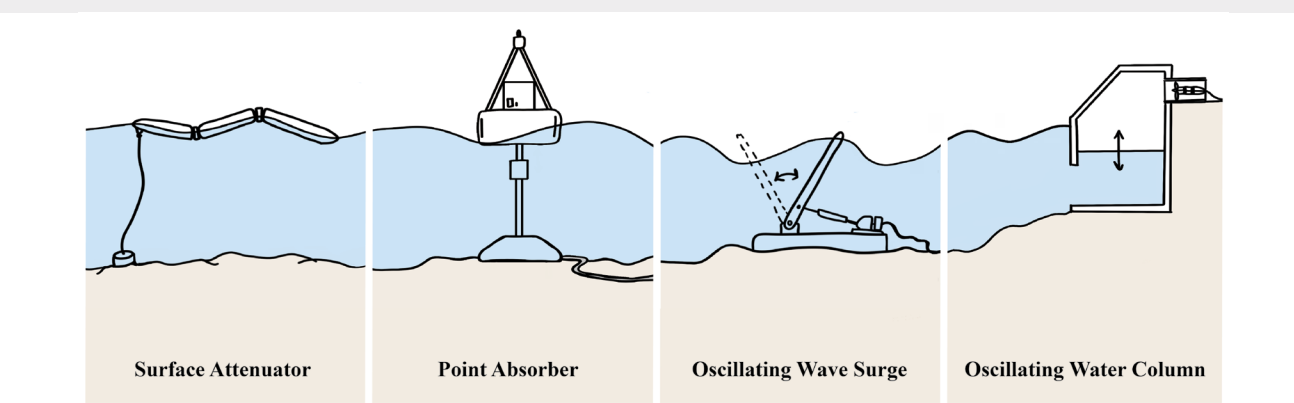
energetic waves occur primarily on coasts adjacent to the oceans. However, the same water motion that is desirable for energy conversion poses a unique challenge for acousticians.

There are several categories of WECs (shown in **Figure 2**) that capitalize on wave motion. These include but are not limited to:

- *Surface Attenuators.* These are snakelike devices with multiple segments connected to one another and positioned parallel to incoming waves. As the attenuator segments move with the waves, generators capture the flexing motion between segments and convert this into a rotation that drives generators (for a video, see bit.ly/wave-attenuator).
- *Point Absorbers*. These consist of buoys that oscillate, usually in the vertical direction, from passing waves and generate power from the force differential between a buoy and a reaction surface like the seafloor (for a video, see bit.ly/point-absorber).
- *Oscillating Wave Surge*. This typically has one end fixed to the seabed or a substructure, whereas the other end can move freely like a paddle or arm perpendicular to the base. The movement of the arm around the pivot point drives a generator (for a video, see bit.ly/oscillating-wave-surge).
- *Oscillating Water Column*. This device consists of a hollow structure open to the sea below the water line and enclosing a column of air on top of a column of water. It takes advantage of the rise and fall of waves to pressurize the column of air and force it through an in-air turbine on the surface. The turbine is usually bidirectional; as waves undulate, the air is pushed or pulled through the turbine. Because the power generation components of this type of WEC are above the water surface, this type of design has more concern for noise emissions in air, whereas the other devices generate more sounds underwater. (for a video, see bit.ly/oscillating-wave-column).

Sounds from WECs most likely originate from the mechanical or hydraulic components of a device that are often housed within a hollow-shelled structure on the water surface that oscillates with the waves. Coupling of these components with the structure can result

Figure 2. *Four common types of wave energy converters (WECs) that include (**left to right**) a surface attenuator, point absorber, oscillating wave surge, and oscillating water column.*



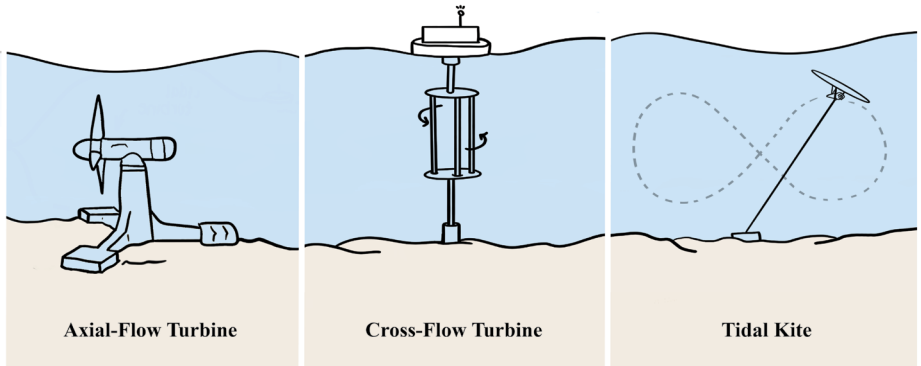


Figure 3. *Three common types of current energy converters (CECs) that include (**left to right**) an axial flow turbine, cross-flow turbine, and tidal kite (**dashed line** shows the path of the device).*

in vibrations and ultimately acoustic emissions into the water column. Hydraulic and electrical generation systems involve rotating components such as gearboxes, pumps, and generators, all capable of producing sounds. Additionally, the electronics used to smooth and regulate electrical power for end use may emit discrete tones and the mooring system used to keep the WEC in place can also produce significant sounds.

Current Energy

Ocean tides are one of the most consistent and predictable natural phenomena resulting from the gravitational pull of the sun and moon on the Earth's oceans. Coastal features such as inlets and passages between islands often constrict water flow and increase current speeds. Current energy converters (CECs) include relatively familiar turbine designs derived from wind as well as a few more novel approaches described in this section.

In addition to tidal currents, there is significant renewable energy potential associated with riverine and major open ocean currents like the Gulf Stream in the Atlantic Ocean or the Kuroshio Current in the Pacific. Although the specifics of the environment in which a current energy converter is deployed dictate some aspects of design, the operating principles are generally the same.

CECs come in a variety of shapes and scales (shown in **Figure 3**) and can be installed as a single device or in arrays. Although water currents are much slower than wind, the thousandfold difference between the density of water and air enables a current turbine with an equivalent power rating to a wind turbine to have a much smaller spatial footprint. Here, we describe a few of the most common types of tidal energy devices.

- *Axial Flow Turbines.* These are functionally similar to commercial wind turbines. They are typically two- or three-bladed, horizontally oriented turbines that face the direction of flow and spin as water moves past (for a video, see bit.ly/axial-flow-turbine).
- *Cross-Flow Turbines.* These might be thought of as similar in design to a kitchen mixer in which multiple blades rotate around a center axis oriented perpendicular to the incoming flow. The advantages of this technology allow the blades to spin and produce power in either direction efficiently, reducing the need for active control mechanisms. These systems can be deployed at the surface from a fixed structure, platform, or barge as well as mounted to the seafloor (for a video, see bit.ly/cross-flow-turbine).
- *Tidal Kite.* This is composed of a hydrodynamic wing equipped with a turbine that is tethered by a cable to the seafloor. Much like how a toy kite moves through the air on a windy day, the wing of the tidal kite leverages the flow of water to lift the wing, causing the device to "fly," looping through the water column as the wing encounters currents (for a video, see bit.ly/tidal-kite).

CECs are subject to relatively high mechanical loads and turbulence that results in blade and system vibrations and measurable acoustic emissions. River and ocean currents can be stable over multiday periods, but tidal currents rise and fall on a roughly six-hour cycle. Because

of this, the radiated noise from CECs in river and ocean settings can be relatively consistent over a longer time period, whereas noise from CECs in tidal channels can change over a period of minutes. Like WECs, other components in the CEC power conversion chain, including bearings, generators, and power electronics, may generate underwater sounds.

Sounds Effects from Marine Energy Converters

The range of device types in combination with a limited number of MEC deployments, has resulted in significant uncertainties around how the introduction of these devices may impact marine ecosystems and wildlife. Audition is the primary sensory modality for many marine species. Marine mammals, invertebrates, and fishes use acoustic signals in the ocean for a host of life functions such as communication, navigation, reproduction, and foraging (Erbe et al., 2019; Popper and Hawkins, 2021). Understanding the effects of anthropogenic contributions to ocean soundscapes is key for assessing ecosystem health (Merchant et al., 2022). A common concern raised in relation to marine energy technologies is the sound radiated by devices during operation, construction, and maintenance and what the broader impacts of this sound will be on the local environment. Fortunately, common sources of underwater sounds, from animal vocalizations to physical processes and anthropogenic noise, have been researched extensively (e.g., Hildebrand, 2009). These studies provide a valuable context that researchers can use in considering the potential impacts from the introduction of new anthropogenic noise sources when they are coupled with knowledge related to auditory capabilities and animal behavior.

Addressing Gaps in Technology and Data

To date, the lack of published measurements of the sound produced by MECs have sometimes delayed the permitting process and increased costs for open water testing and demonstration, slowing the development of MEC technology. Because of this, the International Energy Agency's Ocean Energy Systems (IEA-OES) environmental group (see tinyurl.com/3aufct2z) has produced a series of comprehensive reports on the "state of science" about environmental effects from MECs, including underwater noise (Copping et al., 2016; Copping and Hemery, 2020). In addition, national governments have made investments to ensure that technology for measuring known stressors, including but not limited to sound, are available for monitoring around MECs as the pace of deployments increases (Chang et al., 2021).

To those familiar with oceanographic and acoustic sampling, the inherent challenges of deploying costly equipment and collecting measurements in environments with strong currents (e.g., >3 m/s) or energetic wave climates may be familiar. The conditions where MECs are sited for deployment are often dynamic and unforgiving. The challenges of working in these environments have necessitated the development of dependable and effective equipment and sampling for obtaining reliable measurements across a diversity of sites and device types.

Understanding the Effects on Animals

Often the most suitable and valuable places to install MECs are also some of the noisiest. These devices enter a soundscape teeming with activity: shipping vessels, breaking waves, chattering animals, storms, and the sounds from sediment and cobblestones shifting on the seabed. Distinguishing operational MEC signals from other nearby sources in elevated ambient conditions is no easy task. Thus, along with characterizing sound emissions from MEC systems, efforts to research the frequencies and levels of the sound emitted from MECs and determining if device-generated signals overlap with frequencies used by sensitive marine species are under investigation. The duration or exposure of MEC-associated sound levels and how they impact the behavior of marine cohabitants are all being evaluated in the effort to better understand and quantify the possible environmental impacts of these devices and address data gaps (Copping and Hemery, 2020).

Unlike offshore wind farms in "shallow" water (up to 30 m depth), MECs are rarely installed with pile driving, and therefore device installation activities are usually short lived and produce lower intensity sound. The primary acoustic concern for regulators therefore involves sound generated during the long-term operations. So far, there is no evidence showing sounds produced by individual MECs could cause auditory injury to marine animals, although there have been very few studies on a limited number of species (Tougaard, 2015). Rather, the results from acoustic studies of MECs summarized in Copping et al. (2016) and updated in Copping and

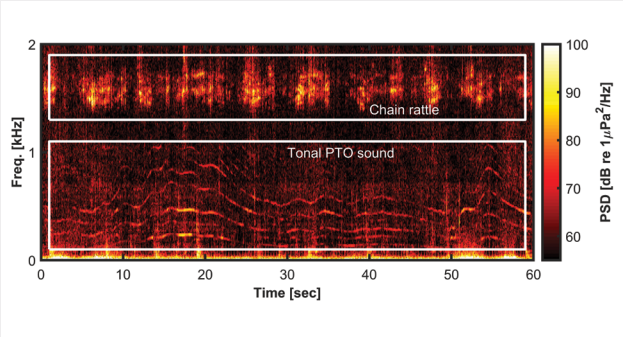


Figure 4. *Power spectral densities (PSDs; dB re 1 μPa²Hz⁻¹) from recordings of a WEC off the coast of Oahu, Hawai'i, showing tonal sounds and harmonics from the power take off (PTO) generator (**bottom**) as well as chain rattle (**top**) from the mooring (from Polagye and Murphy, 2019). At the time of the measurements, the significant wave height and energy period were approximately 4 m and 12.6 s, respectively. The hydrophone was deployed on the seafloor approximately 100 m from the WEC.*

Hemery (2020) indicate that sounds radiated by operational devices could potentially influence behavior or physiological stress responses in various animals.

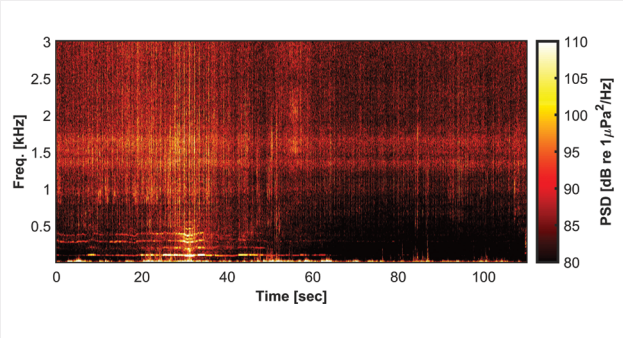
However, the available published measurements are relatively limited in scope (Walsh et al., 2017) and do not cover the great diversity of designs and scales of existing as well as anticipated MECs. The uncertainties around possible acoustic impacts can only be addressed through further study. Moreover, although most of the attention around underwater noise from MECs has focused on marine mammals, Popper et al., (2023) introduce the potential and importance of acoustic particle motion disturbance from MECs as a key measure for the effects on fish and invertebrates. This work further identified gaps in understanding around the effects of MEC sounds from the animals' perspective (Popper et al., 2020), inspired new questions for research, and highlighted areas of concern for the regulatory community.

What We Know About Energy Marine Converter Sounds

WEC sound characterization studies are limited due to a small number of global device deployments where acoustic measurements during operations were prioritized and reported. Thus far, because of technological limitations, many WEC studies have characterized the devices as part of the collective soundscape rather than isolating the sound emissions from the device compared with the ambient environment. Additionally, most of these deployments and recordings are from point absorber devices (**Figure 2**), leaving other archetypes uncertain. Moored hydrophone and drifting hydrophone systems have been used to measure sound at fixed and dynamic ranges from WECs with acoustic data collected from both the seafloor and near the surface. WEC-generated sounds have mostly been observed as low-frequency (<1,000-Hz) pulses and tones that vary in amplitude with passing waves and changing wave conditions (**Figure 4**) and are attributed to the power generation components of the device (Bassett et al., 2011; Lepper and Robinson, 2016). Direct comparisons of WEC-generated sounds have been difficult thus far due to the lack of measurement standardization, but, generally, sound pressure levels integrated over several tens of kilohertz measured at distances ≥100 m from a WEC have been below auditory threshold levels for marine mammal species such as harbor seals (*Phoca vitulina*) and harbor porpoise (*Phocoena phocoena*) (Tougaard, 2015). Other sounds like mooring chains and hull slap have also been observed during WEC acoustic studies, but these signals are not unique to MECs and are found across maritime industries and recreational activities.

Research characterizing sounds from CECs such as tidal turbines have largely been focused in waters near the United Kingdom, with a few exceptions of turbine

Figure 5. *PSDs (dB re 1 μPa²Hz⁻¹) recorded by a drifting hydrophone near an operational cross-flow turbine in Alaska. Note the tones and harmonics correlated with turbine rotation rate and power output (from Polagye and Murphy, 2015). The closest point of approach to the turbine (a direct pass over the top) occurs at around 30 s into the drift.*



deployments in areas of the northeast United States and Canada. One of the technical challenges at these sites has to do with signal contamination from flow noise or pseudosound caused by the flow of water past a hydrophone (e.g., Bassett at al., 2014) that is similar to the sound you hear while trying to talk on a phone on a blustery day. As a result, drifting hydrophones have emerged as the preferred technology for measuring CEC sounds in high-energy currents because of their effectiveness at reducing flow noise.

Like WECs, CECs produce mostly low-frequency (<1,000-Hz) sounds that vary in amplitude with the rotor speed and turbine rotation rate (Risch et al., 2020). In some cases, turbine sounds are tonal, with signals attributed to components of the power electronics (**Figure 5**), whereas other signals have been found to vary with turbine rotation rate. Like WECs, single turbine sound measurements to date have not raised significant concerns for exceeding regulatory thresholds (Lossent et al., 2018), and in some cases are indistinguishable within background levels (Haxel et al., 2022), good news for the industry and for marine life.

Acoustic Technology Research and Development

In addition to the environmental regulatory hurdles facing new marine energy technologies, national governments have recognized the technical challenges inherent to acoustic measurements in the high-energy environments that are most promising for the harnessing of ocean energy. Investments in research and development resulted in significant technology advances and a suite of state-of-the-art acoustic tools equipped to tackle MEC sound characterization challenges (**Figure 6**) (Wilson et al., 2014; Chang et al., 2021). These instruments include the University of Washington's (Seattle) Drifting Acoustic Instrumentation SYstem (DAISY), a system that can be optimized for MEC acoustic measurements in both current and wave environments. The design employs an effective flow shield in currents that reduces the complicating signals from flow noise, incorporates meteorological sensors on the topside buoy and, with several deployed in an array configuration, can provide MEC sound source localization capability. In waves, the flow shield is exchanged for a longer tether and damping plate that isolates the hydrophone from surface buoy motion.

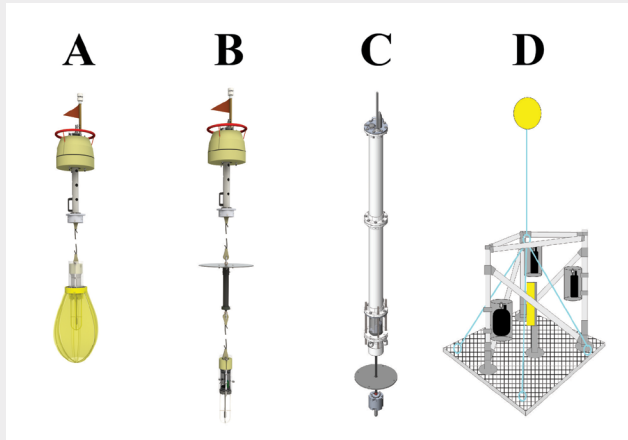


Figure 6. *Schematic diagrams of the University of Washington's Drifting Acoustic Instrumentation SYstem (DAISY) drifting hydrophone design for currents (**A**) and waves (**B**), Oregon State University's spar buoy drifting hydrophone for waves (**C**), and Integral Consulting Inc.'s Noisespotter vector sensor array (**D**). Note that these drawings are not to scale.*

Similarly, the Noisespotter developed by Integral Consulting (**Figure 6D**) comprises a three-dimensional array of vector sensors targeting low-frequency (<3-kHz) acoustic particle motion, sound pressure level measurements, and source localization of MEC sound with a high degree of spatial resolution, advancing the ability to determine both the location and identity of a sound source (Raghukumar et al., 2020). Similarly, Oregon State University, Corvallis; the NOAA Pacific Marine Environmental Laboratory, Seattle, Washington; and the Pacific Northwest National Laboratory, Richland, Washington, have collaborated on the development of a tall, thin, and upright floating ocean spar buoy drifting hydrophone system for open water WEC measurements (**Figure 6**) as well as a fixed seafloor hydrophone system with an underwater acoustic link to a surface buoy for real-time reporting of WEC associated spectral levels (called the Coastal Real-time Acoustic Buoy [CRAB]).

Standards and Acoustic Characterization of Marine Energy Converters

Given the inherent challenges of acoustic data collection at marine energy sites and the general importance of the subject from the environmental consenting perspective, there is an ongoing effort to develop a standard for acoustic characterization of MECs. This process is underway with work by the International Electrotechnical Commission

Technical Committee 114 who released Technical Specification 62600-40: *Acoustic Characterization of Marine Energy Converters* in 2019. This document provides an important set of technical guidelines for acoustic sensor specifications, data collection methodologies, coincident environmental measurements, MEC power performance information, and data analysis and presentation of results. MEC-related sound levels are correlated with the power production state of the device and the time series of environmental conditions, things like tidal current velocity, wave heights and periods, and wind speeds. This type of standardized approach to measurement fosters confidence for those responsible for permitting and licensing marine energy projects, at least from an underwater noise impact perspective.

Looking Ahead

Rapid, iterative testing cycles in real ocean and tidal conditions are critical for the technology advancement of the budding marine energy industry. Fortunately, in the United States and Europe (see emec.org.uk), several MEC test facilities such as the US Navy Wave Energy Test Site (WETS) (see bit.ly/Hawaii-WETS) have been operating for several years, and a new open ocean test center known as PacWave (see pacwaveenergy.org) is currently under construction off the Oregon coast in the United States. As MECs enter the waters of these test facilities, opportunities for acoustic characterization should be prioritized, filling data gaps and supporting the growth and success of a sustainable marine energy industry. In the future, as the marine energy industry moves toward the deployment of arrays at commercial scales and explores potential colocation with offshore wind, stakeholders of all kinds will benefit from the knowledge gained by characterizing individual MECs and understanding the drivers for sound production.

Collectively, offshore renewables are needed to help meet the goals for reduced carbon emissions, develop energy security and coastal resilience, promote energy equity, and power ocean observations and marine-based industries. Marine energy is part of the portfolio of ocean-based solutions, and despite the often nausea-inducing fieldwork deploying equipment in pitching and rolling waves from a small boat or cleaning six months of barnacle growth from a hydrophone, the acoustic data that we collect during MEC deployments are priceless. It is all an important part of the process and evolution toward a better understanding of acoustic emissions and potential effects of marine renewable energy.

Acknowledgments

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For author bio, please go to acousticstoday.org/bios-19-4-2

How Do Computers Understand Human Speech?

Douglas O'Shaughnessy

Introduction

Alexa, Cortana, Siri, How do these commercial algorithms that interpret speech succeed in emulating human listeners? Do they actually "hear" like humans? Similarly, how do cell phones transmit sound efficiently? How do the pressure variations that constitute speech convey information? This article describes how some of these problems have been solved so that digital devices can categorize human voices. It also examines how the human voice is transformed for practical applications such as digital coding and *automatic speech recognition* (ASR). Furthermore, some devices can recognize traits of human speakers, such as identity, language, health, and emotion, and those are also outlined.

People communicate with one another by multiple means such as gestures, writing, and uttering sounds, with speech being the most efficient. At the same time, speech differs greatly from other means of communication. It consists of acoustic sounds that are only indirectly related to human concepts, and those sounds combine to create meaning to listeners who understand that specific language. Ideas in one's head create a sequence of intended words, which consist of logical speech units called *phonemes* (each language has roughly 32 of these sound units, as noted in the International Phonetic Alphabet). Muscle commands to a speaker's *vocal tract* (VT) result in movements of the tongue, lips, jaw, and velum (**Figure 1**) as air is pushed from the lungs by the diaphragm. The *vocal cords* in the larynx vibrate for most sounds (called *voiced*) at a variable rate called the *fundamental frequency* (f_0). In theory, an infinitely long vowel could be periodic, that is, have exact repetitions of a *pitch period,* which is the speech emitted between vocal cord closures. Such a vowel would have energy at multiples of f_0, called *harmonics*.

Air pressure variations form at points in the VT (at the vocal cords or at another constriction), with the VT acting as a filter to shape the sound waveform. When the vocal cords do not vibrate, noisy speech is called *unvoiced*. When vocal cords close abruptly, they generate energy over a broad range of perceivable frequencies. Strong voiced sounds are almost periodic and called *sonorants* (e.g., vowels), whereas weaker noisy sounds are called *obstruents*. The resulting pressure variations from the VT are speech signals, which can be deciphered by listeners or by detailed algorithms.

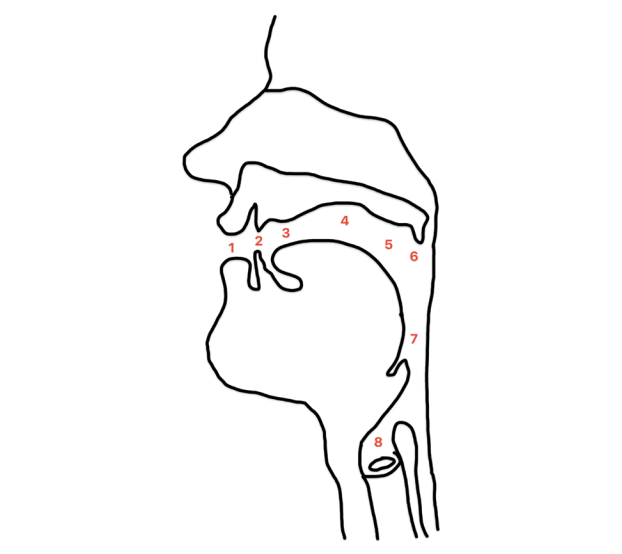

Figure 1. *Vocal tract cross section.* ***1****, Lips;* ***2****, teeth;* ***3****, alveolar ridge;* ***4****, palate;* ***5****, velum;* ***6****, uvula;* ***7****, pharynx;* ***8****, larynx.*

Artificial intelligence has been utilized to translate human speech through an algorithmic process called *analysis*, which produces a compressed version of speech for interpretation (such as conversion into text) or for efficient transmission. Analysis techniques differ across applications. In some cases, they may emulate human speech perception, whereas in other cases, they may use general mathematical models, exploiting computer power.

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The value of analysis is that it can greatly reduce the information rate needed to represent speech in digital computers. For example, basic telephony transmits 64 kilobits/s by exploiting models of how the VT behaves. *Codecs* are algorithms that send speech data on digital communication channels and reconstruct the speech from the data to be understandable by listeners (while preserving naturalness), whereas automatic recognition by computer yields classifications (binary decisions for speaker verification or series of words for ASR). All these applications require data reduction because speech has much redundancy that is used for facilitating communication in adverse conditions such as noise, reverberation, and accents but that is not needed for speech analysis. For example, vowels often have eight or more repeated waveform cycles called pitch periods, but just one of those waveform cycles is enough for listeners to identify phonemes in ideal conditions.

Speech analysis uses algorithms to extract relevant information from utterances. For example, *artificial neural networks* (ANNs) are computer models of biological neural systems that allow machine perception of sight, sounds, and touch. ANNs originated decades ago (Minsky and Papert, 1969) but required modern powerful computers and "big data" to become practical. Spectral methods (e.g., Fourier transform) have also long been utilized for speech analysis (Fourier, 1822). Early artificial intelligence used human-designed "expert" systems (Reddy et al., 1973), now replaced by fully automatic systems. Recent *end-to-end* ANNs do all speech analysis by automatic learning based on observed data. For decades, *hidden Markov models* (HMMs) dominated the speech recognition field. A HMM is a statistical model with states that represent probabilities for data spectra during sequential sections of speech, with transitions between states that model the variable timing of speech (Rabiner, 1989).

Some signal processing can apply to a diverse range of data (audio, video, other physical measurements). However, speech is different from other signals. Speech presents a unique challenge to signal processing because of its highly encoded, dynamic nature. Thus, correlating speech with its meaning using analysis techniques is far more complex than a simpler process like classifying objects in images. To understand speech analysis choices, let us first examine human speech communication.

What Is Speech Communication?

Communication via speech involves its production (coding) and perception (decoding). In artificial communication (e.g., radio, Morse code, sign language), coder and decoder are directly related and may be inverse operations. In speech, coding and decoding differ greatly. Over the course of evolution, mammals evolved to have similar auditory mechanisms to survive, which facilitate hearing time and frequency patterns in sounds but are not necessarily specific for speech. Early mammal communications were likely simple bursts of noise, where breaths were interrupted by constrictions in the VT (Lieberman, 1984). Nowadays, human VTs emit sounds that are easy to interpret (Fitch, 2000). Ordinary breathing can create noise if the vocal cords are narrowed. The 0- to 4-kHz range is the most useful for perception, having approximately 1 resonance/kHz (Fant, 1970). Speech energy tends to decrease with frequency due to the low-pass nature of puffs of air from the glottis.

Speech consists of sequences of words in utterances that are organized by the rules of syntax and semantics that people internalize when learning language. Each spoken word is made up of a series of *phones,* which are physical sounds for intended phonemes. Phones vary in periodicity, intensity, and spectrum; speech analysis exploits these domains.

In creating dynamic speech, speakers vary the VT shape to create sounds with different *formants*, which are resonances whose center frequencies are acoustic cues to listeners to distinguish different phones. In addition to conveying the identities of phonemes to listeners, speech also has information about syntactic structure and emphasis, conveyed by *intonation.* This term covers a range of acoustic phenomena that include f_0, sound amplitude, and phone durations, whose relationships to linguistic information are highly complex.

Speech waveforms vary greatly in time (**Figure 2**), even for the same words produced by one speaker. This is partly due to many small variations in spectral phase, which result from VT losses (friction, thermal) and minute airflow variations. These variations do not convey useful phonetic information, and thus speech analysis often is designed to discard phase as a useful cue. Speakers instead articulate to achieve VT shapes that yield suitable spectral amplitudes (formant frequencies),

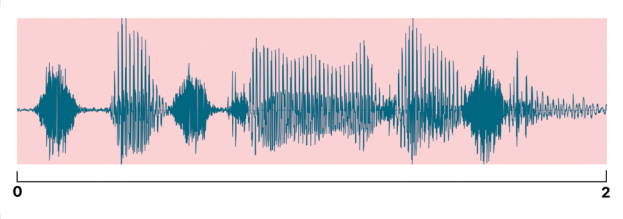


Figure 2. *Speech waveform of the utterance "Speech communication." Note the six strong vowel portions interspersed with weaker consonants.* ***Nos. on bottom:*** *time in seconds.*

and listeners focus on this intended detail for deciphering speech.

Precisely which aspects of speech are relevant for human communication are difficult to demonstrate. Controlled perceptual experiments with human listeners use synthetic stimuli emulating speech (Liberman, 1957). These demonstrate that certain changes in physical stimuli can reliably evoke phonetic perception, but there is only circumstantial evidence that these are actually employed in speech. Because it is difficult to prove direct relationships between acoustic features and perception, some neural speech algorithms avoid all preprocessing (analysis) of speech, instead training recognition models directly on speech waveforms (Ravanelli and Bengio, 2018). However, such neural models effectively learn processing in a way that is similar to mainstream speech analysis.

Analog-to-Digital Conversion

Speech signals vary continuously in time, and so it becomes important that temporal details in speech be preserved in the analysis process. Digital computers need sequences of data for processing, so the *analog-to-digital conversion* process takes sample values from signal intensity at uniformly spaced intervals. The interval at which the computer sampling occurs is called the sample or *Nyquist* rate. This rate must exceed twice the highest frequency in the signal (Picone, 1993) to allow proper representation of the temporal features of signals. Furthermore, an analog low-pass filter must first suppress all higher frequency energy to prevent distortion in the reconstructed speech of codecs. Given the bandwidth (typically 300-3,200 Hz) of standard telephony, 8,000 samples/s (hertz) is a commonly used sampling rate. Nontelephone applications are wideband because listeners may discern frequencies up to 20 kHz (Jacewicz et al., 2023). Some applications (such as compact discs) have sample rates of 44.1 kHz. Other common applications include internet audio at 16 kHz.

Dynamic Energy over Limited Time Ranges

Because speech is nonstationary (dynamic), characteristic measures vary in time. Typically, analysis averages measures over brief time ranges called windows, repositioned regularly at a periodic frame rate. A common standard for much of speech processing is 100 frames/s (Spanias, 1994) that accommodates *coarticulation,* which is VT motion from phone to phone (Öhman, 1966). Speech averages approximately 12 phones/s and has both anticipatory and lagging effects of VT organ movements. The simplest relevant measure of speech is its energy. Energy can help distinguish classes (e.g., vowels from fricatives) as well as distinguish speech from background noise.

Periodicity

Besides energy, the other most salient feature of voiced speech is periodicity. Vocal cords vibrate around 100 times/s for men and 200 times/s for women. The physical f_0 is heard as perceptual *pitch,* as the brain processes the timing and locations of auditory neural firings along the basilar membrane of the inner ear (Moore, 1995). The f_0 is useful in tone languages to distinguish words phonemically and in most languages, syntactically and semantically to delimit phrasal units, distinguish yes/no questions from statements, and give emphasis (O'Shaughnessy, 1979).

Estimation of the f_0 (Rabiner et al., 1976) exploits the regularity of vocal cord closures, each of which causes a speech energy increase, with ensuing gradual decay until the next closure (**Figure 2**). Waveform peaks related to strong harmonics in the first formant often confound simple f_0 estimation. Also, "periods" in sonorants have small deviations in amplitude (*jitter*) and timing (*shimmer*) (Horii, 1979). Most f_0 detection algorithms search for peaks in either the speech waveform or its spectrum and assume small changes from period-to-period (except at voiced/unvoiced transitions).

Measuring periods is most reliable if the signals are simplified in spectral amplitude and phase. Most f_0 detectors do this by reducing the spectral detail irrelevant

to periodic structure (spectrum flattening). A process called *autocorrelation* yields a zero-phase and squared-amplitude spectrum, convolution of a signal with its time-reversed version. This measure, which eliminates phase while retaining spectral amplitude, is also widely used in telephony codecs.

Spectral Analysis

The features of energy and f_0 help classify speech versus nonspeech (Rabiner and Sambur, 1975), but most applications require much more information about the speech signal. A discrete Fourier transform (DFT) provides an energy representation of speech, consisting of N spectral samples (N being the window duration; Picone, 1993). N can be as small as 10 for codecs to model 4-5 formants (using 2 parameters to represent each resonance) or as many as hundreds (when seeking details over multiple pitch periods). Various analysis methods represent the spectral distribution of speech energy because this information correlates well with many aspects of speech production and perception (Fant, 1970).

VT shapes for basic vowels of most languages (/i, a, u/) have widely spaced formants, as seen in spectral displays (**Figure 3**). For consonants, concentrations of energy vary consistently with *place of articulation* (VT constriction). Relevant communicative cues are found in the energy peaks, not in the valleys.

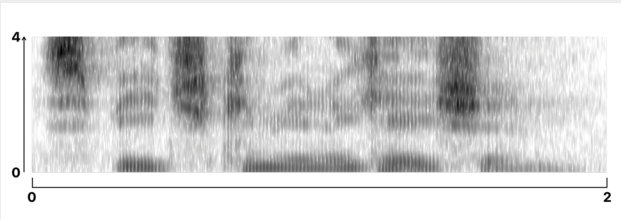
Speech codecs and ASR often use a version of DFT called *subband coding* (SBC) (Crochiere et al., 1976) that exploits the greater energy and better resolution found in human speech and hearing at lower frequencies. In SBC, speech is separated into M distinct spectral ranges by band-pass filters, with ranges following the perceptual *Mel scale*. In this scaling, spacing is linear below 1 kHz and logarithmically wider above 1 kHz; hence, there is less precision as frequency increases (Davis and Mermelstein, 1980). This scale reflects the distribution of sensory hair cells along the basilar membrane. Instead of a DFT transforming N time samples of speech into N spectral values, SBC yields much reduced M time signals of smaller bandwidths, which allows better exploitation of the distribution of spectral information. For codecs, each filter output (*channel*) uses smaller step sizes for more precision at (more perceptually useful) lower frequencies. ASR, which need not preserve waveform detail, simply calculates M channel energies. Some older vocoders used about 20 channels (Picone, 1993); modern ANN ASR uses $M = 40–100$ (Mohamed et al., 2022).

A major challenge for speech analysis is to efficiently represent phonetic information in each frame of speech. One choice is to create hundreds of DFT spectral samples versus 10 *linear predictive coding* (LPC) coefficients (see **Linear Predictive Coding**) (Makhoul, 1973). In most speech (sonorants), the focus is to model major aspects of a spectrum of 4-5 resonances, which appear as a modulation superimposed on dozens of harmonics. High-bit-rate codecs often directly replicate speech samples and minimize a success criterion called the *signal-to-noise ratio* (noise from quantization), but other applications seek phonetic data at frame rates (100/s) much lower than the sampling rates (8,000/s).

Some popular applications (e.g., MP3 players) use a direct encoding of speech spectra in *adaptive transform coding* (Zelinski and Noll, 1977). Although SBC uses a small set of filters, ATC retains all spectral samples. ATC must then inform its decoder about dynamic quantizer parameters. These step sizes and numbers of bits for all spectral samples are assigned in proportion to rough estimates of energy.

A final spectral measure for speech is the *zero-crossing rate,* which simply counts the times the waveform changes the algebraic sign (baseline 0 is normal atmospheric pressure in silence). It roughly estimates the dominant frequency in speech, being low for sonorants and high for noisy sounds. Combined with energy, it can be used for discriminating speech from background noise.

Figure 3. *Wideband speech spectrogram (utterance in* ***Figure 2****). The darkness displays logarithmic energy. Time in seconds is on the* x*-axis and frequency in hertz is on the* y*-axis. Formants show as bands that are roughly horizontal but vary in time.*



Time Windows

Speech is dynamic. It has phones of finite durations, changing center frequencies and bandwidths of resonances and

varying phase. When viewing sonorants through windows, to observe these varying phenomena, DFT does not show (theoretical) discrete components because harmonics are spread over a frequency range inversely proportional to window duration. Typical *narrowband* spectrograms use a window with multiple periods (bandwidth less than f_0 to visualize harmonics), whereas *wideband* spectrograms display precise timing transitions and clear formants (**Figure 3**).

Most speech applications have more interest in the broader envelope of spectra than harmonics because the former relates to VT shape, whereas the latter varies with excitation. Both are relevant for speech coding and synthesis, as their outputs require full signals for human listeners, but ASR focuses on the VT shape for phone identification, frequently excluding consideration of excitation (it is also difficult to integrate relevant information over different timescales).

Linear Predictive Coding

Speech has temporal correlations at widely different ranges: local (within pitch periods), midrange (coarticulation across phones), and global (syntactic and semantic aspects across words). These variations in temporal complexity during the speech production process complicate the speech analysis process compared with signals simpler than speech. For instance, high bit rate codecs using logarithmic quantizers accommodate the non-uniform probability distribution of speech sample amplitudes but do not exploit the relevant temporal variations of speech.

Most speech analysis exploits short time features of speech, which correspond to the VT shape and spectral envelope. One analysis technique is to compare the difference between each speech waveform sample and an estimate of that sample, based on N immediately prior samples (**Figure 4**). This difference is usually far smaller than the differences between the samples themselves, thus allowing smaller step sizes and reduced quantization noise.

The predicted estimate used is typically a linear combination of $N = 10$ prior samples. Codecs in cellular telephony still use this traditional LPC (Makhoul, 1973). As sonorants have primary excitation in each period at vocal cord closure, ensuing samples largely follow the

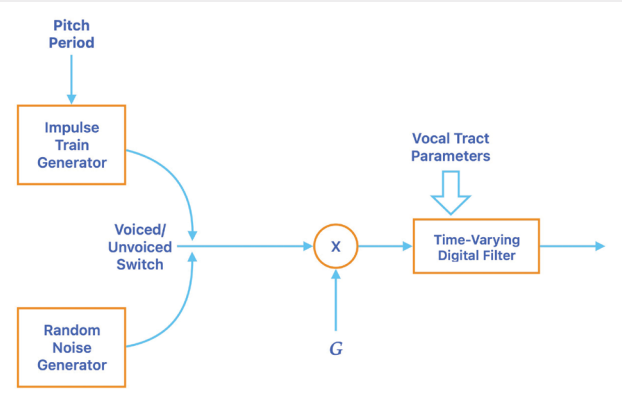


Figure 4. *Linear predictive synthesizer. Noise or periodic pulses (at the fundamental frequency (f_0) rate) simulating breaths from the lungs are multiplied (X) by a gain factor (G). The filter amplifies the resonance frequencies as determined by the vocal tract shape.*

impulse response of the VT (signal from the VT filter with one-sample input).

Mel-Frequency Cepstral Coefficients

For decades, a common method of speech analysis has been mel-frequency cepstral cefficients (MFCCs) (Davis and Mermelstein, 1980). Cepstral analysis originated for *deconvolution,* estimating both components of a filtering. For example, output speech $s(n)$ is modeled as coming from a filter with VT impulse response $h(n)$ excited by input $e(n)$, which is constriction noise or glottal puffs. Cepstral analysis can be used for dereverberation, radar/sonar, and speech. Speech is often viewed as periodic or noisy input to a VT filter; thus, cepstral analysis can estimate both filter and its excitation input.

Although MFCCs are common for speech analysis, simpler logarithmic *band-pass filter energies* (BFEs) (MFCC, but without the final inverse transform) are increasingly used. The inverse step yields uncorrelated parameters, but it does not correspond to human perception. To get each $c(n)$ value, one multiplies the mel-deformed spectrum by an n-period sinusoid and then averages. MFCCs are used because the combined information of all $c(n)$ represents enough detail to distinguish phones.

MFCCs or BFEs can represent the static position of the VT in each frame of speech, but VT velocity and acceleration

are also useful measures (Picone, 1993). Thus, static MFCCs are often augmented by 13 *delta* (frame difference) values and 13 *delta-delta* values. Using 13 MFCCs, one can discriminate spectral differences of approximately 100 Hz, which corresponds to small differences in formants in languages with many vowels, such as English. For example, tongue height differences correlate to f_1 in the range of 300-700 Hz for 5 vowels (/i, I, e, E, ae/).

Analysis methods suffer when audio has distortions (e.g., environmental/channel noise or reverberation). Current methods treat speech spectra globally without distinguishing perceptually important prominences. Future analysis could focus on spectral peaks because they are salient amid typical distortions. Such approaches have been avoided in modern ASR due to the difficulty of integrating such information with common frame-based methods.

Artificial Neural Networks

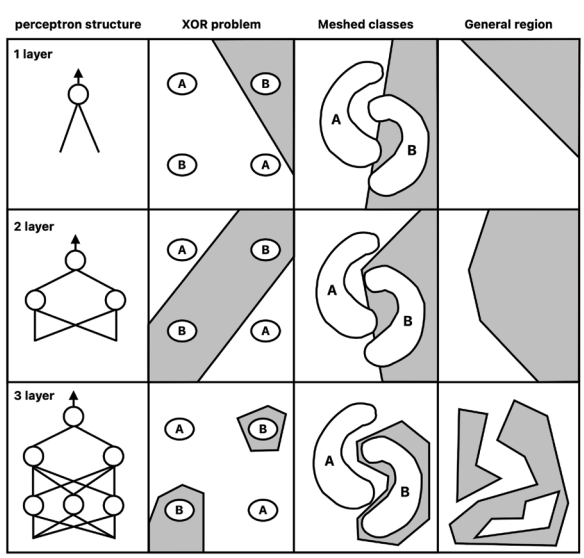
Now we discuss the major tool that is currently used to process almost all speech applications. The function of an ANN is to convert an input data sequence to an output sequence. By using a huge number of nonlinear operations, an ANN has potentially excellent processing power. ANNs are trained on large amounts of data, guided by a *cost* or *loss function* to minimize entropy or a mean-square difference between a target and estimated signals. For ASR or speaker verification, network inputs are speech samples or frame-based spectral representations (MFCCs or BFEs), and the outputs can be probabilities for text corresponding to the speech or a decision on speaker identity. For applications such as speech coding and speech enhancement, an encoding ANN outputs compressed data (for transmission), and then a decoding ANN maps back to reconstructed speech samples (or corresponding spectral vectors).

Because ANNs are based on natural neural systems, consider a biological neuron. Its output is binary (a brief pulse known as an action potential, when the weighted sum of its inputs exceeds a specified threshold). In the human nervous system, neurons at the initial processing group or *layer* receive sensory information (from the eyes and ears). Nodes in an ANN use a nonlinear threshold operation (*activation function*) that is generally smooth and monotonic to facilitate mathematical differentiation, which allows the use of derivatives for gradient-descent parameter modification in iterative training (where the model parameters are updated in proportion to the slope of a *loss* function).

In the simplest form of ANN, each layer has nodes feeding outputs to the next layer. Biological neural networks have hundreds of billions of neurons, whereas ANNs usually have millions of nodes. Nodes may have operations other than binary nonlinear weighting, such as *pooling* (selecting a maximal value among inputs) (Scherer et al., 2010).

For classification of input data, one can visualize an N-dimensional representation space, where N is the number of samples, such as a speech waveform (or spectral) sequence. Each node with these N inputs then determines a flat surface in the space by the linear combination of its weighted inputs; 0/1 output specifies either side (**Figure 5**). Each node thus can act as an elementary

Figure 5. *Possible regions for multi-layer artificial neural networks (ANNs). The shaded/unshaded regions, bordered by* ***black lines****, are two estimated regions for a classification problem between objects* ***A*** *and* ***B*** *(two classes whose borders are shown with* ***circles*** *or* ***lines****). More layers allow more complex regions. ©1987 IEEE. Figure reprinted, with permission, from R. Lippmann, (1987), "An introduction to computing with neural nets."* IEEE ASSP Magazine, *4(2), 4-22.*



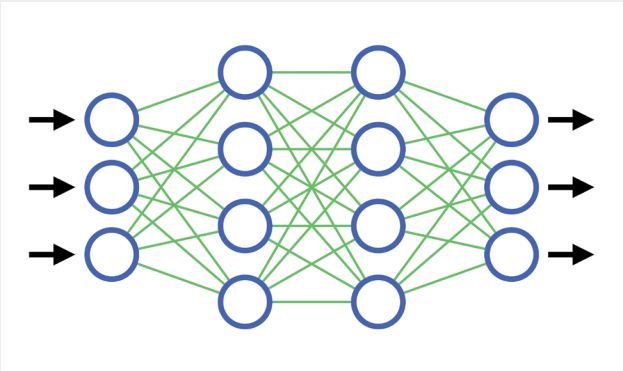


Figure 6. *Structure of a simple 4-layer ANN.* ***Circles:*** *nodes in vertical sets (layers) connected by links (**green lines**) where flow progresses from **left to right**. Each link corresponds to a weighting, and each node sums the weighted inputs and outputs as a thresholded binary value.*

classifier. With three or more layers, an ANN may optimize the combined locations of surface boundaries of complex class regions in the space. In addition, choices for model parameters allow for decisions that are more complex than binary. Such complexity is often needed to handle the huge variability in many applications, including speech. However, this complexity hinders heuristic interpretation of ANNs. The parameters of ANNs (node weights and biases) are available during design, but the ANNs complex operation greatly hinders direct parameter manipulation (debugging).

ANN parameters are trained to minimize a differentiable loss function, which is modeled as a cost to minimize errors. Direct minimization of errors is infeasible because the relationship between network parameters and classification errors is extremely complex. As ANNs derive directly from many examples, they must avoid *overfitting,* where models become too close to matching observed data points when using limited training. To generalize models, training data are often modified by artificial distortion (additive noise and/or deletion of random portions in time and frequency) (Ko et al., 2015).

Basic ANNs are *fully connected feedforward neural networks* (FFNNs), meaning that all nodes in each layer feed all nodes in each successive layer (**Figure 6**). This, however, is overly general for most applications because patterns to be analyzed tend to have a diversity of local and global aspects. For example, objects often occupy only small portions of an image or identifying a vowel using BFEs may only need small subsets (limited frequency or temporal portions of a spoken vowel). To exploit the often-local nature of classification, one may use *convolutional neural networks* (CNNs) (LeCun and Bengio, 1995). A CNN processes input data over small ranges called *receptive fields.* CNNs were first developed for image recognition, to enhance edges. Applied to speech, CNNs can filter formants in a spectrogram. However, edges in spectrograms are less relevant as features for speech than they are for images.

Whereas CNNs exploit local data correlations, *recurrent* networks handle longer range patterns (Schuster and Paliwal, 1997). Pertinent information in speech is distributed very unevenly in time and frequency. Thus, sections of speech with low energy are far less useful than portions with strong formants, and coarticulation and intonation affect speech over tens and hundreds of frames, respectively. Both ANNs and HMMs struggle to exploit this nonuniform distribution of information; basic ANNs do best with static patterns (Lippmann, 1987).

Recurrent neural networks (RNNs) have architectures with feedback to get over the problem of uneven distributions of variability, such as those found in speech. They use distributed hidden states that store information about past input. A common recurrent method is *long short-term memory* (Hochreiter and Schmidhuber, 1997). In human perception, listeners internalize portions of speech (several seconds) in some analyzed form in their short-term memory. Utilizing such a wide range of data in FFNNs and CNNs is exceedingly difficult. The range of analysis of an RNN can extend well beyond the very limited scope of CNN kernels or of context-dependent HMMs.

Automatic Speaker Verification

Automatic speaker verification (ASV) is a speech-analysis task that has followed research like ASR, despite being a very different task. ASR extracts phonetic information from VT shape via acoustic analysis, whereas ASV distinguishes different VTs. ASV can be more difficult to accomplish than other speech tasks because what distinguishes behavioral output such as speech is far less definitive. Impostors can simulate others' voices, and recordings can be used surreptitiously (*spoofing*) (Wu et al., 2015).

Final Comments

This article has considered how to analyze speech to understand how humans and machines go about their perception. Spectrograms formed the basis of speech analysis until 1970. A major breakthrough in the speech analysis and decoding field was LPC, which is still used in cell phones today. Versions of spectral analysis have been used for speech applications, including SBC and MFCCs. Although ANNs have existed for 50 years, they are only recently dominating applications for speech, due to improvements in computing power and the availability of large databases.

Because many of the analysis methods were developed years ago, one may speculate about future breakthroughs. Efficient methods have not yet come close to human performance for many speech applications, and current approaches are fragile. For example, ASR trained on limited data does not generalize well to variations in speakers, contexts, and environmental degradations such as noise. Human listeners can handle the huge variability of speech from different speakers and under many distortions. ANNs try to generalize via various types of regularization, but such methods do not reflect many actual acoustic conditions. Also, current methods struggle to exploit the full range of information in speech, given the diverse ways that phonetics, syntax, and semantics are embedded. Anyone who has struggled with Siri or Alexa devices to understand what they are trying to say can relate. Hence, the speech-analysis field has more to explore.

Acknowledgments

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For author bio, please go to acousticstoday.org/bios-19-4-3

David Geffen Hall and the Evolution of Acoustics at Lincoln Center

Paul H. Scarbrough

In 1962, Leo L. Beranek published *Music, Acoustics and Architecture*, the landmark book documenting his study of 54 famous concert halls and opera houses around the world. In this pioneering work, Beranek sought to understand and frame a set of criteria that would correlate subjective judgments of acoustic quality with the physical principles at work in the concert hall. He had used the findings in his study of famous concert halls and his designs for buildings like the Koussevitzky Music Shed at Tanglewood, Lenox, Massachusetts, to inform designs for the new Philharmonic Hall at Lincoln Center, New York, New York. At the time, Leo believed Philharmonic Hall would validate his findings and lay the foundations for successful acoustical design long into the future (Beranek, 1962). Sadly, forces beyond Beranek's control would undo his thoughtful designs for the hall and set in motion one of the most famous acoustic failures of the twentieth century. It would take another 60 years, multiple minor renovations, and two major reconstructions before the hall would finally possess acoustics worthy of the New York Philharmonic Orchestra.

Genesis of Philharmonic Hall

Lincoln Center was conceived in the 1950s as a way to secure New York City's preeminence as the cultural capital of the United States. John D. Rockefeller III, Robert Moses, and Mayor Robert Wagner identified Lincoln Square at the intersection of Broadway, Columbus Avenue, and West 65th Street in Manhattan as the site for their new performing arts center. Despite protests from the residents of the vibrant neighborhood, the city acquired over 16 acres of land, evicted the residents, and demolished much of the neighborhood.

With the site secured, Lincoln Center selected a star-studded board of architects to design the center, including Wallace Harrison, Max Abramovitz, Eero Sarinen, Philip Johnson, and Pietro Belluschi. Harrison chaired this board and parceled out the projects, keeping the design of the new Metropolitan Opera House for himself, while giving the design of Philharmonic Hall to his partner Max Abramovitz.

Lincoln Center designated Philharmonic Hall as the first building to be erected on the campus. Carnegie Hall, the world-famous New York City concert hall and home of the New York Philharmonic, had previously announced plans to demolish the 1891 icon, leaving the Philharmonic, founded in 1842 and the world's third oldest orchestra, homeless, lending some urgency to the work.

Abramovitz collaborated with Beranek to develop the designs for the new hall, which were unveiled to the public in May 1959. Drawing on a long familiarity with and affinity for Symphony Hall in Boston, Massachusetts, Leo had designed a shoebox hall seating 2,400 people (Parmenter, 1959). This was when the trouble began, with some newspaper editorial boards criticizing Lincoln Center about the seat count. Here, they argued, was proof that Lincoln Center was not really for the masses because the new hall would seat some 400 fewer people than Carnegie Hall. Explanations that the seat count had been driven by acoustical considerations left the press unmoved, noting that many famous and well-regarded halls like Carnegie Hall and Symphony Hall sat more than 2,400 people.

Lincoln Center, concerned that their entire endeavor was in jeopardy, directed Abramovitz to add at least 200 seats to the hall over Beranek's objections. With the foundations for Philharmonic Hall already being poured, adding seats would be no easy feat. To increase the seating area, Abramovitz first relaxed the geometry of the sidewalls of the hall, breaking out of the straitjacket of Beranek's shoebox concept so that the hall could get wider at the rear than it was near the stage. Abramovitz seized the opportunity

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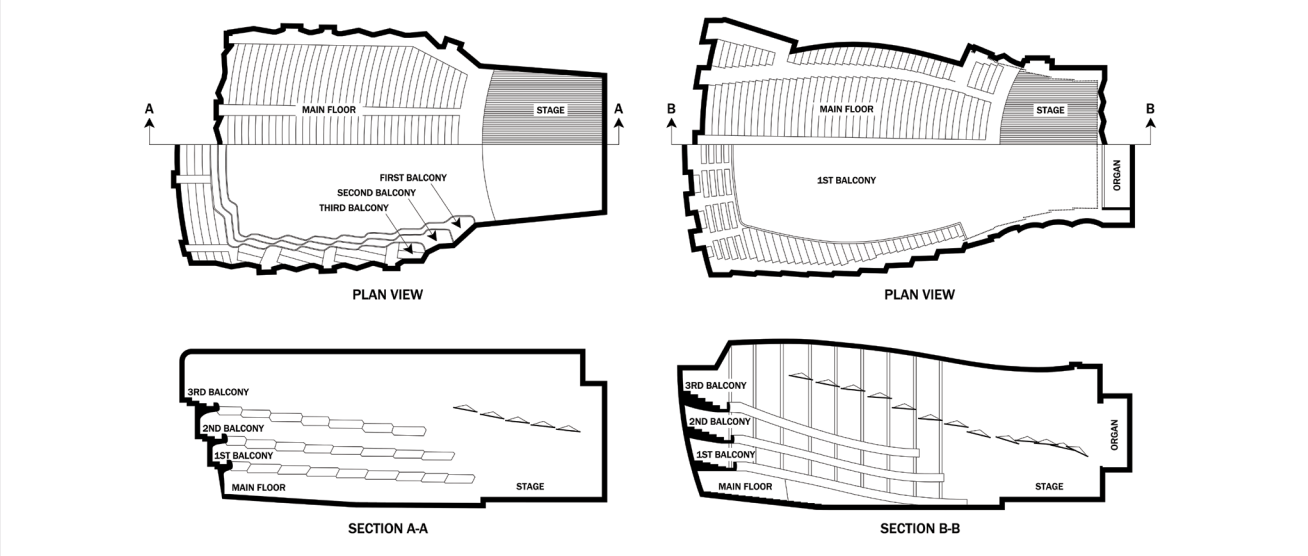

Figure 1. *Floor plans and sections comparing the original 2,400-seat design for Philharmonic Hall as unveiled to the press in May 1959 (**left**), versus the revised 2,646-seat design that was ultimately built (**right**). In the plan views, note how radically the geometry has changed in the revised design and how much the revised hall has grown compared to the original design. In section A-A, note how the underside of the stepping side balconies are essentially horizontal, in contrast to section B-B where the side balconies slope steeply down.*

to make other important changes to the designs. The side tiers, which had originally been horizontal, now sloped sharply down, so that the first balcony sloped down to connect to the main floor, the second balcony down to the first and the third balcony down to the second (see **Figure 1**).

Philharmonic Hall: The Early Years

Acoustics in the new Philharmonic Hall got an icy reception from music critics and musicians. The hall was found particularly lacking in bass warmth. Beranek's studies of the finished hall revealed flaws in the design of the overhead hexagonal acoustical canopy panels and indicated that the panels, if increased in size and rearranged, could correct the poor bass response in the room. The total cost of the revamp was estimated to be $60,000. Unfortunately, some music critics and conductors were unrelenting. Harold C. Schonberg, the powerful music critic of *The New York Times*, was quite critical (Schonberg, 1962a,b). So too was George Szell, the longtime music director of the famed Cleveland Orchestra, Cleveland, Ohio, whose advice to the Lincoln Center Board comprised three recommendations: tear the hall down, start all over, and fire Beranek.

Lincoln Center and the Philharmonic formed a committee of advisers including Vern Knudsen (a physicist and former chancellor of the University of California, Los Angeles, and third president of the Acoustical Society of America), Paul Veneklasen (an acoustical consultant), Heinrich Keilholz (a former Deutsche Grammophon Tonmeister), and Manfred Schroeder (from Bell Telephone Laboratories, Murray Hill, New Jersey) to study the hall and opine on Beranek's remediation plan. Initially, the relationship between Beranek and the committee seemed collegial but that would soon change. By May 1, 1963, Beranek thought that he and the committee had come to a consensus on a plan of improvements for the hall that largely reflected the recommendations he had made to Lincoln Center in December 1962. Sometime between early May and June, the situation evolved, and Abramovitz informed Beranek that he was adopting the committee's plan. Knudsen summarized this plan in the meeting minutes of the Building Committee on August 22, 1963 (NYPhil Digital Archives, 1963):

- Eliminate echoes from the back of the audience chamber by reprofiling the fascias of all three balconies and adding sound absorptive material on the rear walls of the second and third balconies.
- Extend the canopy to within six inches of the rear wall of the stage and add infill panels at the upstage rear corners.
- Build new risers for the orchestra on stage.

Table 1. *Octave-band reverberation time: Philharmonic Hall with simulated audience*

Octave-band center frequencies, Hz					
125	250	500	1,000	2,000	4,000
Reverberation time, s					
3.0	2.6	2.2	2.2	2.1	1.6

Data from Beranek, 1962.

This plan was apparently so at odds with what he had proposed that, on the September 18, 1963, Beranek formally disavowed any association with the ongoing efforts to improve the hall's acoustics (Beranek, 1963).

In all of these deliberations, there was no consideration of how Abramovitz's changes to the design of the hall might have impacted the acoustics, particularly the perception of reverberance in the hall. Toward the end of the tuning process for the hall, Beranek had collected the octave-band reverberation-time data shown in **Table 1**.

These data suggested that the hall should have been quite reverberant, but many observers described the sound as dry. Over the past 60 years, acoustical designers have developed a firmer grasp of how the shape of a hall can impact its reverberance. Shoebox concert halls (with long parallel sidewalls) are acknowledged to create reverberant fields that are quite strong relative to the direct sound, whereas fan-shaped auditoria of equal cubic volume and sound-absorptive properties are known to have weak reverberant fields relative to the direct sound of the sound source. The final floor plan of Philharmonic Hall was actually more fan shaped than shoebox shaped, which undoubtedly reduced the perceived reverberance of the hall.

By late 1963, Keilholz had emerged as the key voice directing the work. Although Knudsen remained the titular head of the committee, his reports and letters to the Building Committee increasingly refer to Keilholz's recommendations. Keilholz was a curious choice, being an engineer with little knowledge about architectural acoustics (Fantel, 1976). He was, though, held in high regard by the conductor George Szell and by spring 1965, the ongoing acoustical work at Philharmonic Hall was under his direction.

In 1969, Keilholz made his final changes to the hall, removing all of Beranek's acoustical clouds and replacing them with a stepped wood ceiling. **Figures 2** and **3** show how the hall had changed from 1962 to 1969. Keilholz also replaced the original audience seating with new chairs featuring thinner upholstery, allowing the seat count to grow to 2,836 seats (Henahan, 1969). The results seemed to assuage some of the hall's most severe critics, most notably Schonberg who, on October 12, 1969, called the renewed acoustics "a complete success." He did note, however, that the bass was still weaker than desired (Schonberg, 1969). With Schonberg now quieted, leaders around Lincoln Center could breathe more easily.

The hall remained largely unchanged until 1976, with the exception of some experimental concerts that Philharmonic Music Director Pierre Boulez instituted in June 1973. These concerts, referred to as the "Rug Concerts," involved temporarily removing seats from the orchestra floor, pushing the Philharmonic downstage, and allowing the audience to lounge on carpets (Ericson, 1973). The concerts were popular with the public, but the costs to stage them, coupled with the reduced revenue occasioned

Figure 2. *Philharmonic Hall as it appeared shortly before opening in 1962. Photograph by Ezra Stoller, courtesy of the New York Philharmonic Shelby White & Leon Levy Digital Archives.*

Figure 3. *Philharmonic Hall after Keilholz completed the last of his renovations in 1969. Photograph by Sandor Acs, courtesy of the New York Philharmonic Shelby White & Leon Levy Digital Archives.*

by removing so many seats, made this a short-lived experiment, surviving for only five seasons. However, one finding endured with more than a few observers noting that the Philharmonic sounded distinctly better when it moved off the stage and into the auditorium. This observation would surface many times in the coming decades.

Avery Fisher, Philip Johnson, Cyril Harris, and the 1976 Reconstruction

By the mid-1970s, grumbling had resumed about the hall's acoustics. In 1975, Avery Fisher made a $10,000,000 gift to the New York Philharmonic and the building was renamed in his honor. After securing Lincoln Center approval, the Philharmonic asked Fisher if he would consent to his donation being used for a major makeover of the hall. Fisher agreed.

Philharmonic Chairman Amyas Ames asked acoustician Cyril Harris to design the renovations to the hall. Harris was well regarded for his work on the Kennedy Center Concert Hall, Washington, DC (1971) and Orchestra Hall, Minneapolis, Minnesota (1974). He initially demurred, fearing he would not be able to make the changes he deemed necessary. Ames persisted however, and Harris ultimately agreed subject to three conditions:

- That Lincoln Center give him as much space in the building as he deemed necessary.
- That Harris has ultimate decision-making authority in the event of a dispute between the architect and the acoustician.
- That Philip Johnson be given the architectural commission for the renovation (Bliven Jr., 1976).

Audiences returned to a dramatically different hall in the fall of 1976 (see **Figure 4**), and the initial acoustical reviews were fairly positive, with music critics Schonberg (1976) and Henahan (1976) and architecture critic Ada Louise Huxtable (1976) all remarking favorably about the acoustics of the hall. Curiously, reverberation times in the new Avery Fisher Hall were actually shorter than what Beranek reported for the original Philharmonic Hall, particularly at low frequencies (see **Table 2**). Here lay the seeds of future discontent with the renewed hall.

1992 Stage Renovations

By the early 1990s, musician dissatisfaction with the stage acoustics surfaced again. Music Director Kurt Masur was well-known for his exacting standards, and the musicians of the Philharmonic were frustrated that they could not hear one another on stage, inhibiting their ability to meet Masur's expectations.

The last thing Lincoln Center President Nathan Leventhal wanted was to reopen the matter of acoustics in Avery

Figure 4. *Avery Fisher Hall after the 1976 Renovation. Photograph by Norman McGrath, courtesy of the New York Philharmonic Shelby White & Leon Levy Digital Archives.*

Table 2. *Octave-band reverberation times: Avery Fisher Hall with audience*

Octave-band center frequencies, Hz					
125	250	500	1,000	2,000	4,000
Reverberation time, s					
1.60	1.76	1.78	1.74	1.74	1.80

Data from Beranek, 1996.

Fisher Hall, but in 1990, he reluctantly allowed the Philharmonic to commission an acoustical study, provided all parties agreed that the exclusive focus would be the stage acoustics.

J. Christopher Jaffe and Paul Scarbrough conducted this initial study, which assessed three changes:

- Extending the stage approximately 16 feet out into the audience chamber.
- Suspending lower acoustical reflectors over the downstage part of the orchestra.
- Adding diffusive panels to the upstage wall behind the brass and percussion sections.

The assessment included eight configurations tested over the course of two special orchestra rehearsals. These ranged from the orchestra in its normal position with no added canopy or diffusers to the orchestra on the stage extension with the canopy and diffusers in place.

To obtain more reliable subjective responses to these changes from the musicians, the rehearsals were recorded using three binaural heads placed on stage: one among the violins, one near the woodwinds and brass, and one among the cellos and double basses. One binaural head was also set in the audience. Masur and a jury of musicians then ranked a series of A-B comparisons assembled from the binaural recordings.

Jury testing confirmed that the combination of the overhead canopy and upstage wall diffusers together produced the most positive responses from the musicians, although nearly a third of the musician jurors preferred another configuration under some circumstances. This diversity of responses suggested that more was at play in the musicians' stage experience than the three elements under test.

Comprehensive acoustic measurements with and without the test elements also yielded revealing findings. A sense that a lack of diffusion on the stage was giving it a brittle and harsh acoustic quality seemed to be confirmed when the musicians reported a marked improvement with the addition of the upstage wall diffusers. These subjective impressions correlated well with measurable reductions in Zwicker sharpness, a psychoacoustic metric not usually considered relevant in concert hall acoustics.

Disturbing, however, were the room acoustic findings in the auditorium itself. These confirmed a long-standing critique of Avery Fisher Hall, namely its poor bass response. Analysis of octave-band decay characteristics showed a marked decrease in reverberation time and strength at low frequencies (250 Hz and below) compared with midfrequencies (500 and 1,000 Hz). Increased strength at low frequencies has been correlated with subjective impressions of bass warmth in symphony halls, so this finding was not surprising. Although the charge had been to focus strictly on the stage acoustics, the observation about the poor bass response was included in the final report, something that Lincoln Center did not appreciate.

When the time came to act on the report findings, Lincoln Center engaged Russell Johnson and ARTEC Consultants to conduct further studies and implement changes. ARTEC's changes, which included quite large diffusive elements on the side walls of the stage and a complex overhead acoustical canopy, debuted with the start of the 1992–1993 Philharmonic season (Kozinn, 1992). Philharmonic musicians from that era gave these changes decidedly mixed reviews.

A New Hall for a New Century

With the approach of the 40th anniversary of the opening of Philharmonic Hall, Lincoln Center began planning a comprehensive $1.2 billion redevelopment of its campus. Renovating Avery Fisher Hall would kick off the effort, with London-based Foster + Partners tapped to lead the design in 2002. Initial planning moved forward into 2003, but the effort stalled when the New York Philharmonic stunned the music world on June 1, 2003 by announcing that it

would leave Lincoln Center and return to its former home, Carnegie Hall (Blumenthal and Pogrebin, 2003). Negotiations between the Philharmonic and Carnegie dragged on into the fall of 2003, but by October 7th, the deal was dead (Pogrebin 2003a). Carnegie Hall, which had not had an orchestra in residence since 1962, had not anticipated just how much the Philharmonic would dominate its schedule and unacceptably curtail Carnegie's own program of internationally renowned touring orchestras and soloists. The Carnegie debacle also had an unfortunate consequence, poisoning the waters between Lincoln Center and the Philharmonic and souring Lincoln Center President Reynold Levy's enthusiasm for the Avery Fisher Hall renovation (Pogrebin, 2003b).

In May 2004, the Philharmonic announced that it would proceed with interior renovations to Avery Fisher Hall based on plans developed by Foster + Partners. Unfortunately, by this time, renovation plans for Alice Tully Hall, the smaller concert hall at Lincoln Center, were nearly complete. Lincoln Center could not countenance both Avery Fisher Hall and Alice Tully Hall being out of service at the same time, and so work at Fisher would have to be delayed until the Tully renovation was complete (Pogrebin, 2004). This stalled momentum for the project and the plans were quietly shelved.

The Mostly Mozart Experience

In 2004, Jane Moss, artistic director for Lincoln Center, was looking to refresh the Mostly Mozart Music Festival, an annual music series that Lincoln Center had started in 1966 to fill the hall while the Philharmonic performed elsewhere in the summer. She charged theater consultant Josh Dachs and acoustician Mark Holden with rethinking how the festival could be presented in Avery Fisher Hall. Dachs proposed moving the orchestra onto a 30-foot extension to the stage. And because Mostly Mozart used a much smaller ensemble than the New York Philharmonic, space to the sides and rear of the orchestra could be populated with audience seating. To provide acoustical support for the orchestra, Holden designed an overhead array of 19 eight-foot-diameter fiberglass discs. Dachs added attractive light fixtures to the mix, which together with the discs appropriately scaled the massive stage to the smaller ensemble and the more intimate repertoire it performed. The new setting, debuting in July 2005, was a hit with the public and music critics (Tommasini, 2005), once again demonstrating how moving the orchestra forward into the auditorium yielded significant acoustical benefits.

Third Time the Charm?

In 2013, a joint committee of Lincoln Center and the New York Philharmonic selected our consultancy, Akustiks, to work with theater consultant Fisher Dachs Associates on plans for a makeover of Avery Fisher Hall. Early work focused on studies of the many concert halls that had been completed in recent years. A team of Lincoln Center and Philharmonic board members and staff visited many of these halls, including those in Reykjavik, Iceland (see bit.ly/48viMGO); Helsinki, Finland (see bit.ly/465Mu3R); Paris, France (see bit.ly/3teLueX); and Hamburg, Germany (see bit.ly/462X1MV) while also studying other successful examples such as the Schermerhorn Symphony Center, Nashville, Tennessee (see bit.ly/3PSQY8n), the Walt Disney Concert Hall, Los Angeles, California (see bit.ly/3t2OFX3), and La Maison Symphonique, Montréal, Quebec, Canada (see bit.ly/3EWPlzS).

To frame the issues for Lincoln Center and the Philharmonic, Fisher Dachs and Akustiks began developing renovation scenarios. One critical issue to be resolved was the form of the new concert room. Many newer halls in Europe and the Disney Hall were of the vineyard type, with seating surrounding the orchestra in steeply raked terraces. This concept was pioneered by architect Hans Scharoun and acoustician Lothar Cremer in their designs for the Philharmonie Berlin, Germany (see bit.ly/48qpe1Z). Design studies quickly revealed that a vineyard concert hall seating at least 2,000 patrons would not fit within the exterior walls of Avery Fisher Hall, but everyone also agreed that the rigid shoebox form of the existing hall placed too much of the audience at too great a distance from the stage to the detriment of visual and acoustical intimacy.

By late spring 2015, a consensus had emerged around a 2,200-seat shoebox concert hall with audience seating wrapping around the sides and rear of the orchestra stage. The hall would feature an orchestra floor with two side tiers and balconies. By late July 2015, a project brief outlined the parameters that would govern the design of the new concert hall. This plan would essentially gut the interior of the building to the iconic perimeter travertine colonnade and construct a new building within its framework.

Propelled in part by the announcement that the renowned music producer, film studio executive, and philanthropist David Geffen (see en.wikipedia.org/wiki/David_Geffen) had donated $100 million to jumpstart the renovation, the selection process for a new architect gained momentum. After a diligent vetting process, the team of Thomas Heatherwick of London and Diamond Schmitt Architects, Toronto, Ontario, Canada, emerged successful in December 2015. Excitement around the selection of the architects was soon tempered by management changes at Lincoln Center and the Philharmonic, with both institutions now finding themselves without chief executives as the daunting task of raising hundreds of millions of dollars bore down on them.

Fortunately, the search for new leadership did not take long, with Lincoln Center tapping Debora Spar to take their helm, while the Philharmonic enticed Deborah Borda to return to New York. Borda was well versed in the Philharmonic from her stint as its president in the 1990s. She also possessed deep experience with concert hall building projects, being widely viewed as the driving force who put the Los Angeles Philharmonic's Walt Disney Concert Hall project back on track and brought it to a successful conclusion in 2005 (Cooper, 2017a).

One of Borda's first actions was to thoroughly assess the plans for the Geffen Hall renovation with her Lincoln Center colleague Spar. They did not like what they saw. The project budget, initially set at $500 million, was on track to top $750 million. Meanwhile, the construction schedule, which had originally been pegged at 27 months, was expanding past 33 months, ensuring that the Philharmonic would lose not two but three full seasons in the hall. No orchestra had ever weathered such a prolonged absence from their principal concert venue. Concerned that audiences would not return to Lincoln Center when the hall reopened, Borda and Spar abandoned the Heatherwick/Diamond Schmitt scheme (Cooper, 2017b).

Within six months, Lincoln Center and the Philharmonic recommissioned key members of the previous design team including Diamond Schmitt, Fisher Dachs, and Akustiks to reconceive the project, working within some key constraints that included a project budget not exceeding $550 million and a phased construction plan that minimized the amount of time that the Philharmonic would be out of the hall. Heatherwick was released from the team.

A workable plan was in place by early 2018. The concert hall would essentially be gutted to the perimeter of the original 1962 concert hall and a new room built within its shell. Taking cues from the Philharmonic "Rug Concerts" and Mostly Mozart, the stage would push out into the auditorium by almost 25 feet. Most importantly, the seat count in the room would be cut by over 500, to just around 2,200. The side tiers would be rebuilt and a sizable chunk of the third tier removed. The cubic volume would increase by pushing the sidewalls at the third tier out and by demolishing the original stage ceiling and creating acoustic chambers above a new 10-piece acoustical canopy. The public spaces would be improved and refreshed but would remain largely within the confines of the original floor plates.

The construction schedule relied heavily on offsite prefabrication of key components and would unfold in two phases. A first closure would happen in May 2022, with the hall reopening the following November. The orchestra would then play an abbreviated season in the partially finished hall. The building would close again in May 2023 for some 10 months, with a gala reopening planned for March 2024.

Detailed design work for the scheme resumed in early 2019, at which time the architectural firm Tod Williams Billie Tsien Architects joined the design team and Lincoln Center welcomed a new president, Henry Timms. While Diamond Schmitt remained the architect of record and retained primary responsibility for the design of the concert hall interior, Williams and Tsien took the lead in redesigning the public spaces of the building, with a charge to make these spaces more welcoming. In December 2019, Lincoln Center and the Philharmonic unveiled the designs to the press and public (Cooper and Pogrebin, 2019).

With the designs sufficiently advanced to allow construction of a 1:20 scale model of the design, Christopher Blair undertook extensive acoustical model testing, confirming the soundness of the overall design concept. Simultaneously, work proceeded with the musicians and operating staff of the Philharmonic to finalize the layout for new stage risers for the musicians, a system of platforms that elevate groups of musicians so that they can all better see and hear one another. The riser system was to be fully mechanized, meaning it was critical to get the layout

correct. To vet the riser layout, the stage crew taped out the new stage shape and riser layout. The orchestra then rehearsed in that configuration, allowing the design team to consult with the musicians to understand what worked and what didn't work about the layout. The session proved invaluable, yielding subtle but important refinements to the layout. Close collaboration with the architect resolved other important details, including diffusion on the walls of the hall and the designs for sound-transparent mesh panels to conceal the existing plaster ceiling, one of the only elements retained from the 1976 hall.

With drawings and specifications nearly complete and fundraising progressing well, it seemed that a renewed David Geffen Hall might finally be within grasp. Then disaster, in the form of the Covid pandemic, looked like it might derail the project yet again. In March, New York Governor Andrew Cuomo closed theaters throughout the state. No one suspected that the disruptions caused by Covid would last not weeks or even months but rather years.

Project leadership saw opportunity in the forced closure of Lincoln Center. They asked the design and construction teams whether the project could be accelerated and collapsed into one construction phase. The design team and contractors soon concluded that the project could be accelerated. Some costs would increase to accelerate the work, but others would decrease, particularly the costs associated with staging a shortened Philharmonic season in a partially completed hall. And the best news? The new hall could be completed and reopened in October 2022, some 18 months earlier than originally contemplated. Lincoln Center and the Philharmonic saw this as a win-win scenario, one that would send a message of hope and confidence to a city reeling from Covid. By the end of 2020, Lincoln Center and the Philharmonic had agreed to move forward, and wholesale demolition and reconstruction of the old concert hall proceeded. For the next 18 months, daily supervision by the architects with weekly site visits from the acousticians kept the construction work moving forward at a brisk clip.

As the late summer of 2022 closed in, the moment of truth arrived for acoustics. On Monday, August 15, 2022, promptly at 10 a.m., Maestro Jaap van Zweden raised his baton to lead the Philharmonic in the fourth movement of Beethoven's *Symphony No. 6* (see **Figure 5**). Initially,

Figure 5. *The New York Philharmonic on stage for the first rehearsal in the new David Geffen Hall on August 15, 2022.*

van Zweden experimented with different seating arrangements for the strings to see what sounded best. He finally settled on seating first and second violins on stage right, cellos across from the second violins, and violas across from the first violins. On Tuesday, pianist Emanuel Ax played portions of Mozart's *Piano Concerto No. 17*. Other tuning repertoire included excerpts from Bartok (*Concerto for Orchestra*), Bruckner (*Symphonies No. 4* and *No. 7*), Strauss (*Don Juan*), Stravinsky (*Firebird Suite*) and Rachmaninoff (*Symphonic Dances*).

As tuning week proceeded, surveys of the orchestra gathered impressions about on-stage hearing and the overall sound of the hall, leading to several changes to the elevations and attitudes of the overhead acoustic canopy panels. Requests to improve cross-stage hearing resulted in changes to the angle of the canopy panels flanking the sides of the stage, increasing their tilt angles to direct more sound energy across the stage. By the end of the week, there had been substantial progress.

On October 8, 2022, the New York Philharmonic inaugurated the renewed David Geffen Hall with Etienne Charles' *San Juan Hill*, a new multimedia work featuring Etienne Charles, his Creole Soul ensemble, the Philharmonic, images, and video. The work was amplified, so it was not a true test of the symphonic acoustics, but it did show off the versatility of the new hall and the ability of a new adjustable acoustic banner and curtain system to dampen the reverberance of the hall to better facilitate

amplified sound, something that had been quite problematic in the old hall.

A few days later, on October 13, the Philharmonic gave the natural acoustics a proper workout with a concert featuring Marcos Balter's new work *Oyá*, John Adams's *My Father Knew Charles Ives*, Tania León's *Stride*, and Respighi's *Pines of Rome*. The response of music critics has been overwhelmingly positive and that of musicians even more so. Over the course of the first season, there have been occasional adjustments to the acoustical elements around the stage, and the Philharmonic continues to hone and refine its sound in response to the new acoustics. The adjustable features incorporated into the designs allow for dramatic changes to the sound of Geffen Hall. With the Philharmonic in a transitional period as Music Director Jaap van Zweden winds down his tenure at the end of the 2023–2024 season, further adjustments may wait until 2026 when Gustavo Dudamel takes over as music and artistic director of the New York Philharmonic.

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From the Musicians' Perspective: A Brief History of Stage Acoustics

E. K. Ellington Scott

Introduction

Architectural acoustics has played a significant role in tailoring the auditory experiences of concert halls, opera houses, and other musical spaces around the world (see Scarbrough, 2023, p. 43 in this issue). Planning for these spaces, designs, and implementations typically focuses on the audience experience. However, a successful performance starts from the stage. Without a proper stage, musicians may feel they cannot hear themselves or others. A bad design may also force a musician to play excessively loud, which may cause playing out of tune or out of sync with others. Correct enclosure design, material placement, distribution of geometric elements, and many other variables all create a desirable stage experience for the musician. It should also be considered that a musician is not only passively listening to the instruments and voices around them, but there is also an active listening component where the musician is critically listening and playing their instrument. The musician also listens to themselves and others while playing. This requires far more focus and cognitive load than passively listening from the audience. Such a dramatic difference calls for a study dedicated to their auditory experience.

Musicians and vocalists must trust the stage (and the interaction of the stage with the hall) to provide them with feedback from the environment to understand the dynamics, timbre, balance, and blend of their performance with others on the stage. Indeed, professional musicians may constantly adapt from the feedback, or response, from a less-than-ideal acoustic environment that they are more familiar with, but adapting is more difficult for touring or visiting performers because they have minimal experience with new acoustic environments. The inability of an orchestra or soloist to adjust to a lack of response with the performance venue will inhibit them from interpreting their sound as they might when performing on a familiar stage. Thus, not being able to fully adjust to a new space in which an orchestra or soloist is performing may ultimately affect the experience of the audience.

Researchers, acoustic consultants, and other acousticians have developed parameters to describe the acoustic phenomena of spaces to help remedy some of the issues that prohibit an exemplary musical performance, a better aural experience, and an improved response from the hall.

At the same time, the acoustic and auditory needs of the musician may be considered less because the focus of these parameters has not been from the perspective of the musician, but it has, instead, been dominated by the audience's auditory experience. These acoustic parameters are also often correlated to subjective attributes, judgments, and auditory experiences of the audience. However, rather than focus on the audience experience, this article focuses on and describes various examinations and landmark studies of stage acoustics conducted by esteemed acousticians. The development of objective parameters and the correlation to subjective attributes and preferences of stage acoustics are also explored. Additionally, the advancement of standardized measurements utilizing spatial measurement techniques is also reviewed.

A Musician's Auditory System

Before considering objective criteria to evaluate stage acoustics, we must investigate the perceptual effects that may impact how a musician or vocalist perceives sound on the stage of a performance venue.

Masking

One of the most prominent effects is masking. Auditory masking occurs when an auditory event or perceived sound is affected by another auditory event, referred to as the masker. The presence of a masker can reduce the

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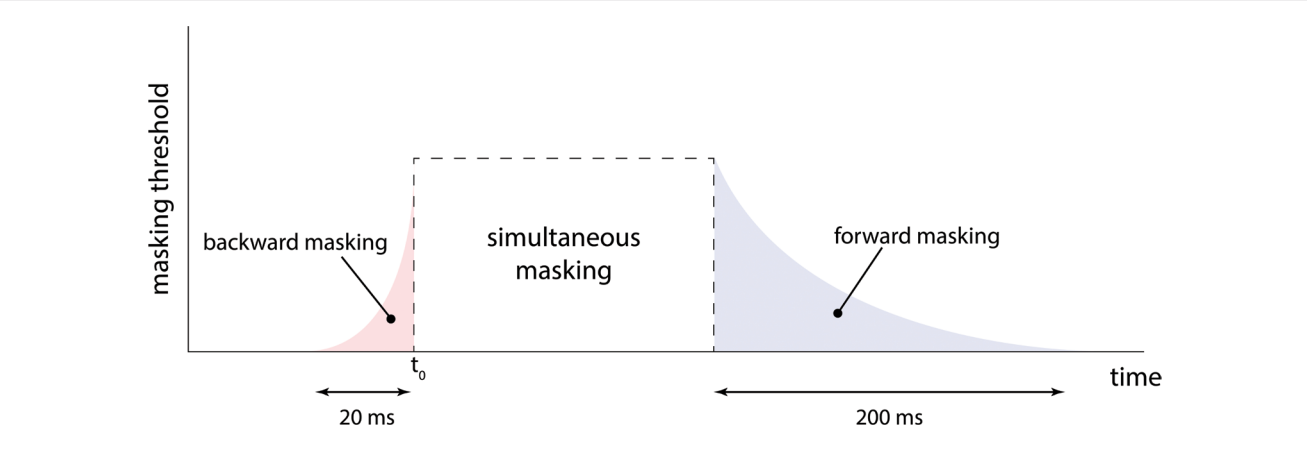


Figure 1. *Illustration of simultaneous and temporal masking. Onset of the masker,* t_0. *Forward masking occurs when the masker has been stopped and the signal is reduced or inaudible within 200 ms. Backward masking occurs when the signal is masked by a subsequent masker within 20 ms.*

loudness of the sound or completely render it inaudible (Fastl and Zwicker, 2007). Within this context, loudness is defined as a subjective sensation correlated to the sound pressure level but is also frequency dependent.

Two types of masking are simultaneous masking and temporal masking. Simultaneous masking describes the phenomenon that occurs when two auditory events, a masker and a signal defined as the sound of interest to the listener, occur at the same time, making the signal difficult to perceive. Temporal masking exists in two basic forms: forward masking and backward masking (**Figure 1**). Forward masking is observed when the listener is trying to perceive a signal just after a masker has ended. This effect can last up to 200 ms after the end of the forward masker. In backward masking, or premasking, the listener's perception of a signal is affected by a masker that is presented after the signal ended; the time window is approximately 20 ms before the end of the signal (Moore, 2014).

Precedence Effect

Another form of signal masking is related to a phenomenon referred to as the precedence effect or the law of first wave front. In normal auditory environments, direct sounds reach a listener's ear and are perceived, while indirect sounds (reflections) reach the ears from different locations (e.g., reflecting off the floor, walls, and ceiling) and with a delay relative to the direct sound (Litovsky et al., 1999). These delayed sounds are not perceived. Engineers designing sound systems for spaces such as auditoria and lecture halls will exploit this phenomenon to enhance the auditory experience for the audience. Sound waves received later from different locations can enhance the auditory experience because they are not perceived as separate auditory objects.

Without proper aligning of the loudspeakers' signals relative to a human speaker, the "fusion" has broken down the sounds into individual auditory events so that the direct and indirect signals appear to be separate. However, even if there are two auditory events within 10 dB (or higher in some cases), the first sound to reach the listener will take precedence in the perceived direction of the auditory event (Panton, 2017). For a musician, if the lagged auditory event is delayed too much, there is no precedence, and echoes are perceived by the musician, causing directional confusion. This limit is known as the echo threshold.

The Cocktail Party Effect

The cocktail party effect (Yost, 2013) is another perceptual effect that characterizes the listener's ability to focus on a single auditory event (e.g., their own music) while surrounded by multiple sound sources (e.g., instruments) from different directions and with different spectral and temporal characteristics. Perhaps the best example of this effect is in its own name. Consider a listener at a cocktail party trying to focus on the speech of another person with whom they are having a conversation (signal), but there are many competing maskers (voices) from multiple

directions. It turns out, however, that the location of the signal (speaking companion) may help the listener perceive that source above the masker compared with a situation where the signal and masker are emitted from the same location (Blauert, 1997).

Another important feature of the cocktail party effect is that the frequency and timing differences between the masker and the signal may help a listener pick out the signal from the background noise. Thus, the spatial, spectral, and temporal cues may be particularly helpful for a musician listening to a specific instrument or vocalist within the orchestra or ensemble.

Musicians' Subjective Experience

In his book *Music, Acoustics, and Architecture*, Beranek (1962, p. 73) states, "The technical data about the acoustics of a concert hall tell only a part of the story." There must be a balance between the technical objective study and the subjective study, which often deals with the perception and preference of the acoustic experience in various venues. Subjective studies also allow for a vocabulary describing these perceptual impressions to be produced. These terms or subjective attributes, such as an overall auditory impression, hearing ensemble (the ability to hear others), or reverberance, describe the perceptual preference and judgment of a performance space. Acoustic parameters of the concert hall, such as reverberation time, are meaningless without correlation of a subjective attribute or judgment that describes the auditory experience in the acoustic performance space. The subjective studies measuring these attributes also give acousticians an idea of preference and desirable ranges for measured acoustic parameters. This gives a guide during the design process for a performance space. In fact, acoustic measurements, ethnographic interviews, and perceptual tests all contribute to make a holistic study and design of a space or potential space.

Subjective Studies of Stage Acoustics

Beranek's (1962) initial interviews with musicians, critics, and conductors revealed the importance of reverberation attached to a musician's impression of how their music sounds in a hall. Subsequently, Gade (1981) conducted an exhaustive study, interviewing 32 instrumentalists, conductors, and vocalists, with the goal of refining a vocabulary to describe their acoustic concerns. The finalized vocabulary from these interviews was reverberance, support, timbre, time delay, hearing each other, and dynamics. These terms were compiled from each musician's interviews expressing their acoustic concerns about performance spaces encountered and the relative importance of each.

- *Reverberance* is the perceived reverberation of a space and also describes how notes are connected aurally. It can blur or accentuate the separation of the projected notes of the voice or instrument.
- *Support* details how much the response or feedback of a venue helps "support" the musician or vocalist to produce their desired notes while performing. A venue without proper support can cause a musician to fatigue from having to expend too much mental focus and physical energy to project their desired sound.
- *Timbre* relates to the color or tonal quality influenced by the spectral properties of the room. Each hall emphasizes or extenuates certain frequency ranges, giving a unique coloration of sound in each performance space.
- *Time delay* is a consequence of the distance between ensemble members. The greater the distance between musicians, the more difficult for the performers to play together with respect to time and rhythm (rhythmic synchronicity).
- *Dynamics* corresponds to how the room interacts with the perceived loudness of the instrument and how it relates to the intention of the musician's desired loudness. In other words, does the intended dynamic of the musician correspond to the dynamic received from the response of the hall?

To summarize the various subjective attributes required for the musician to play on stage, Meyer (1994, 2009) addressed the acoustic needs necessary to engage in desirable stage communication. There are three levels of quality.

(1) The first degree represents the need of the musician to play correctly. A projected sound that is late compared with other musicians degrades the rhythmic integrity and precision of the performance. Moreover, a sound that is too soft relative to other musicians degrades the intonation and clarity of the projected note.

(2) The second degree describes the sound quality of the musician's instrument beyond the projected note. A good overall auditory impression within a venue allows for ease of playing and hearing the ensemble. In other words, the hall allows the musician or vocalist to easily project within a space

without too much mental focus centered toward the first degree mentioned above, allowing more nuance and character in the projected note. This, in turn, increases the dynamic range, unforced playing, and blends with the ensemble.

(3) The third degree represents the ensemble or orchestra. It describes the ability of the sections of the ensemble to blend and integrate melody and harmony, particularly the strings. To achieve this balance within the ensemble, the conductor's position plays an important role in hearing each of these sections and ensuring they are well-balanced from the stage.

Ueno et al. (2005) conducted similar interviews directed toward smaller ensembles. These interviews and discussions highlighted the acoustical needs of a performer while playing in a smaller ensemble, such as a chamber music ensemble. The study found that hearing each other and making harmony were the two crucial qualities needed for a successful performance. Hearing each other was described as hearing both themselves and the other performers. Making harmony illustrates the necessity to blend and not separate projected notes to harmony and unified sound (Ueno et al., 2005).

Proposed Stage Acoustic Parameters

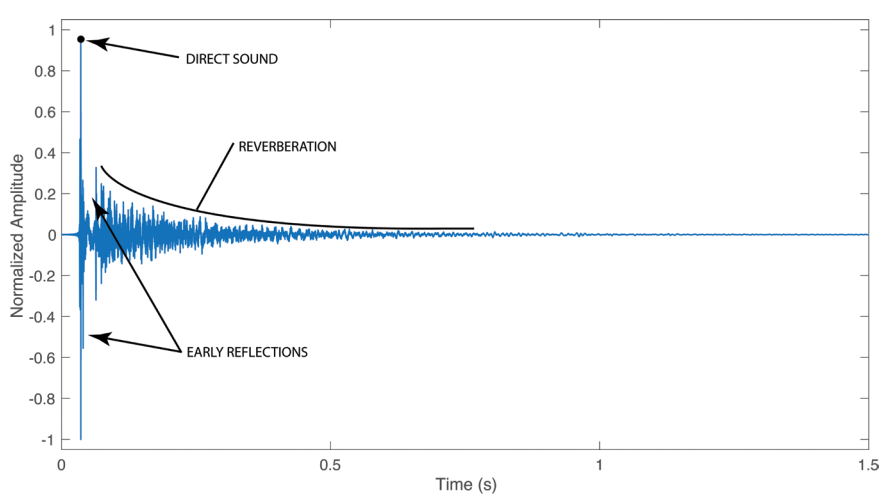
The subjective studies of experiences on the stage has garnered enough momentum to propose stage acoustic parameters. A landmark study by Marshall et al. (1978) introduced the importance of early reflections for ease of playing when a soloist performs with an orchestra. Early reflections, especially in the high-frequency range, from the walls of the stage enclosure, reflectors, ceilings, or underside of the balcony contribute to the musician's ability to play with ease within a venue (Marshall et al., 1978).

Stage Support

The most widely used stage acoustic parameters were determined by Gade (1989a) during his study of support to assess soloistic and ensemble conditions. Gade proposed three acoustic parameters describing stage support: early stage support (ST_{early}), late stage support (ST_{late}), and total stage support (ST_{total}).

These parameters are calculated using a measured impulse response (**Figure 2**). The impulse response uniquely characterizes the temporal and spectral properties of each venue or even each seat position within the venue. Because the square of the measured pressure from the impulse response is proportional to the energy, many parameters take advantage of this, comparing the energy of different time segments of the impulse responses. The stage support parameters compare energy in the early (20-100 ms), late (100-1,000 ms), and total (20-1,000 ms) time segments of the impulse response. The measurement is performed with a receiver (microphone) position of 1 m, approximating a direct instrument-to-ear sound path of most instruments (Gade, 1989a).

Figure 2. *Example of impulse response measured in a concert hall. The impulse response is typically divided into three regions: (1) direct sound, which is the path directly from the source to the receiver, (2) early reflections from the floor, wall, ceiling, and other surfaces; and (3) reverberation, which are more dense, smaller reflections similar to a noise-like signal.*



A further study by Gade (1989b) showed a high correlation between the stage support acoustic parameters and the subjective attributes expressed by the musicians for describing overall auditory quality and timbre. However, investigations by Kim et al. (2007) showed a wide variation of stage support across one stage, questioning the reliability of the acoustic parameters that had been determined. Kim and colleagues suggested changing the time segment used to calculate stage support to omit the direct sound of the impulse response, creating more consistency in the measurement. Nonetheless, the stage support parameters are all included in the International Organization for Standardization (ISO) 3382-1:2009 (2021) for acoustics measurements in performance spaces.

In the 2000s, Dammerud investigated many various audience-focused parameters to apply them to stage acoustics. In particular, he studied the strength parameter (G). Originally developed to measure loudness by the audience, Dammerud (2009) determined two variations of the strength parameter, G_{early} and G_{late}. Each variation was used to determine the strength of a signal across the stage during orchestral conditions at certain time segments of the impulse response. Similar to the stage support, the variations in strength focusing on the stage acoustics used energy ratios to understand the perceived loudness on stage (Dammerud, 2009).

Spatial Acoustic Parameters

The parameters mentioned in ***Stage Support*** are normally measured using a microphone that is omnidirectional. This means that the transducer is equally sensitive in a desired frequency range to all directions while recording the acoustic measurement. However, some microphones can weigh in different directions, allowing spatial impulse-response measurements of a sound field and spatial acoustic parameters. Only two spatial parameters are presented in ISO 3382-1:2009 (2021) the interaural cross-correlation coefficient (IACC) and lateral fraction (LF). These are calculated utilizing an impulse-response measurement from a binaural dummy head (see Paul, 2009) for the IACC and a combination of various microphones for the LF. However, the standardized measurements are correlated more toward the audience experience.

The growing popularity of spherical microphone arrays (**Figure 3**) has allowed a more comprehensive study of three-dimensional sound fields. Explicitly, spherical microphone arrays allow the user to understand the directional characteristics of a sound field by using spatial filtering. Spatial filtering, known as beamforming, applies a combination of weights to the measured signals from the spherical microphone array to point in a specific azimuthal (horizontal) and elevation angle. This enables the user to essentially point a virtual beam with user-defined horizontal and vertical angles to determine the sound field in that particular direction. In research done by Guthrie (2014) and Panton (2017), combinations of these beams were used to determine the directional behavior of stage acoustics parameters. In doing so, the homogeneity of various stage acoustics parameters can be realized in all directions on the stage.

Figure 3. *Example of a spherical microphone array. The black object has 19 microphone capsules embedded in a rigid body. For more information about the placement of the microphone capsules, design, and implementation of spherical microphone arrays, see Rafaely (2019).*

Auralizations

Another advantage of using spherical microphone arrays for acoustical measurements is the application of laboratory-controlled experiments. Historically, auralizations ("aural visualization") were rendered using binaural impulse-response measurements. But, the spherical microphone array enables measurements to re-create the physical sound field using a spatial audio technique called Ambisonics (see ambisonic.info/index.html).

Ambisonics is a spherical playback format that produces a three-dimensional sound field to enable spatialization of a virtual or recorded sound. By convolution, anechoic ("no echo" or no reflection) recordings of music, speech, or soundscapes can be rendered as if they were in the space that has been measured. In other words, the convolution applies the temporal and spectral effects of the acoustic venue to the anechoic recordings to simulate a desired position on stage (or in the audience). This allows for direct comparison between acoustic spaces without depending on the auditory memory of the subject (Panton, 2017). Consequently, musicians can compare auditory experiences of concert halls directly without depending on the memory of performances.

Summary

Stage acoustics is an essential part of architectural acoustics to enhance and better the experience for the performer as well as for the audience. Although stage geometry and enclosures are thoroughly designed, the correlation of subjective attributes from the musician's perspective and object parameters is still a complex, multidimensional problem. This article covered only a few of the studies on the topic to introduce the reader to a vast field that has only been studied on the surface.

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For author bio, please go to acousticstoday.org/bios-19-4-5

Conversation with a Colleague: Andy Piacsek

Andrew Piacsek
Conversation with a Colleague Editor:
Micheal L. Dent

Meet Andrew Piacsek

Andrew (Andy) Piacsek is the next acoustician in our "Sound Perspectives" series "Conversation with a Colleague." Andy is a professor of physics at Central Washington University (CWU), Ellensburg, having completed his BA in physics at Johns Hopkins University, Baltimore, Maryland, and a MA and PhD in acoustics at The Pennsylvania State University, State College. Andy is a Fellow of the Acoustical Society of America (ASA) and has served numerous roles in the Society over the years, including chairing the Committee on Public Relations, the Virtual Technology Task Force, and the Technical Committee on Musical Acoustics. We asked Andy to give us his elevator pitch and then to elaborate on his inspirations, contributions, and hopes for the future.

Give your "elevator speech" about the thrust(s) of your scholarly work over your career.

My career has been a fusion of undergraduate physics education, acoustics research, and fostering public understanding of science. The focus of my research has evolved and diversified over three decades, driven by the interests and constraints of the undergraduate physics students who work in my laboratory.

My early career was centered on modeling the propagation of sonic booms and other weak shock waves, but when our department moved to a new building with a bespoke acoustics laboratory, including an anechoic chamber and a laser-scanning vibrometer, I shifted my focus to experimental projects, particularly in architectural, structural, and musical acoustics.

In one set of studies, I have been working with students to explore the possibility of noninvasively monitoring changes in intracranial pressure by measuring skull resonances. In other studies, we are developing tools for quantifying uncertainty in the violin frequency-response measurements and investigating the popular belief that new violins improve their sound after being played for some time.

In fact, I find that there is a fruitful synergy between what I learn in the laboratory and what I teach in the classroom. My research background helped me create new courses at CWU in the areas of acoustics and computational physics, which, in turn, have attracted students who bring new ideas to my laboratory and motivate me to expand the tools I use in my research. Underlying both my classroom teaching and mentoring of student research is the goal of fostering the habits of scientific inquiry, with which students are comfortable applying broad physical concepts to specific problems using mathematics, analyzing data, and asking questions.

What inspired you to work in this area of scholarship?

There are three people who exerted a strong influence on the direction of my career. The first was Bill Kuperman at the Naval Research Laboratory in Washington, DC, who arranged for me to work for a year in his group after I graduated from college, uncertain about what to do with my physics degree. I spent that year mainly writing code to graphically display the results of underwater sound propagation models but also sitting in on many animated discussions of acoustics between Bill and his colleagues and attending my first ASA meeting. This experience

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fostered an appreciation for acoustics as a diverse and fascinating area of applied physics, so I pored over the ASA guide to graduate schools and successfully applied to the program at Penn State.

As I was wrapping up a master's thesis involving cavitation noise, I asked Allan Pierce if he would take me on as a PhD student. Not only did Allan lead me into the fascinating world of sonic booms and nonlinear acoustics, but he also taught me how to approach problems with rigor and persistence, in other words, to think like a scientist. By coincidence, the computer program I wrote for my doctoral dissertation was based on a theoretical approach developed by Bill Kuperman and Ed McDonald, who also provided the connection to my third important mentor, John White.

John hired me as a postdoc at the Lawrence Livermore National Laboratory in Livermore, California, to model the underwater propagation of weak shock waves arising from clandestine nuclear tests. John was an expert in shock physics, but he was also passionate about science education, and he was developing a course called Physics Appreciation that he taught at San Jose State University in nearby San Jose, California. John recruited me to review the textbook he was writing for the class and this spurred my interest in the philosophy of science and how scientific thinking should be a skill that is taught to everyone, not just scientists. I am also grateful to John for indulging my passion for cycling while I worked for him; we learned to avoid scheduling morning meetings because I was often late when I rode to work, which involved going over a sizable mountain pass between my apartment in Tracy, California, and Livermore.

Of all your contributions during your career, which are you most proud of and why?

This is a difficult question for me because my professional work has multiple components that are all important to me. My compromise would be to highlight one contribution from each of the three areas I mentioned in the "elevator speech": research, teaching, and public outreach.

A brief summary of my rather nonlinear academic career will provide some context. In 1994, as I was finishing my doctoral dissertation, I followed my then fiancée, Lisa Ely, to CWU, where she had been hired as an assistant professor in the Geology Department. A year later, I left for Livermore to start my postdoc. Shortly after Lisa and I married in 1996, I was hired as a lecturer, with full-time teaching responsibilities in the Physics Department at CWU (see cwu.edu/physics). I held that position for 10 years, during which time I took on a variety of administrative roles, such as supervising a National Science Foundation (NSF)-funded Science Honors Program that supported undergraduate research. In 2007, I was hired to a tenure-track position, which enabled me to devote more time to doing research. However, when I became Department Chair six years later, the bulk of my responsibilities were again outside the laboratory. The latest chapter of my career began when I completed my term as Chair and initiated a variety of research projects utilizing the facilities in our new building.

My ongoing research projects in musical, structural, and architectural acoustics are very exciting and may end up being quite impactful down the road, but I take great pride in my early and midcareer work on focusing sonic booms. When I began this work as a PhD student in 1990, there were competing hypotheses to explain how atmospheric turbulence produced the observed variability in sonic boom signatures recorded on the ground. I created a numerical model, based on McDonald and Kuperman's time-domain formulation of the parabolic equation (known as the NPE), to test Pierce's idea that turbulence led to focusing and defocusing of sonic boom wave fronts and that focusing could produce "folded" wave fronts with multiple peaks. My simulations showed that mesoscale turbulence can lead to alternating regions of rounded and spiky (folded) wave fronts, qualitatively like observed sonic boom signatures. I also identified and explored the parameter space of nonlinearity and diffraction that determines whether a focusing weak shock folds or straightens out.

This work led to an invitation to participate in a NASA-funded project, the Superboom Caustic Analysis and Measurement Program (see ntrs.nasa.gov/citations/20150019419), to evaluate the capability of models to predict the detailed signature of sonic booms that focus near the ground, becoming extra loud due to the acceleration or other maneuvers of supersonic aircraft. This was part of NASA's ongoing effort to develop and evaluate commercial supersonic aircraft designs that produce "quiet" sonic booms. Working with sonic boom expert Ken Plotkin (who passed away in 2015) to adapt my code to the particular

geometry and physics of this problem was one of the intellectual highlights of my career.

In the field of physics education, I am most proud of a course that I developed, called Physics of Musical Sound, and that I have been continuously refining. This is a General Education course that satisfies a science requirement for students in non-STEM majors. Beyond getting students to recognize the essential features of sound and vibration, to use simple tools to analyze sound, to appreciate the mathematical basis of musical scales, and to describe the rudiments of speech and hearing mechanisms, I see the class as a vehicle for teaching powerful physical concepts, such as the conservation of energy, instilling an appreciation for the usefulness of math, and developing habits of scientific inquiry. These are lofty goals (and I often don't succeed in all of them), but I leverage the students' natural curiosity about sound and music to get them to do something that doesn't come naturally to most people: think quantitatively. Over the 25 years of teaching this course, I have developed a variety of pedagogical tools and strategies, which I've shared at ASA meetings; likewise, I have utilized ideas picked up at those meetings to improve my teaching.

My path in following in John White's footsteps to spread "science appreciation" far and wide has taken me in multiple directions, from teaching interdisciplinary courses on pseudoscience and conspiracy theories to giving public lectures about the applications of acoustics and how science works. But I am proudest of the work I have done serving on the ASA Public Relations Committee (PRC), which I chaired from 2009 to 2018. With the committee's support, and the involvement of Student Council, I began a tradition of organizing interdisciplinary special sessions aimed at helping ASA members improve their media relations skills. Offered every two or three years, these sessions typically include a mix of media professionals sharing tried and true strategies for effectively communicating science to the public and ASA members sharing their own experiences (positive and negative).

More recently, under the leadership of PRC chairs who have followed me, these sessions have evolved into media training workshops that provide interactive activities in which participants practice specific skills and strategies for describing their scientific work to a journalist. The value of this work is the increase in science literacy among the public that comes from broadening the number of researchers and practitioners who are comfortable telling the stories of what they've learned, how they learned it, and why it's important. This kind of communication is essential for fostering public trust in science and scientists, which is increasingly at risk.

What are some of the other areas in which you feel you made substantive contributions over your career?

I was chair of the Physics Department at CWU during a crucial period in which the number of students and faculty positions doubled. The groundwork for this "inflationary period" of our department had been laid by my predecessor, but it fell on me to manage it, most importantly by overseeing the hiring of five new tenure-track faculty (as well as several interim lecturers to tide us through the enrollment jump). As many readers will likely know, the process of hiring new faculty is fraught with difficult choices. This is especially true in a small department where collegiality is prized; we were looking not just for talented educators and researchers, but future colleagues with whom we could work collaboratively for decades. I am very proud, then, of the incredible group of young faculty that we recruited and brought on board, three of whom are women. They have collectively transformed the department, as I had hoped, bringing not just new expertise but also a new attitude and a different kind of energy. It is no coincidence that the camaraderie and work ethic displayed by the faculty is also evident among the physics students. As the horizon of my career approaches (still distant, but now visible), I am grateful that the department I helped to shape is thriving and poised to become even better.

What do you think are the most pressing open questions that you would like to focus on over the next 5-10 years?

As an educator, a scientist, and a citizen, the most pressing question for me is how to make a significant impact on public scientific literacy. This is not just about improving standardized test scores or ensuring that everyone graduates high school with an understanding of Newton's laws, redox reactions, and the Krebs cycle, but actually demystifying the process of science for the vast majority of people who are not professional scientists. I am convinced that a lack of understanding of what science is and how it is done underlies the susceptibility of the

public to letting a political or cultural affiliation override their trust in science; as the Covid epidemic showed, the consequences of this lack of trust can be dire. One of my goals for the next few years is to develop high-school level educational materials centered on musical acoustics that will not only improve students' quantitative and reasoning skills but will also help them default to using those skills when confronted with new information or unfamiliar problems. The goal is to reach students who might otherwise avoid science and math classes by leveraging their natural curiosity and interest in music and sound.

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Vantage 2023: A Report on the Acoustical Society Foundation Fund

James H. Miller

This is the fourth annual "Vantage" report. In it, we 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 where it is headed (to learn more about the Foundation Fund, see bit.ly/3QpuHzq). Past Vantage reports from 2020, 2021, and 2022 and other reports about the Foundation Fund are available at bit.ly/ATC-Foundation. Like last year's report, this report features three graduate students and one postdoctoral fellow who have benefited from the generosity of our donors.

The Acoustical Society Foundation Fund Board

The Fund Board is made up of dedicated, hard-working ASA member volunteers including Freddie Bell-Berti, David Feit, Ron Freiheit, John Hildebrand, Ben Markham, Ed Okorn, Scott Pfeiffer, ASA Treasurer Judy R. Dubno (ex officio), and me as the Board chair. The Board makes recommendations to the ASA Executive Council about the levels of the awards, prizes, fellowships, and scholarships supported by the Fund (see Miller, 2022, **Table 1**, or bit.ly/ATC-Foundation for a list).

Financial Performance in 2022

Contributions in 2022 to the Fund from members and friends of the ASA totaled $208,345, an increase of 273% over 2021. This increase included $35,270 in individual donations to the new ASA Fund to Promote Inclusive Acoustics. This Fund is intended to support the inclusion and advancement of individuals from those groups that have been underrepresented in acoustics and the ASA. Specifically, the new Fund will support activities to advance underrepresented minorities that are developed by several other ASA groups including the ASA Committee to Improve Racial Diversity and Inclusivity (CIRDI; e.g., Summer Undergraduate Research or Internship Experience in Acoustics [SURIEA]); the ASA Committee on Women in Acoustics (e.g., Young Investigator Travel Grants); and by other diversity-related programs developed by ASA administrative and technical committees.

Other significant components of the increase in donations to the Fund are $5,665 in individual donations to the James E. West Minority Fellowship, a gift of $40,000 to the Frank and Virginia Winker Memorial Scholarship for Graduate Study in Acoustics, and $6,307 in individual donations to the Student Transportation Fund.

Fund Expenditures in 2022 in Support of the ASA

In 2022, the Fund was very active in supporting the many programs of the Society. The total amount of the awards, prizes, fellowships, and scholarships (see Miller, 2022, **Table 1**, for a list) supported by the Fund was $215,789, an increase of 10% compared with 2021. You can find details of the programs at bit.ly/3we52wg. After reviewing these programs, think about any for which you or your students or postdoctoral fellows might apply or where you might like to donate.

The support for travel to ASA meetings by students through the Student Transportation Fund is one of the most important programs of the Fund and one of those with the greatest need. The Foundation Fund awarded $23,821 to students for travel to the spring 2022 meeting in Denver, Colorado, and the fall 2022 meeting in Nashville, Tennessee, which was only about 25% of the funds requested.

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Recent Recipients of ASA Scholarships and Fellowships

Four recent recipients of scholarships and fellowships supported by the ASA Foundation Fund were kind enough to send me descriptions of their work and how their awards have benefited their research.

Scott J. Schoen is a postdoctoral fellow at the Massachusetts General Hospital Institute of Health Professions, Boston. He is a recipient of the 2022 Frederick V. Hunt Postdoctoral Research Fellowship in Acoustics.

"My research is concerned with improving ultrasound imaging techniques vital for the identification of chronic liver disease. Specifically, patients with obesity are at an elevated risk for disease progression but present challenging imaging geometries because the ultrasound waves are distorted and the resulting images degraded. Methods to correct this aberration are typically computationally intensive, a problem only compounded for volumetric imaging. During my fellowship time, I am working to develop fast, spectral correction schemes and adapt them to novel array geometries (row-column arrays) to abdominal ultrasound to address some of these computational problems. Together with machine-learning approaches for property estimation, these techniques will allow a complete pipeline for improving ultrasound images for those most at risk. The Hunt Fellowship has been instrumental in furnishing the time to pursue this basic research, which I am humbled to pursue in part at Hunt's institution."

Jonathan M. Broyles is a graduate student at The Pennsylvania State University, State College. He is a recipient of the 2022 Frank and Virginia Winker Memorial Scholarship for Graduate Study in Acoustics.

"I am an architectural engineering doctoral candidate at the Pennsylvania State University, with Nathan Brown in the Building Design Group as my advisor. My research interests lie in the intersection of architectural acoustics, structural design, sustainability, and computational design. Specifically, my research on the acoustic transmission performance of optimized concrete structures provides a unique insight on the design consequences of structural optimization strategies within a building context. Recently, I expanded my studies by investigating how advanced computational techniques can better inform the acoustic design of concert halls and how sustainability-driven building design affects the architectural acoustics in a building. My research emphasizes why acoustic considerations are necessary in early building design regardless of the building application. The financial support from the Winker Scholarship enabled me to expand my research breadth to applying machine-learning techniques in architectural acoustics and explore acoustic-decarbonization building design trade-offs."

Kashta Dozier-Muhammad is a graduate student at the University of Memphis, Memphis, Tennessee. He is a recipient of the 2022 James E. West Minority Fellowship.

"My research centers on optimizing 'ultrafast' acquisition schemes for diagnostic pulse-echo ultrasound imaging. These ultrafast methods achieve imaging frame rates greater than 30 times faster than conventional focused-transmit methods, yet with comparable image quality. Ultrafast sequences are particularly useful in functional and super resolution imaging. I hope that my work in increasing the imaging field of view can further improve the diagnosis of vascular abnormalities. The James E. West Fellowship Award has allowed me to accelerate my education and training toward a doctoral degree in biomedical engineering while continuing to expand my research and explore topics of slow flow and vascular ultrasound imaging in greater depth."

Hilary Miller is a doctoral candidate at Boston University, Boston, Massachusetts. She is a recipient of the 2022 Raymond H. Stetson Scholarship in Phonetics and Speech Science.

"I am a doctoral candidate in the Department of Speech, Language, and Hearing Sciences at Boston University. My research interests are broadly focused on applying neurocomputational

models and neuroimaging methods to better understand the neural bases of motor speech disorders. My dissertation research investigates how patients with primary progressive aphasia and progressive apraxia of speech learn new speech sequences. With this information, we can determine the brain regions that support successful learning and if the patients' patterns of brain atrophy are predictive of their learning success. A further arm of this research analyzes the extent to which we can use clinical measures of speech production to predict learning outcomes in this population. The support from the Stetson Scholarship has been critical in enhancing my work on this project and preparing me for an independent research career."

What Would You Like the Foundation Fund to Do?

The Fund does a lot of good in supporting ASA's 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 you want to support ASA's 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?

Ways to Give

Donors have several options for giving to the Fund. These include the following types of gifts:

- Cash
- Publicly traded securities
- Life insurance
- Bequests
- Pooled income funds
- Charitable trusts
- Charitable annuities

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

As you can see, the Acoustical Society Foundation Fund is doing important work for the ASA with the generous support of our donors. Please reach out to me at miller@uri.edu if you would like to learn more about how to make a difference in acoustics. I would enjoy hearing your ideas and discussing how they might be implemented.

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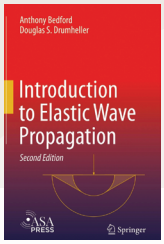
Book Announcement
ASA Press

ASA Press is a meritorious imprint of the Acoustical Society of America in collaboration with Springer International Publishing. All new books that are published with the ASA Press imprint will be announced in *Acoustics Today*. Individuals who have ideas for books should feel free to contact the ASA, asa@acousticalsociety.org, to discuss their ideas.



Introduction to Elastic Wave Propagation

Authors: Anthony Bedford and Douglas S. Drumheller

- Discusses the traditional methods used to analyze steady-state and transient waves in linear elastic materials
- Introduces advanced topics such as the four-pole solution for layered media and waves in nonlinear elastic materials
- Includes many exercises with solutions

Find out more about *Introduction to Elastic Wave Propagation* at **bit.ly/ASA-IEWP-book**

Effective Leadership

Tracianne B. Neilsen, Kathleen E. Wage, Arezoo Talebzadeh, and Anna Diedesch

Leadership, according to United States President Dwight D. Eisenhower, is the "art of getting someone else to do something you want done because he wants to do it" (see bit.ly/3RsDbXl). The Acoustical Society of America (ASA) has seen many great leaders since its founding in 1929, from presidents of the Society to students holding leadership positions. Here, we discuss leadership as we recognize two prominent women leaders, Lisa Zurk and Brigitte Schulte-Fortkamp, who were honored at the Women in Acoustics (WIA) luncheons during the ASA meetings in December 2022 and May 2023, respectively.

Leadership is one of the many things for which acousticians and educators typically do not receive formal training. To share ideas on leadership, we sent a questionnaire about leadership to past presidents and vice presidents of the ASA to gather suggestions. Their comments and examples from the honored women have been compiled in this column, which is complementary to the other WIA columns found at womeninacoustics.org/news (see also bit.ly/AT-WIA).

Lisa Zurk

Lisa Zurk was a trailblazer, admired for her innovative technical work and the work she inspired and enabled others to do. With unique expertise in both acoustics and electromagnetics, Lisa incorporated insights from physics to develop new algorithms for sonar and radar signal processing. She held herself and others to high standards, but as Jenn Watson (division head at the MIT Lincoln Laboratory, Cambridge, Massachusetts) noted in her remarks at the WIA luncheon, "if you wanted to learn and grow, [Lisa] would spend a tremendous amount of time helping you."

Lisa exhibited leadership throughout her career (see bit.ly/45QZN7u). After completing a doctorate at the University of Washington (UW), Seattle, Washington, she joined the MIT Lincoln Laboratory, one of only 3 female full technical staff members in her division and, eventually, one of the first 10 women promoted to laboratory management. In 2005, Lisa founded the Northwest Electromagnetics and Acoustics Research (NEAR) Laboratory at Portland State University, Portland, Oregon. From 2005 to 2016, she advised more than 40 students in the NEAR Laboratory. In 2018, Lisa returned to the UW as a full professor in electrical engineering and executive director of the Applied Physics Laboratory (APL-UW). Lisa was the first woman to serve in that role in the laboratory's 75-year history. In an interview she said, "As a woman in engineering, you have unique challenges that come up along the way, and it causes you to think, 'Is this the right field? Do I fit in?' Studies have shown that female role models can make women comfortable. That can change an environment and create an example that other women can feel more in touch with" (see bit.ly/3rcv3iJ).

Throughout her career, Lisa broke barriers and was a role model for many in the acoustics and engineering communities. Her leadership was felt at the ASA as the first woman chair of the Underwater Acoustics Technical Committee, chair of the WIA Committee, and national meeting chair. Her absence has been felt since she passed away on January 12, 2022, but her legacy endures in the research she sparked, the colleagues she mentored, and the students she advised.

Brigitte Schulte-Fortkamp

Brigitte Schulte-Fortkamp, professor of psychoacoustic, noise effects, and soundscape research, recently retired from the Technical University of Berlin, Berlin, Germany. Brigitte focused her career on the importance of soundscapes, a new concept in noise research in the 1990s (for more details, see bit.ly/3sKtqJq). This new area was inherently interdisciplinary, relying on sociology, political science, and acoustics. Brigitte led international soundscape research for three decades, and today, almost all acoustic conferences have at least one session on soundscape.

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Brigitte's leadership, marked by its multidisciplinary scope and global influence, presents a remarkable intersection of vision, dedication, and impact. She has fostered fairness and teamwork throughout her career on multiple committees and in acoustical societies. For example, as part of an International Organization for Standardization Committee on Soundscape Quality, her role goes well beyond scientific oversight and into managing a diverse group of international scholars to find common ground and work together.

Brigitte dedicates her time to educating and empowering the next generation of soundscape researchers, motivating them to be persistent, determined, and relentless. Her outstanding mentoring efforts continue. She tirelessly encourages and guides early-career researchers throughout their journey and helps them build connections and sustainable academic paths. Her mentorship goes beyond her students and into the community. In 2012, Brigitte, together with Judy Dubno, initiated and started the ASA School "Living in the Acoustic Environment," which will hold its sixth event for graduate and early-career acousticians in the spring of 2024.

Schulte-Fortkamp's leadership is characterized by fairness, honesty, and encouraging others' suggestions during the decision-making process. Her patience and perseverance bring solutions and high spirits into any situation. Her legacy is etched not only in awards and honors but in the very fabric of the acoustic world she has helped shape.

Personally, Brigitte considers her most important contribution to be those as a wife and mother, and her impact is visible through her two successful sons. As the echoes of her accomplishments continue to resonate, her leadership inspires current and future generations of acousticians, scholars, and upcoming leaders alike.

Leadership Advice

Building off these two wonderful examples of leadership, we now summarize key characteristics of leaders and advice from ASA past presidents and vice presidents. The comments in this section were collected during a survey sent by the authors. A sentiment analysis of the comments led to the word cloud shown in **Figure 1**.

Figure 1. *Word cloud generated from a sentiment analysis of the survey results.*

What Makes an Effective Leader?

The 10 survey responses highlight 3 areas: preparing, communicating, and building relationships. The first step to effective leadership is mostly behind-the-scenes: the time a leader takes to observe, learn about, and investigate the organization, individual team members, goals, and issues. This preparation often involves asking questions that allow the leader to understand the context around different issues and how they relate to the goals and objectives of the organization. These significant preparations are most productive when the leader can effectively communicate with others.

Good communication is essential for effective leadership. Some principles for effective communication include being authentic, direct, open, and consistent. The survey respondents indicated that a significant part of effective communication relies primarily on listening, asking good questions, and acknowledging the efforts, expertise, and ideas of others.

Both preparation and communication skills allow the leader to gain additional information and consider different points of view. Leaders have the interesting double-sided task of (1) keeping an open mind and (2) keeping the group discussion moving in a positive direction. As leaders exercise good communication skills, they can develop relationships of trust and respect within the group. As leaders exhibit fairness and openness, a sense of teamwork develops and individuals feel their contributions matter. Over time, the trust, respect, and teamwork build confidence and empower members of the group to develop and contribute more fully.

What Is Your Leadership Style?

Within these broad descriptions of leadership, each leader gets to find their personal approach. Our previous ASA leadership collectively describe their leadership styles as direct, inclusive/collaborative, organized, decisive, and timely. They recommend leading by example and not asking anyone to do something that you yourself would not agree to. A leader should listen more than talk; give credit to others; take responsibility when needed; embrace the power of a sincere apology; be open to new ideas; empower their team; display fairness; and promote good communication. Peggy Nelson (ASA president 2022–2023; director, Center for Applied and Translational Sensory Science [CATSS] and associate dean, University of Minnesota, Minneapolis) encourages us to "figure out your own style and build on your unique leadership qualifications. Not all of us are boisterous or outgoing, but we can build on our strengths."

What Challenges Do Leaders Face?

Previous ASA presidents and vice presidents were asked about the challenges they faced in leadership roles. Many of the respondents discussed the balancing act of working with groups who hold different views. Insightfuly, one former president stated that, at times, some individuals cannot come to a compromise. When making a final decision, "[those individuals] will not love you, and that is all right." At times, you must consider what is best for the overall organization or team.

Some challenges are directly related to women in leadership roles. One survey responder observed how "as a woman, there is a narrow window of leadership styles that are acceptable compared with those of a man, based on societal norms. You cannot be dictatorial; you cannot be too assertive; you must rely more on social skills." Sometimes leaders must overcome a perception that they are too inexperienced for a leadership role, a perception that can also be influenced by gender.

Another response noted that balancing the work required in leadership roles with being a parent can be challenging as well, particularly when trying to spend time with your family but still wanting to do a good job in a leadership position.

How Do You Handle Difficult Situations?

Leaders often face challenges. The survey responses provide insights on how to handle difficult situations. First, it is best to not avoid the situation but to deal with it in a timely manner. Second, transparency and direct, straightforward communication are key. Third, a leader must be prepared, or even overprepared, for meetings and keeping the discussion on track. To ensure fairness, all sides of an argument should be heard equally, without letting one party talk more, while the leader refrains from taking sides. Listen without interrupting, show kindness, and even display humor when faced with difficult situations. Try to see both sides of an issue while remaining neutral.

The outcome of such difficult discussions is hopefully that a compromise can be reached in which all sides can see how the decision made will benefit the organization. However, such a favorable outcome is not always achievable. One great piece of advice for when it comes to making a final decision that sides with one party or the other is to not be rushed and give yourself room with the difficult decision. In a timely manner, back up your decision with written explanations. Finally, once you have made an informed and deliberate decision, trust that you have made the right call.

How Can Someone Get Started in Leadership?

When people begin participating in the ASA, they often ask how they can get involved. Josh Gladden (ASA vice president 2021–2022; vice president of research, Temple University, Philadelphia, Pennsylvania) recommends you "Say yes to opportunities and requests: chair a session, be a reviewer, look for opportunities to contribute. It is noticed and you will be tapped for leadership roles." Maureen Stone (ASA president 2021–2022; Professor Emerita, University of Maryland, Baltimore) suggests to first lead "in a small environment and work to bigger ones. Don't be afraid of doing something foolish; you'll get past it. You'll learn from each opportunity and get better at leading." As you begin to lead, reach out to colleagues who you feel are good leaders and ask them to be your mentors.

To begin volunteering on one of ASA's administrative committees, complete the sign-up form. A description

of the technical and administrative committees can be found at acousticalsociety.org/volunteer.

How Can You Know If You Should Accept a Leadership Role?

As time progresses and your leadership skills develop, you will likely be asked to take on larger leadership roles. To determine if a new leadership role is a good fit for you, Ronald A. Roy (ASA vice president 2016–2017; professor of mechanical engineering, the University of Oxford, Oxford, United Kingdom) recommends "A good litmus test is to ask yourself how you can best advance the objectives of your institution. Is it through your own contributions or by enabling those of others? If the latter, then you are poised to lead." Before you decide to accept a large leadership role, Ilene Busch-Vishniac (ASA president 2003–2004; currently, Acoustical and Higher Education Consultant; former president of Saskatchewan University, Saskatoon, Saskatchewan, Canada) recommends identifying "at least two people already in such positions and interviewing them carefully to determine the full shape of the position, the parts that have caused personal or professional strain, and those that have caused personal or professional pride." Once you understand what the role entails and your motivations, you will be able to make an informed decision.

Always More to Learn

This column has provided some ideas for developing as a leader. We, the authors, have learned a lot from observing their leadership styles and hope you find their feedback helpful. As you embrace leadership roles, Subha Maruvada (ASA vice president 2022–2023; Therapeutic Ultrasound Program Lead, Acoustics Research Engineer, United States Federal Drug Administration) recommends that you "read books by those whose leadership style you admire and take courses on communication, coaching, facilitation and leadership" (see **Suggestions for Further Reading** for some helpful books). We encourage everyone to observe leaders closely. Learn from the good ones how to be effective and from the bad ones how to not be ineffective. As you embrace the leadership roles you are offered, you can develop effective leadership skills and contribute greatly in your personal, community, and professional organizations.

Suggestions for Further Reading

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My Journey into Underwater Acoustics

Gail Scowcroft

As I look toward retirement and reflect on the winding road of my career, I feel much gratitude for the underwater acoustics community, in which I have been engaged for the second half of my career. This has bought me many satisfying opportunities to contribute to the field. In addition, the friendships I've made with several of my ocean acoustic colleagues have been a highlight of my career. As the principal investigator for the Discovery of Sound in the Sea (DOSITS; see dosits.org) project for over 22 years, I have led a team of scientists and education professionals in making significant contributions to the nonexperts' understanding of ocean acoustics and the multiple subdisciplines under its umbrella. We have held the highest bar possible, peer-reviewed research, in developing content on these topics, always striving to make complex acoustics concepts and research results understandable for a variety of audiences.

My career did not start out in ocean acoustics. When I decided to become a scientist almost 50 years ago, ocean acoustics, or acoustics in general, was not a consideration for my studies. As a geology major at the University of Rhode Island (URI), Kingston, I fell in love with the history of the Earth and its systems. I was fortunate to be able to take two graduate level micropaleontology courses with Eugene Tynan and was bit by the micropaleo "bugs" (in this case, Silicoflagellates and Archaeomonadaceae). In 1975, a new team conducting paleoceanography research at the URI Graduate School of Oceanography (GSO; see web.uri.edu/gso) was seeking staff and students. With my micropaleo experience, I was a good fit. At the GSO, my ocean science education provided me with a wealth of opportunities to do independent research and work with a world class team of oceanographers. I became one of 119 researchers, who were contributing their data to the Climate Long Range Investigation, Mapping, and Prediction (CLIMAP) project, which focused on describing the global climate at 18,000 years ago. This research informed the development of the first major global climate model (GCM) (ClLIMAP Project Members, 1984). My first large scientific meeting was a CLIMAP synthesis meeting held at Columbia University's Lamont-Doherty Earth Observatory, Palisades, New York, in 1978. There, Syukuro Manabe of Princeton University, Princeton, New Jersey, gave a presentation based on CLIMAP data in which he predicted that increased levels of carbon dioxide in the atmosphere would lead to an increase in Earth's global average surface temperature of as much as one degree by 2100. He was the first scientist to issue such a prediction. The CLIMAP reconstructions would describe boundary conditions for atmospheric GCM's for years to come. Manabe went on to win the Nobel Prize for the physical modeling of the Earth's climate in 2021.

Following the CLIMAP Project, I participated in the Cenozoic Paleoceanography Project (CENOP), another large, multiinstitutional project that reconstructed ocean conditions during the Miocene. Paleogeography, stratigraphy, water mass circulation and distributions, temperature, biogeography, and many other parameters were identified by CENOP's participating scientists. Working with large teams across disciplines and institutions at a relatively young age was great preparation for my future endeavors. As CENOP ended, I left the GSO and went to work for Woods Hole Oceanographic Institution (WHOI), Woods Hole, Massachusetts.

Frustrated by the lack of the public's understanding of climate change and the growing misinformation about it in

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the mid-1990s popular media, I decided to begin taking classes in science education pedagogy and psychology to learn about how people acquire knowledge and what makes it stick. I eventually had enough credits to be qualified to teach high-school science and took a five-month leave of absence from WHOI to teach ninth-grade Earth Science. I learned more about education in those five months than in all of my combined previous education.

Returning to the GSO after my classroom stint, I began collaborating on proposals to conduct climate change education programs. Within a year, I had received grants from the Environmental Protection Agency, the National Aeronautics and Space Administration, and the Department of Agriculture for a suite of climate change education initiatives. I began teaching two graduate courses for educators in climate change and oceanography at the GSO. With my grant-funded projects, I was able to teach all middle-school science teachers in the 36 Rhode Island school districts and assist them in incorporating climate and ocean science into their districts' curriculum. Another of my projects, funded by the Department of Education, created a marine science magnet school in the city of Providence. Every teacher, even the art and physical education teachers, in this inner-city elementary school with a population of over 80% minority students received training in ocean and climate science.

The 2000s were busy and productive, including my entry into the ocean acoustics community. In 2001, I was approached by Kathleen Vigness-Raposa of Marine Acoustics Inc. (now at Inspire Environmental, Newport, Rhode Island; see bit.ly/47xEYjj) to see if I wanted to collaborate on a proposal to the Office of Naval Research (ONR) to develop educational materials for nonexperts related to underwater acoustics. Kathy had been working with Peter Worcester (see bit.ly/3OFVZiu) at the Scripps Institution of Oceanography, La Jolla, California, on the Acoustic Thermometry of Ocean Climate (ATOC) project off Hawai'i. There was significant public opposition to this research because people believed that the underwater ATOC sound source would harm humpback whales in the vicinity, even though research had shown that this was unlikely. Kathy approached me because of my experience in translating science and conducting programs for nonexperts. Although I knew very little about the science of underwater acoustics, the partnership of educational outreach with acoustic technical knowledge proved incredibly fruitful for Kathy and me as well as for the underwater acoustics community.

Our proposal for the DOSITS project to the ONR was funded in 2001, and I have been fortunate to serve as the principal investigator and work with Kathy for the last 22 years on this very rewarding project. I have been able to leverage several other projects that I have had funded over the years to introduce ocean acoustics to a variety of audiences. From 2003 to 2012, I received National Science Foundation (NSF) funding to direct a large, national program for educators, the Teacher Research and Mentoring ARMADA Project, which placed educators in ocean- and climate-related research experiences from pole to pole, many of which involved time at sea. We involved over 120 US educators, who all were introduced to DOSITS resources and underwater acoustics during their training.

Overlapping with DOSITS and the ARMADA Project, I became the executive director of NSF's Centers for Ocean Sciences Education Excellence (COSEE) program (2008-2015). Charged with building a national network of ocean science research and education institutions, I was able to draw on my early experience of being involved in large networks of researchers and institutions. With over 300 institutional members, COSEE provided training for two-thirds of the ocean science workforce and engaged over 10,000 formal and informal education professionals. We were able to promote DOSITS resources and content throughout the COSEE network. As an outcome of COSEE, I cofounded and have been coleading the Global Ocean Science Education (GOSE) Workshops since 2015. The 2023 workshop (see bit.ly/47x7yRU) was focused on ocean acoustics and brought together 71 ocean scientists, policy makers, business leaders, and education professionals.

In 2013, the organizers of the third meeting on the Effects of Noise on Aquatic Life (see an2022.org) in Budapest, Hungary, invited me to moderate a workshop for the international regulatory community. Bringing ocean acoustics experts and policymakers together highlighted the need for educating the people who are making decisions about how people can use sound underwater. The DOSITS project began developing resources for this community and in 2015 began offering an annual webinar series (see bit.ly/47CRVbu) on a variety of topics

related to ocean acoustics. Since then, we have conducted several needs assessments of the international regulatory community and, working with the ocean acoustics community, do our best to provide content that is in high demand (bit.ly/3OY0qXg).

We have recently received ONR funding for the next three years (2023–2026). During this time, we will be expanding our activities to develop a new professional development program in ocean acoustics for educators of students aged 13 through undergraduate level. We will continue to conduct our annual webinar series and regularly synthesize new research as it is published. During this funding cycle, I am planning to retire from the URI. However, I hope I can stay involved in DOSITS on a volunteer basis. It feels a bit like having your child graduate from college and go off into the world without you.

It was a winding road toward ocean acoustics, and once I arrived, I was met by a kind and gracious community of scientists. I remain ever grateful for the opportunities that my career has brought and, most of all, for the wonderful people with whom I have had the pleasure of working with for the last 22 years.

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