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Summer 2023 Volume 19, Issue 2

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The "Sounds" of Black Holes

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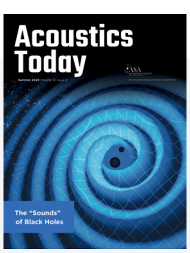
Featured Articles

Sound Perspectives

Departments



About the Cover

Illustration of the gravitational waves emanating from binary black holes, from "The 'Sounds' of Black Holes" by Delilah E. A. Gates (page 21). Image credit: LIGO/T. Pyle.

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www.acousticalsociety.org

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From the Editor

Arthur N. Popper

This issue of *Acoustics Today* (*AT*) has interesting and diverse material. The first article is by a non-ASA member, Bruce A. Carlson, who has a great acoustics-related story about electric fishes. Electric fish are truly fascinating animals that communicate using electric signals, but many of the characteristics of this communication are parallel to acoustic communication. If you are not familiar with electric fish or maybe you have some as pets, you will find that communication in these animals is fascinating and, in many ways, very familiar to you.

By coincidence, the second article is also by a non-ASA member, Delilah E. A. Gates, who has another different, and very interesting, story. Delilah is a physicist working on black holes, and one of the things that she is most interested in are the sounds produced by these astronomical phenomena. Of course, there is much more to black holes, and Delilah shares a good deal of interesting information.

The third article is by Sheri L. Martinelli, D. Keith Wilson, Andrew S. Wixom, and Chris L. Pettit. Sheri and her colleagues share thoughts about using computational models in acoustics (see bit.ly/ATCollections-Computational for other articles on computational acoustics). Using the Lloyd's mirror effect as an example, they share how models can enhance our understanding of acoustic issues in every discipline covered by ASA members and beyond.

In the fourth article, Kha Nguyen, Lei Zhang, and James Friend talk about an area that was totally new to me, acoustofluidics. For those, like me, who do not know anything about acoustofluidics, it is the physical effect of a passing acoustic wave on a fluid and particles suspended within it. Kha and colleagues discuss the history of the field and then show how acoustofluidics can be used in a variety of ways, particularly in medical diagnostics.

In the fifth article, Marina Salorio-Corbetto and Brian C. J. Moore discuss hearing aids and how they deal (and do not deal) with noisy environments. Of course, this is a topic of considerable interest to any ASA member, and the article is particularly relevant because it talks about what hearing aids can and cannot do to help hearing, especially in noisy environments. (Other articles on hearing health are at bit.ly/AT-Health)

As a New Yorker (at least for the first 25 years of my life), I have always been fascinated by tall buildings. But since my youth, buildings have gotten even taller and much thinner. This results in interesting acoustic issues for these very tall and very thin buildings and for their occupants. In the final article, Bonnie Schnitta and Sean Harkin share some of the fascinating ways that are used to test and then control the sounds in the buildings so that they can be occupied without having sounds that annoy occupants, particularly on windy days. (See bit.ly/Schnitta for an earlier article by Schnitta on residential quietude.)

As usual, this issue of *AT* has several "Sound Perspectives" essays on diverse topics. The "Conversation with a Colleague" series (see bit.ly/ATC-CWC) features Jordan Cheer, whose broad work focuses on the reduction of unwanted noise and vibration or finding ways to enhance and manipulate sound.

This is followed by an essay by Megan S. Anderson of the ASA Student Council. Megan features stories from a number of more senior ASA student members who share insights into their research. (Other Student Council articles are at bit.ly/ATC-Students.)

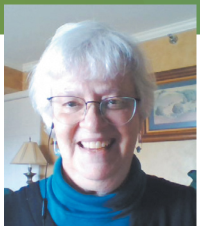
The third essay is by University of Texas (Austin) graduate student AJ Lawrence. Although AJ's research is on other aspects of acoustics, he got fascinated learning about the late Alan Lomax, a pioneering ethnomusicologist who was very focal in raising awareness of the immense breadth of folk music in the United States and worldwide. One of Lomax's most important "discoveries" was a folk singer (and jail resident) now known as Lead Belly. Having grown up at the height of interest in folk music in the United States and a great admirer of both Lomax and Lead Belly, I encourage every member not only to read this essay but to also listen to the amazing music.

Our last essay is by our 2022 *AT* intern Erik Alan Peterson. Erik is very interested in the experiences of acousticians who complete some portion of their training abroad. His first essay (see tinyurl.com/2t8recs3) discussed US students who travel abroad for study. The essay in this issue discusses the experiences of foreign students who come to the United States.

Let me end by again encouraging all ASA members to consider writing for *AT*. Even if you just have an idea, I would value exploring it with you. It may be a topic that will help educate and inform many thousands of readers in the ASA and beyond.

From the President

Peggy Nelson



Greetings one last time to my acoustics family. When you read this, the long-awaited Chicago, Illinois, meeting will be done, Stan Dosso will be the new president, and we will be making all our arrangements to gather in Sydney, Australia. Exciting times continue in the Acoustical Society of America (ASA).

This, my last president's column, is a chance for me to do something we all might consider doing: I'm taking a moment to look back and forward at the same time. What a couple of years it has been! We as individuals and we as a Society have faced challenges we never could have anticipated. I am so grateful for the leadership of the Executive Council and officers of the Society, and I am beyond grateful for the incredible ASA staff at headquarters. Together we have not only kept the ship aright, but we are moving it in positive directions.

We have put our strategic plan into action, despite global conditions that were entirely unexpected. One of the goals of our last strategic plan was to engage members outside the meetings. Another goal was to identify and promote emerging scientific and technical areas. We have had some terrific success in both. Our webinars reach 100-200 people each session, even though we had not seriously considered this possibility before 2020. Many of these participants are nonmembers from around the world. Check out the details at acousticalsociety.org/asa-webinar-series if you have not already done so. I am grateful to Linda Polka for her excellent leadership in this area.

We have proceeded with another of our strategic goals as well, to better engage our practitioners and industry members. We are very pleased to have established a new ad hoc committee, the Committee of Practitioners and Industry (CoIP) headed by Derrick Knight. The committee has done great work in giving visibility to those who work as practitioners in the acoustics field. Please join them in our efforts to strengthen the voices of practitioners who have been an integral part of our Society since its inception.

As always, the excellence of the science and practice of acoustics is at the heart of what we do. We are very proud of the publications team who have steadily improved the quality of our journals. As measured by the number of submissions, the number of downloads, and the all-important *The Journal of the Acoustical Society of America* (*JASA*) two-year impact factor (approaching 2.5!), our journals are a credit to the Society.

Although there is still much to do, we have also grown our commitment to diversity, access, inclusion, and belonging in multiple ways. We are improving the accessibility at meetings for those with hearing loss by promoting live captioning of sessions and events. We have experimented with hybrid meetings and will proceed with a one-time trial of a fully virtual meeting for fall 2024, potentially improving access for many who are unable to attend meetings in person. We hope you and your team are already planning on ways you can be engaged in this experiment.

We are putting our funds into action as well. The Acoustical Society Foundation Board has established the Fund to Promote Inclusive Acoustics to support the inclusion and advancement of those who have been underrepresented in acoustics and in the ASA. We have expanded giving opportunities for the James E. West Minority Fellowship Fund (supporting minority students in their pursuit of graduate-level degrees in acoustics) and are building the Campaign for Early Career Leadership (supporting Early Career Leadership Fellows). These funds are at work promoting activities that are broadening access to acoustics for people who have been historically underrepresented.

We have enrolled our third cohort of undergraduate students in the Summer Undergraduate Research or Internship Experience in Acoustics (SURIEA 3.0!; see https://acousticalsociety.org/suriea), and we are sponsoring affinity group meetings during each ASA conference. All this work is building on the excellent work of the Committee to Improve Racial Diversity and Inclusivity (CIRDI) and Member Engagement. If you would like to be more involved with member engagement, please contact the new committee chair, Kim Riegel (riegelk@farmingdale.edu).

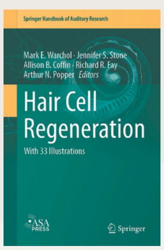
We have focused in recent years on getting our ASA fiscal household in order as well. With the leadership of Treasurer Judy Dubno, Finance Director Mike McGovern, and everyone at headquarters, we have improved our fiscal systems and are making important strides toward balancing our budget. There may be a few painful decisions ahead, but I am confident that we are on the right road. Thanks to our Investments Committee, we have a healthy reserve fund even in light of recent economic trends. Together with the Executive Council and our Finance Committee, we are thinking strategically rather than reactively. Our 2023 budget is a strong step in the right direction.

It is no wonder that I have been proud to help steer this important society as president. Our leadership and our membership are exemplary. We rely on each of you as well. If you are not already a full member of the Society, please do so by linking to acousticalsociety.org/asa-membership. Full membership will allow you to vote and to determine the future priorities of the Society. It's important work, and I hope you will consider it.

Thank you for the opportunity to serve as ASA President. As always, I hope to see you on a webinar, at a committee meeting, and in person soon. Let me know what you think we can do together. I will pass the information along to our new president, Stan Dosso.

Book Announcement | ASA Press

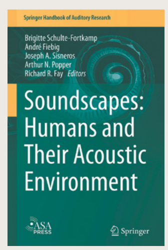
ASA Press is a meritorious imprint of the Acoustical Society of America in collaboration with Springer International Publishing. All new books that are published with the ASA Press imprint will be announced in *Acoustics Today*. Individuals who have ideas for books should feel free to contact the ASA,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



Hair Cell Regeneration

Editors: Mark E. Warchol, Jennifer S. Stone, Allison B. Coffin, Arthur N. Popper, Richard R. Fay

- Delivers a comprehensive understanding of the status of hair cell regeneration research
- Emphasizes prospective views of the various facets of regeneration research
- Includes coverage of studies that have applied gene and drug therapy to promote regeneration in mammals



Soundscapes: Humans and Their Acoustic Environment

Editors: Brigitte Schulte-Fortkamp, André Fiebig, Joseph A. Sisneros, Arthur N. Popper, Richard R. Fay

- Presents latest developments in soundscape theory and practice
- Combines smart growth concepts, urban design and soundscape for the first-time
- Highlights the applicability of soundscape to solve everyday noise problems in living areas

Find out more about *Hair Cell Regeneration* at **link.springer.com/book/10.1007/978-3-031-20661-0**

Find out more about *Soundscapes: Humans and Their Acoustic Environment* at **link.springer.com/book/10.1007/978-3-031-22779-0**

Weakly Electric Fishes and Auditory Processing

Bruce A. Carlson

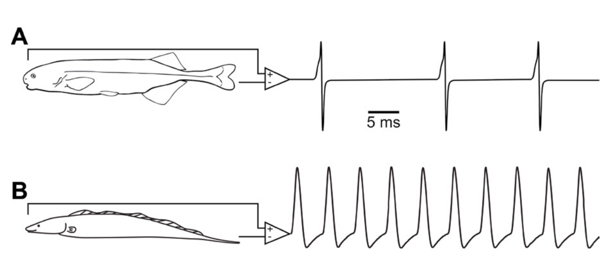
Electrosensory systems share numerous similarities with auditory systems, including a shared evolutionary history reflected in hair cell sensory receptors and similar brain pathways; key roles for spectral and temporal stimulus features in information processing; and similar neural computations for determining the spatial location and identity of stimuli. Moreover, many people are familiar with strongly electric fishes such as the electric eel and torpedo ray that use electricity as a weapon. Indeed, the writings of ancient Greeks and Romans make it clear they were aware of the special powers of strongly electric fishes, although not yet of the nature of electricity (Finger and Piccolino, 2011). Even earlier evidence of this knowledge in the form of artwork dates back more than 5,000 years to ancient Egypt (see bit.ly/3StnlKf).

Less commonly known than the strongly electric fishes are the weakly electric fishes, so named because they generate electric fields with much less voltage than strongly electric fishes. The electric fields in these species are so weak that they usually cannot be felt by humans even when these fish are handled. In fact, detecting their electric fields requires electrodes and special equipment.

Some weakly electric fishes can be found in the aquarium trade. It is not uncommon to spot a black ghost knifefish (*Apteronotus albifrons*; see bit.ly/3kjBcGC) or elephantnose fish (*Gnathonemus petersii*; see bit.ly/3IubLde) in your local pet store. Their behavior is fascinating to watch, but few observers realize that these fish are constantly generating an electric field in the water surrounding them (see bit.ly/3EV3YV9). In addition to electric organs that actively generate an electric organ discharge (EOD), these fish also have electroreceptors that detect EODs (see bit.ly/3ZfFcGR). These EODs are too weak to serve as any kind of a weapon. Instead, weakly electric fishes use EODs to communicate, much like we use sound to communicate. These fishes are also able to navigate and detect objects in their environment by detecting distortions of their EOD in a process called active electrolocation, which shares some similarities with echolocation.

Weakly electric fishes come in two basic types. Pulse-type fishes generate brief EODs separated by longer gaps of silence (**Figure 1A**). In wave-type fishes, the interval between each EOD matches the duration of a single EOD, resulting in a continuously oscillating, almost sinusoidal, EOD (**Figure 1B**). Electric organs have evolved at least six times independently among fishes (Gallant, 2019). Research on two lineages in particular, the African mormyrids and neotropical gymnotiforms, has led to numerous foundational insights into neural mechanisms for sensory processing and the control of behavior (Bullock et al., 2005; Carlson et al., 2019). Many of these insights have, in turn, fostered subsequent discoveries in auditory processing and have helped place our understanding of auditory processing into a broader evolutionary context.

Figure 1. *Electric organ discharge (EOD) recorded from two weakly electric fish species. Placing a pair of wires in the water near a fish and connecting them to an amplifier allows visualization of the EOD on an oscilloscope or computer.* ***A:*** *pulse-type EOD recorded from the mormyrid* Paramormyrops kingsleyae. ***B:*** *wave-type EOD recorded from* Gymnarchus niloticus*, the closest living relative to mormyrids.*



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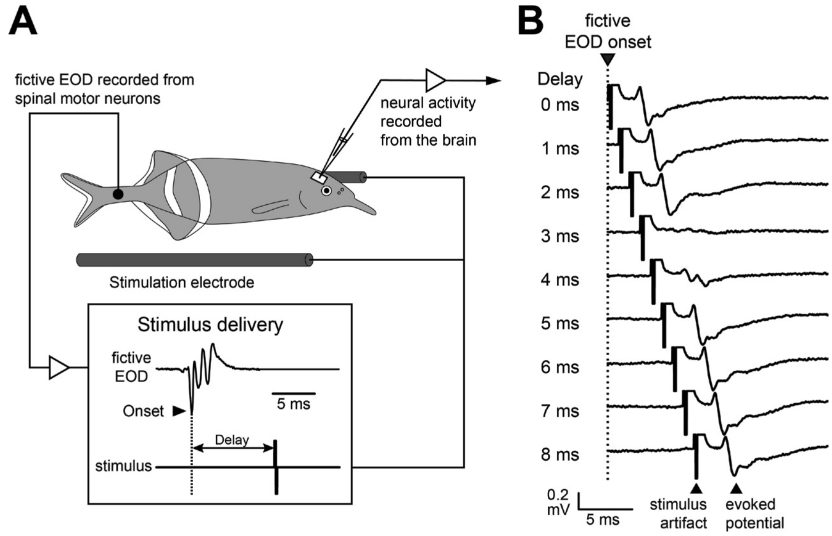

Figure 2. *Studying the effects of corollary discharge on sensory processing in mormyrid fishes.* ***A:*** *fish is paralyzed and its EOD is silenced. However, the activity of spinal motor neurons that normally result in an EOD can be recorded using an electrode placed next to the tail. Electrosensory stimuli can be delivered at fixed delays relative to this fictive EOD while recording the responses of sensory neurons in the brain to these stimuli.* ***B:*** *recording of electrosensory responses from neurons in the exterolateral nucleus in the brain. Stimuli are delivered at various delays following the fictive EOD. An electrical stimulus artifact is visible at the timing of stimulus delivery, and this is followed shortly by an evoked potential that represents the summed activity of numerous neurons near the recording electrode. This evoked potential is blocked at delays of 3-4 ms due to corollary discharge inhibition. Modified from Fukutomi and Carlson (2020).*

How to Distinguish Self from Others

When humans move their eyes, there is a dramatic shift in the visual stimulus hitting the retinas, but we perceive a stable, unmoving world. When external objects move, however, we perceive that as visual motion. Although humans and other animals distinguish between these different sources of visual stimulation effortlessly, this ability relies on sophisticated neural processing. Whenever an animal performs a behavior, a signal is sent from motor regions of the brain that control that behavior to sensory regions of the brain. Referred to as a “corollary discharge” (Sperry, 1950), this signal informs sensory regions about the timing of behavioral output, causing sensory neurons to respond differently to self-generated stimuli versus stimuli coming from the outside world.

Corollary discharges are critical for sensory processing and the control of behavior (Crapse and Sommer, 2008). There is even evidence suggesting that corollary discharge dysfunction may play a role in schizophrenia by impairing an individual’s ability to distinguish self from other (Ford et al., 2001). However, corollary discharges can be challenging to study because this requires the monitoring of sensory and motor systems in animals that are actively behaving. Electric fishes, however, are unique in that they produce a behavior, the EOD, that does not involve any muscle contractions and is much simpler than most behaviors. Because of this, decades of research in African mormyrids has led to numerous insights into corollary discharge functions and mechanisms (Fukutomi and Carlson, 2020).

Mormyrids produce pulse-type EODs (**Figure 1A**). When performing a neurophysiological experiment, the fish is immobilized with a drug that blocks the neuromuscular junction and prevents movement. This drug also silences the electric organ, so the fish no longer produces an EOD. However, neurons in the spinal cord that normally excite the electric organ continue to fire, and their activity can be recorded noninvasively by placing a small wire next to the tail, much like an electroencephalogram (EEG) is used to record human brain activity. Electrical activity in these spinal motor neurons is referred to as a “fictive EOD” because it reflects when an EOD would normally occur in a fish that hadn’t been silenced and thus can be used to monitor the timing of behavioral output. At the same time, electrodes can be placed in the brain to record the activity of sensory neurons, and stimuli can be delivered at precise times relative to these fictive EODs (**Figure 2A**).

Neurons within a region of the brain called the exterolateral nucleus respond strongly to external electrical stimuli. However, these responses are suppressed when stimuli are delivered around 3-5 ms after a fictive EOD (**Figure 2B**) (Fukutomi and Carlson, 2020). This is the exact window of time when the EOD of a freely behaving fish whose electric organ had not been silenced would stimulate its own electroreceptors. The suppression of this response at these delays is due to a corollary discharge.

A small group of neurons in the brain called command neurons control the timing of EOD production (**Figure 3**). Every time these neurons fire an electrical spike, or action potential, they excite spinal motor neurons, which, in turn, excite the electric organ, causing the fish to generate an EOD. In addition to the signal they send to the spinal cord, the command neurons send a copy of that signal to a brain region called the electrosensory lobe, the region of the brain that receives input from the fish's electroreceptors. Whenever a fish generates its own EOD, the electrosensory response to that EOD coming from its receptors arrives at the same time as the corollary discharge signal. The corollary discharge inhibits electrosensory responses. As a result, responses to self-generated EODs are blocked, and this information never makes it to the next stage of processing, the exterolateral nucleus. External EODs coming from other fish are, however, not time-locked to this corollary discharge inhibition, ensuring that information about external EODs makes it through. Thus, this particular sensory pathway only "hears" EODs coming from other fish, reflecting a dedicated role in communication behavior.

Since the initial discovery of this inhibitory corollary discharge, similar kinds of motor-related suppression of sensory systems have been found throughout the animal kingdom (Fukutomi and Carlson, 2020). However, the details of the underlying circuitry mediating these effects often remains obscure due to the challenges of studying corollary discharge in more complex behaviors. One notable exception is in the auditory pathway of crickets, in which a mechanism very similar to that operating in the mormyrid electrosensory system was found to suppress auditory responses during chirping (Poulet and Hedwig, 2002).

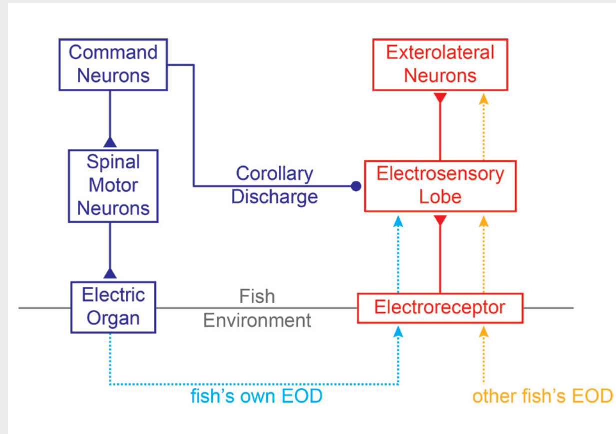

Figure 3. *A corollary discharge selectively blocks responses to self-generated EODs in mormyrids.* ***Blue:*** *different components of the electromotor system that controls EOD production.* ***Red:*** *different components of the electrosensory system that processes EOD stimuli.* ***Triangles:*** *excitatory connections between components;* ***circles:*** *inhibitory connections. EOD production is controlled by a group of command neurons in the brain. The command neurons excite spinal motor neurons, which, in turn, excite the electric organ, causing the fish to generate an EOD. The command neurons also generate a corollary discharge that inhibits neurons in the electrosensory lobe. Electroreceptors respond to both self-generated EODs (**cyan**) and the EODs of neighboring fish (**orange**). Information about both kinds of EODs gets sent to the electrosensory lobe. However, the corollary discharge inhibition coming from the command neurons is only active when the fish is generating its own EOD, so it selectively blocks responses to the fish's own EODs. Other fish's EODs do not occur at the same time as the corollary discharge inhibition, so responses to external EODs are not blocked and this information makes it through to the exterolateral neurons.*

Active electrolocation in mormyrids is mediated by a different type of electroreceptor that gives rise to a separate electrosensory pathway. For active electrolocation, the problem faced by a mormyrid is the opposite of the problem it faces in communicating with other fish. For communication, the fish needs to ignore its own EOD while detecting the EODs of other fish, but for active electrolocation, the fish needs to ignore the EODs of other fish while detecting its own EOD. Unsurprisingly, then, the effect of the corollary discharge on this sensory pathway is also opposite. Whereas corollary discharge inhibits the communication pathway, it excites the active electrolocation pathway. Because this excitation is only active when the fish generates its own EOD, it selectively boosts sensory responses to the fish's own EOD (Fukutomi and Carlson, 2020). Similarly, in the auditory system of bats, corollary discharge appears to suppress responses during calls (Suga and Schlegel, 1972) but enhance responses during echoes (Schuller, 1979).

Generating Expectations

A short window of inhibition is sufficient to block responses to brief, fixed stimuli like an EOD. However, sensory inputs resulting from an animal's own actions are often more complex, varying over space and time. For example, when an animal moves its eyes, the entirety of the images hitting the retinas shift, and the nature of that shift depends on whether the animal moved its eyes directly using ocular muscles or indirectly using neck muscles to move the head. The nature of that shift also depends on how fast and in which direction the eyes moved. In many cases, a corollary discharge activates a so-called "efference copy," which is a "negative image" of the sensory response predicted to result from a behavior (von Holst and Mittelstaedt, 1950). It is more complex than a brief window of inhibition that simply blocks sensory responses and is instead a precise template that can cancel out responses to self-generated stimuli that vary in space and time. As a result, responses to self-generated stimuli are subtracted out, whereas responses to external stimuli get through.

Research in mormyrid fishes yielded the first experimental demonstration of how brains can implement an efference copy (Fukutomi and Carlson, 2020). In addition to the electroreceptors that mediate communication and active electrolocation, mormyrids have a third electroreceptor type that mediates passive electrolocation. Passive electrolocation is to active electrolocation what hearing is to echolocation: the identification and localization of objects in the environment using external cues rather than feedback from self-generated stimuli. Passive electrolocation is far more widespread than active electrolocation, being an ancestral vertebrate sense found in living lampreys; cartilaginous fishes such as sharks and rays; certain bony fishes such as sturgeons and paddlefish; aquatic salamanders; and mammals such as the platypus (Bullock et al., 1983). Much like neurons that maintain an electrical potential across their membrane due to an uneven distribution of ions inside and outside the cell, living organisms in an aquatic or marine environment maintain an electrical potential across their skin surface because the concentrations of ions in their bodies are different from those in the surrounding water. These small potentials can be used to precisely locate living organisms. Passive electrolocation is typically used to detect prey at short range but can also be used to detect predators and potential mates.

These passive electroreceptors are far more sensitive than the electroreceptors mediating active electrolocation and communication because they must pick up faint signals naturally emanating from living organisms rather than from comparatively "loud" EODs being actively generated by electric organs. As a result, these receptors respond strongly to the fish's own EOD. However, unlike the electroreceptors that mediate communication, which have very brief responses to EODs, the responses of the passive electroreceptors are complex and can last as long as 100 ms. Simply blocking responses throughout this window of time would render the fish unable to detect external stimuli for an extended period of time.

Instead, an equally complex and long-lasting efference copy is used to cancel responses to self-generated EODs while maintaining sensitivity to external stimuli (Fukutomi and Carlson, 2020). What's more, as environmental conditions change, the responses to self-generated EODs can also change. Thus, this efference copy is not hardwired but is continuously updated in real time. Recently, a similar process was found to occur within the mouse auditory system, in which an efference copy was generated and continuously updated in response to sounds that were associated with licking behavior (Singla et al., 2017).

Temporal Hyperacuity

Timing plays a critical role in both auditory and electrosensory processing. The most extreme example of temporal sensitivity in the auditory system is the detection of interaural time differences (ITDs) that many land vertebrates use to determine where a sound originates from (see bit.ly/3EugfQ8). Sounds originating directly in front of the listener arrive at both ears simultaneously. Sounds that come from one side, however, hit the near ear before the far ear, resulting in an ITD. Humans can detect ITDs as small as about 10 µs (Klumpp and Eady, 1956).

Much like humans detect differences in the timing of auditory inputs to the two ears to determine where a sound is coming from, weakly electric fishes also use differences in the timing of the responses of electroreceptors on different parts of the body surface to get information about the outside world. In mormyrids, such timing differences are used to determine the EOD waveform of neighboring fish, which varies with species, sex, age, reproductive status, and relative dominance (Hopkins, 1986a).

In contrast to the pulse-type EODs of mormyrids, their closest relative, *Gymnarchus niloticus*, generates a wave-type EOD (**Figure 1B**). Wave-type EODs are also found in numerous gymnotiform species from Latin America. During active electrolocation, wave-type fish use small timing differences in the feedback from their self-generated EODs to detect electrical capacitance, which allows them to distinguish living from inanimate objects (von der Emde, 1998). Timing differences are also important during social interactions. When two fish are in proximity to one another, their EODs interfere to create modulations in signal amplitude and phase (Heiligenberg, 1991). The rate of modulation is equal to the magnitude of the frequency difference between the EODs and is identical for frequency differences of equal magnitude but opposite sign. Distinguishing positive from negative frequency differences requires a fish to analyze the relationship between amplitude and phase modulation and thus depends on the ability to detect small-phase modulations (Heiligenberg, 1991). Because EOD frequency varies in wave-type fish with species, sex, and relative dominance, this ability is crucial in identifying neighboring fish. It also underlies performance of the jamming avoidance response, in which fish with similar EOD frequencies shift their frequencies away from each other to avoid jamming their active electrolocation abilities (see bit.ly/3Eu35Cw).

Weakly electric fish outperform humans in their temporal sensitivity. They can detect differences in the timing of electrosensory stimuli as small as tens to hundreds of nanoseconds (Kawasaki, 1997). This remarkable sensitivity may have evolved because, unlike acoustic signals, electric signals do not propagate as waves but exist as localized, nonpropagating electrostatic fields (Hopkins, 1986b). Whereas acoustic communication signals are degraded due to absorption, reflection, refraction and reverberation, the fine temporal structure of electric signals is preserved, allowing information to be accurately transmitted at much shorter timescales (Hopkins, 1986b).

Detecting Submillisecond Timing Differences

Neurons transmit information using electrical spikes that are called action potentials. Typically, action potentials are generated close to the cell body, or soma, of a neuron and then propagate at a finite speed down a long biological wire called an axon. The end of that axon comes into close contact with a target neuron, forming a synapse for communication from the presynaptic neuron to the postsynaptic neuron. Sometimes these synapses are located on the soma of the postsynaptic neuron, but often they are located on dendrites, which are small, branching fibers that emanate from the soma.

A typical action potential in a neuron lasts about 1 ms. Even the fastest synapses operate in the range of milliseconds to tens of milliseconds. Thus, the degree of temporal acuity found in the auditory system of humans and the electrosensory systems of weakly electric fishes is remarkable. How can nervous systems detect differences in the arrival times of stimuli at different sensory receptors that are several orders of magnitude shorter than the signals the nervous system itself uses to process information?

Following the discovery of ITD sensitivity in humans, Jeffress (1948) devised a model for how a neural circuit could detect a range of ITDs. According to this model, auditory inputs from the two ears enter a neural circuit on opposite sides (**Figure 4A**). An action potential traveling along an axon coming from the left ear will reach neurons on the left end of the circuit first and neurons on the right end of the circuit last. However, an action potential coming from the right ear goes in the opposite direction. These axons traversing the length of the circuit are referred to as “delay lines,” because the inputs they provide to their postsynaptic targets arrive at increasing delays as an action potential travels down the axon. Postsynaptic neurons within the circuit respond maximally when they receive simultaneous inputs from both ears, which is referred to as “coincidence detection.” Thus the Jeffress model (1948) is a model based on “delay-line coincidence detection.”

A sound coming from in front of the listener will reach both ears at the same time. The resulting action potential from the left ear will enter the left end of the circuit at the same time as the action potential from the right ear enters the right end of the circuit. These action potentials

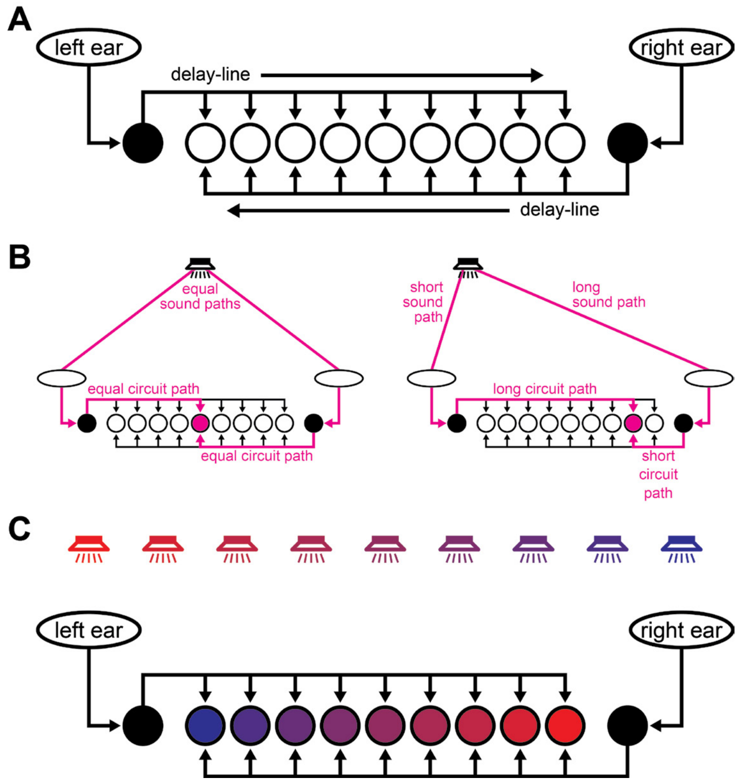

Figure 4. *The Jeffress model relies on delay-line coincidence detection to convert interaural time differences (ITDs) into a map of sound source location.* ***A:*** *axons relaying auditory input from the left and right ears enter the circuit at opposite ends and traverse the length of the circuit, synapsing on postsynaptic neurons throughout. This establishes delay lines running in opposite directions for the two ears.* ***B:*** *postsynaptic neurons are coincidence detectors that respond maximally when they receive simultaneous excitatory input from the left and right ears.* ***Magenta lines****, paths that a sound takes to first reach the two ears and then the paths of action potentials traveling through the circuit to coincide at the neuron in the circuit (****magenta circles****). For a sound coming from straight ahead, the sound path to the two ears is equal in length and arrives at the two ears simultaneously. The inputs arising from the two ears will therefore be coincident in the middle of the circuit where the two circuit paths are also equal in length. If a sound comes from the left, however, then there is a shorter path to the left ear. Therefore, the inputs arising from the two ears will be coincident at a location in the circuit where there is a shorter circuit path from the right ear compared with that from the left ear, at which differences in circuit path length compensate for differences in sound path length.* ***C:*** *this combination of delay lines and coincidence detection leads to a spatial representation of sound source locations.* ***Top row:*** *sounds coming from different positions in space as a spectrum of colors from the left side of the head (****red****) to the right side of the head (****blue****).* ***Bottom row: colored circles*** *indicate which postsynaptic neuron responds maximally to sound coming from each of these different locations. From Carlson (2019).*

will arrive simultaneously at postsynaptic neurons in the middle of the circuit, which will respond more strongly to sounds coming from this particular location compared with neurons on either side of the circuit (**Figure 4B**). If a sound comes from one side, however, the closer ear will get a head start over the farther ear. For a sound coming from the listener's left, the action potential arriving from the left ear will enter the left side of the circuit before the action potential arriving from the right ear enters the right side of the circuit. As a result, these action potentials will arrive simultaneously at postsynaptic neurons toward the right side of the circuit, and these neurons will respond more strongly compared with other neurons in the circuit (**Figure 4B**). Sound sources that are even further to the listener's left will maximally excite neurons that are even closer to the right edge of the circuit, and sounds that are to the listener's right will maximally excite neurons that are toward the left side of the circuit.

Thus, the Jeffress model (1948) provided a hypothetical mechanism by which a neural circuit could convert small differences in the arrival times of sounds at the two ears into a map of sound source location (**Figure 4C**).

Forty years after Jeffress published his model, Carr and Konishi (1990) discovered that the auditory system of barn owls processes ITDs using this mechanism. Additional comparative studies in alligators, chickens, and emus revealed that they use the same mechanism, suggesting that all reptiles and birds detect ITDs this way (Carr et al., 2009). However, later work in mammals revealed that they detect ITDs using different mechanisms. The exact mechanisms by which mammalian auditory systems detect ITDs remain unclear because there is evidence supporting a variety of different mechanisms (Carlson, 2019). However, it is clear that mammals solve this problem in a fundamentally different way from birds and reptiles.

The neural circuits responsible for processing submillisecond timing differences in weakly electric fishes have been studied in pulse-type mormyrids, wave-type gymnotiforms, and the wave-type *Gymnarchus*. These different fishes solve this problem in fundamentally different ways that also differ from the ITD processing circuits of reptiles/birds and mammals (Carlson, 2019). Like reptiles and birds, mormyrids rely on axonal delay lines to shift the timing of excitatory input to their postsynaptic neurons (Friedman and Hopkins, 1998). However, mormyrids also rely on precisely timed inhibition to postsynaptic neurons. Thus, the mormyrid circuit for processing submillisecond timing differences implements “delay-line *anti*-coincidence detection” (Lyons-Warren et al., 2013). In other words, the neurons in this circuit respond best when delayed excitation and inhibition is *not* coincident. Another key difference is that the axonal delay lines in mormyrids follow a convoluted and tortuous path and do not establish a spatial map of timing differences, unlike the spatial map of ITDs found in the brains of reptiles and birds.

Wave-type electric fish solve the problem of detecting submillisecond timing differences in yet another way. Both gymnotiforms and *Gymnarchus* use delay-line coincidence detection, similar to reptiles and birds (Carr, 2004). However, they use dendritic delays rather than axonal delays. A synaptic input to the dendrite of a neuron will require the resulting electrical activity to travel down the dendrite before reaching the soma, thus causing a delay compared with a synaptic input directly onto the soma. If the stimulus driving a dendritic input occurs before the stimulus driving a somatic input, then that dendritic delay will compensate for this difference in stimulus timing, and the two inputs will reach the soma at the same time, maximally exciting the neuron. Despite this similar mechanism in the two groups of fishes, there are key differences in the circuitry for implementing this delay-line coincidence detection. Most notably, the relevant circuit is found in completely different parts of the brain in *Gymnarchus* and gymnotiforms.

The Evolution of Temporal Processing

Mammals and birds/reptiles evolved tympanic ears along with the neural circuitry for processing ITDs independently (Christensen-Dalsgaard and Carr, 2008). Similarly, gymnotiforms evolved their electrosensory systems independently from mormyrids and *Gymnarchus* (Lavoué et al., 2012). Thus, it is remarkable that all five of these circuits share numerous similarities at the cellular level, including large somas, large-diameter axons with thick insulation (called myelination), minimally branching dendrites (or no dendrites at all), large synapses, and fast-acting synapses (Carr et al., 2001). These features increase the speed and reliability of action potential propagation and synaptic transmission and thus reduce timing errors. These similarities thus reflect the power of natural selection to predictably shape the evolution of neural circuits.

Nevertheless, these similar building blocks are used to construct different circuits. Why do five different circuits that all serve a similar function do so using different mechanisms? Chance may have dictated which one evolved in a given lineage. However, these differences may also reflect adaptation and evolutionary history (Carlson, 2019). The earliest reptiles appear to have had larger heads and sensitivity to lower frequency sounds compared with the earliest mammals, and ITDs work best for sound localization with low-frequency sounds and large distances between the ears. Thus, the earliest reptiles may have already been using ITDs for sound localization, whereas mammals that evolved enlarged heads and low-frequency hearing may have had to repurpose existing circuitry to process ITDs (Grothe and Pecka, 2014). Moreover, although mammals and birds/reptiles need to make a single timing comparison between the two ears, weakly electric fishes have dozens of electroreceptors, requiring far more timing comparisons. Furthermore, although pulse-type mormyrids need to detect a range of timing differences to identify a variety of EOD waveforms, wave-type electric fishes simply need to detect stimulus advances or delays to identify capacitive objects or determine the frequency difference between their EOD and that of a neighboring fish. These functional differences may have necessitated different computational strategies for efficiently processing this information (Carlson, 2019).

Regardless of the ultimate reasons these circuits evolved to solve this problem in different ways, it is clear that findings in one species cannot simply be extrapolated to other species. Comparative studies across the electrosensory and auditory systems of multiple species have revealed numerous similarities and differences. In the study of any behavior and its neural basis, comparative studies are necessary to identify which features are shared across species, which features differ between species, and why these differences exist.

Conclusion

Research on electric fishes has led to fundamental insights into how nervous systems distinguish self from other, generate expectations about sensory input, and detect submillisecond timing differences, as well as other important discoveries not described here, such as how nervous systems process stimulus envelopes, integrate amplitude and timing information, and modify behavioral output. Indeed, the jamming avoidance response remains, to date, the only vertebrate behavior for which we have a complete understanding of its neural basis, from sensory input to sensory processing to motor control to behavior (Heiligenberg, 1991). Electric fish research has proven synergistic with research into auditory and other sensory systems. In some cases, the findings in electric fishes have stimulated research on other sensory systems. In other cases, these findings have helped contextualize our understanding of other sensory systems, improving our knowledge of how and why brains have evolved. Electric fishes are a testament to the neuroethological approach to behavior: choosing a study organism not because it is convenient to house in a laboratory or because of genetic tools but because unique aspects of its behavior make it amenable to addressing specific questions of broad relevance to understanding all nervous systems.

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The “Sounds” of Black Holes

Delilah E. A. Gates

Black holes may seem like mysterious objects from science fiction, but observational evidence suggests that they are, in fact, quite common. Supermassive black holes, of masses 100,000 to 10,000,00 times that of our Sun, are believed to lie at the heart of every galaxy. Additionally, there are several smaller black holes, of masses roughly 3 to 200 times that of the Sun, strewn throughout every galaxy. Current estimates suggest that there are upward of 10^{19} black holes in the universe (Sicili et al., 2022).

The defining feature of a black hole is its event horizon, a region from which nothing can escape, not even light. On the face of it, this would seem to make observing black holes difficult. Evidence of black holes thus relies on observing the effects that they have on things, like stars and gas, around them. Moreover, black holes have been found to cause wave-related phenomena: frequency shifting of light, reverberation of sounds (which constitute the lowest known notes produced in the universe) through their surrounding medium, and even ripples throughout space and time.

Gravity and Black Holes

Black holes as a concept seem far removed from us here on Earth. To truly understand black holes, we must first understand gravity. As residents of Earth and popular science consumers, we are all, intuitively, aware of gravity.

Newtonian Gravity

Most of us internalize this notion of gravity along the following lines: the more massive an object is, the harder you are pulled toward it, and the closer you are to a massive object, the harder you are pulled toward it. Our intuitive understanding is usually aligned with the description of gravity laid out by Isaac Newton (1687). Newton’s universal law of gravitation states that the force between two objects is proportional to the masses of the objects and inversely related to the square of the distance between the objects. This conception of gravity describes why planets travel in elliptical orbits around the Sun, explains why you can jump higher and fall slower on the moon than on Earth, and tells us how fast we need to propel rockets to launch them into space.

Launching rockets into space from Earth’s surface requires consideration of the escape velocity. Escape velocity, which can be derived from Newton’s law of gravitation, is the velocity with which an object on the surface of a massive body, like a planet, must be launched to “escape” the gravity of the massive body. If launched with a speed less than the escape velocity, the object eventually slows to a stop and falls back to the surface. Escape velocity depends crucially on the ratio of the body’s mass and radius.

Newtonian gravity (and escape velocity therein) seeded the first conception of what we would now call a black hole. In 1783, philosopher John Michell posited the existence of “dark stars,” bodies so massive that their escape velocities were the speed of light. Today, this idea of a body from which objects cannot escape sounds remarkably like a black hole. The radius from which the escape velocity is the speed of light marks the black hole’s defining feature, the event horizon (Michell, 1784).

Newtonian gravity provides a reasonable description for most of our everyday life and was accurate enough to take us to the moon during the 1969 Apollo 11 mission. But even in 1969, Newtonian gravity was known to be only an approximate description of how gravity works in our universe. Indeed, in 1915, Albert Einstein wrote a more precise description of gravity called the general theory of relativity (colloquially known as general relativity or Einstein gravity) (Einstein, 1916).

Einstein Gravity: General Relativity

Understanding the theory of general relativity demands we radically shift our way of thinking about gravity. Where Newtonian gravity tells us that gravity is a force of attraction felt by objects due to mass, Einstein’s

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equations for gravity directly relate the geometric shape of space-time to the distribution of matter and energy in the space-time. Heuristically, general relativity says, in the words of physicist John A. Wheeler, "space-time tells matter how to move; matter tells space-time how to curve" (Wheeler and Ford, 1998).

The concept of "space-time" was seeded in Einstein's 1905 theory of special relativity (Einstein, 1905). The defining feature of special relativity is that everyone measures the speed of light to be 2.998×10^8 meters/second. Special relativity implies that what we perceive as the three-dimensional (3D) space and the passage of time are all part of a four-dimensional geometric object called "space-time" (Minkowski, 1908). Special relativity does not include gravity and is only a good approximation when masses are sufficiently small so as not to cause large amounts of curvature in space-time.

Evidence in support of Einstein gravity over Newtonian gravity was immediately available because Einstein showed that general relativity solved a long-standing problem of explaining the orbit of Mercury around the Sun (Einstein, 1916). Another test Einstein proposed to determine whether general relativity better models nature than Newtonian gravity was gravitational lensing. Gravitational lensing is the deflection of light around massive bodies and is so named because massive objects cause light to travel on bent paths in a manner similar to light through an optical lens. Measurements made of the 1919 total solar eclipse supported Einstein gravity (Dyson et al., 1920; Gates and Pelletier, 2019).

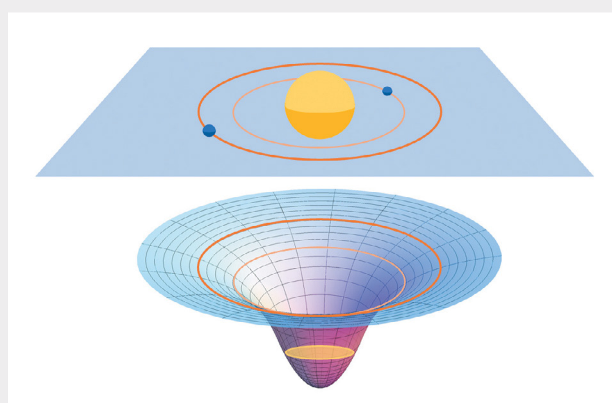
When Einstein wrote his theory of gravity, he never expected anyone to be able to come up with a solution for a space-time shape that would exactly satisfy his equations. But, rather quickly, Schwarzschild (1916) calculated the solution describing the space-time around a nonrotating mass. Unknown to Einstein, Schwarzchild had studied the mathematics of curved three-dimensional space, although not four-dimensional space-time, a decade earlier. The Schwarzschild solution held a remarkable feature: the possibility of a black hole! In the Schwarzschild solution, there is a critical radius, now called the Schwarzschild radius. One can think of this critical radius as a one-way door. Objects can travel from the region outside the critical radius to the region inside the critical radius. However, once inside, objects can never travel back out. Thus, if the mass is compact enough to fit inside the Schwarzschild radius, this radius marks the event horizon of a black hole!

Although the possibility of black holes was once again mathematically realized in general relativity, just as the dark stars were in Newtonian gravity, Einstein himself was skeptical of their existence. Interpretation of the Schwarzschild solution (1916) was a topic of great debate among Einstein and his contemporaries. It remained an open question whether the matter in our universe was compressible enough to achieve the densities needed to create black holes. Excitingly, the matter in our universe does seem to allow for black holes, and we now live in a time where astronomical observational technology has allowed us to push the existence of black holes from scientific speculation to scientific fact.

Visualizing Space-Time Curvature

To understand observational evidence of black holes, imagining what is meant by "the curvature of space-time" is beneficial. When trying to visualize the space-time curvature, images like those in **Figure 1** are often shown. While instructive, their interpretation can be subtle. If we consider small objects moving in a plane around a more massive body, the objects appear to move on curved paths around the massive body (**Figure 1**, *top*). In actuality, the plane to which motion is confined has a curvature

Figure 1. *Gravitational potential.* ***Top:*** *motion of small objects (**blue**) traveling in a plane around a massive body (**yellow**). The orbits of the objects are shown in **orange** and **pink**.* ***Bottom:*** *gravitational potential is shown as a basin. The motions of objects in the plane are a projection of their motions along the surface of the potential. See text for detailed explanation.*



that can be analogized to the two-dimensional surface of, say, a basin (**Figure 1**, *bottom*).

The depth of the basin represents the "gravitational potential" and is set by the mass of the central body. When there is no massive body, objects move in the plane as expected; however, when a massive body curves the space-time, objects move similarly to marbles along the surface of the basin.

In the basin analogy, we can imagine a marble on a myriad of orbits: closed orbits like elliptical or circular orbits; hyperbolic orbits that start far from the central mass, approach it, then zoom back out; and orbits that spiral in/out of the basin. We can visualize the change in speed that objects experience along their orbits, increasing and decreasing as they approach or move away from the basin center. We can also imagine escape velocity: how hard must we flick a marble in the well of the basin for it to climb out entirely and not eventually slow to a stop before turning around and falling back toward the center? Light also moves along this curved space in similar ways; however, its speed is always constant.

Observing Black Holes with Waves

Several observational signatures of black holes are related to wave phenomena. These signatures make use of three types of waves: electromagnetic waves, pressure waves, and gravitational waves.

Electromagnetic Waves

It may come as no surprise that electromagnetic wave (light) observations are a common way to gather evidence of black holes because most astronomical objects are identified with telescopes. Tracking the motion of stars in our own galactic center has allowed us to locate and measure the mass of the supermassive black hole central to the Milky Way, earning the scientists who led these efforts a Nobel Prize in 2020 (see tinyurl.com/galactic-center-star-orbits) (Ghez et al, 2008; Abuter et al., 2022). The black hole is named Sagittarius A* (Sgr A*). Additionally, the first images of the extreme lensing of light around black holes on the scale of a few Schwarzschild radii have been produced by the Event Horizon Telescope (see eventhorizontelescope.org). The first of these images, made in 2017, showcases a behemoth of a supermassive black hole named M87* that lives at the center of the Messier 87 (M87) galaxy (see tinyurl.com/eht-m87); the second image is that of Sgr A* released in 2022 (see tinyurl.com/eht-sgra) (Akiyama et al., 2019 , 2022). But both these methods of black hole observations are narrowly applicable with current technology. Observations that make use of the wavelike nature of light can be applied more widely.

Electromagnetic radiation is composed of transverse waves of the electric and magnetic fields; that is to say, the direction of travel is perpendicular to the direction in which electric and magnetic fields vary. The frequency of an electromagnetic wave is proportional to its energy and, for visible light, is related to its color. Short wavelength/higher frequency light appears bluer, whereas longer wavelength/lower frequency light appears redder. Like sound waves, electromagnetic waves can be Doppler shifted by the motion of the light source relative to the observer. Imagine that I am standing still, shining a laser at you, and you note the color of the light. If I shine the same laser while moving away from you, the light will appear redder. Similarly, the light will appear bluer if I move toward you. This is called relativistic Doppler shifting and is a consequence of special relativity.

Within general relativity, Einstein established a concept called the equivalence principle, which says one cannot distinguish between feeling gravity or standing on an object that is accelerating. It is taught in physics class that the acceleration of gravity felt on Earth (at its surface) is $g = 9.8$ meters/second^2. If blindfolded, you would not be able to distinguish between the feelings of standing on the surface of the earth and of being pushed against a spaceship accelerating through space at g. Unless you have a window to look out of, you cannot make the distinction. (This is the rationale behind creating artificial gravity with spinning space stations like those seen in *2001: A Space Odyssey*, *Interstellar,* and *The Martian*.)

The equivalence principle gives rise to gravitational redshift, which says that the light gets frequency shifted as it climbs into or out of a gravitational potential, just as it would be if emitted by a source moving toward or away from you (Einstein, 1916). Returning to our basin analogy, marbles (massive objects) lose energy as they move away from the steeper center of the basin toward the shallower edges, decreasing in speed, and increase in speed, gaining energy, as they fall into the basin. So, too, does light experience energy shifts as it climbs into or out of a gravitational well; however, the speed of light is constant, so the change in energy is manifested as a shift in frequency.

Today, gravitational redshift has been measured for thousands of galaxy clusters by comparing the frequency of light at the edges of the clusters with the centers where the gravity is stronger (Wojtak et al., 2011). Gravitational redshift has also been measured for our own galactic center by tracking the frequency of light from one of the stars orbiting close to Sgr A* (Abuter et al., 2018).

In some cases, gravitational redshift has been used to measure the rotation rate of black holes. Black holes can rotate like stars and planets. For a nonrotating black hole, the event horizon is at the Schwarzschild radius (1916). But as the rotation rate of the black hole increases, the event horizon gets more compact, shrinking the radius. Therefore, light can be emitted from deeper inside the gravitational potential created by a more rapidly rotating black hole and must incur an even greater redshift to reach an observer far from the black hole like us (Reynolds, 2019).

Acoustic/Pressure Waves

You may have heard “there is no sound in space.” This adage arises because most of space is a vacuum where particles are too dilute to constitute a fluid that can support an acoustic wave. Galaxies, which host supermassive black holes, and galaxy clusters can be surrounded by significant amounts of gas that can support sound. Indeed, black holes can churn the gaseous medium and cause compression waves. Although we cannot hear sound waves in the gas around black holes, here on Earth, we can image the medium that supports such waves if the gas is hot and gives off light.

The Perseus cluster is a large galaxy cluster that hosts thousands of galaxies enveloped in extremely hot gas. Pressure waves in the Perseus cluster (see www.nasa.gov/chandra/multimedia/perseus-cluster.html) were discovered by imaging the intracluster gas that glows in the X-ray band of the electromagnetic spectrum using the Chandra X-ray Observatory (see chandra.harvard.edu). The image shows a pattern of over- and underdensities that constitutes a compression wave with a period almost 10^7 years long. This translates to the note B flat 57 octaves under middle C. For comparison, the lowest period humans can here is about 0.05 s (or the frequency of 20 Hz) (see

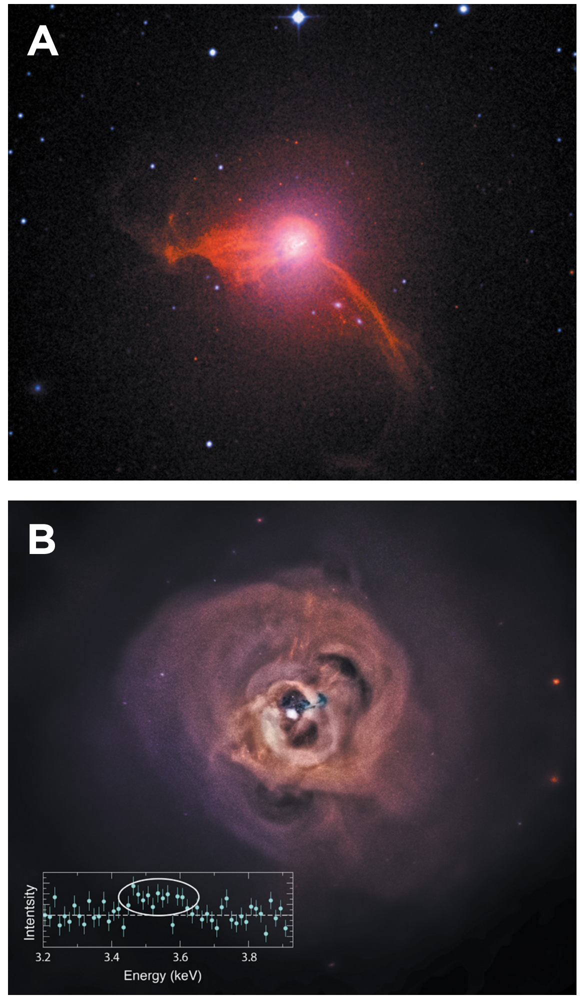


Figure 2. *The Perseus galaxy cluster and the elliptical galaxy M87* ***Top:*** *image of Perseus cluster (see www.nasa.gov/chandra/multimedia/perseus-cluster.html or chandra.harvard.edu/photo/2014/perseus) created using data taken by NASA's Chandra X-ray Observatory. Image credit: X-ray: NASA/CXC/SAO/E. (Bulbul et al., 2014).* ***Bottom:*** *image of M87 galaxy (see chandra.harvard.edu/photo/2006/m87) seen in both X-ray (**red**) and optical (**blue**) spectra. Image from X-ray: NASA/CXC/CfA/W (Forman et al., 2007). Optical: DSS, 2006. Both images were constructed from data taken by NASA's Chandra X-ray Observatory (see chandra.harvard.edu/photo/image_use.html).*

chandra.harvard.edu/photo/2003/perseus) (Fabian et al., 2003).

Evidence of black hole sounds has also been detected in the gaseous environment of M87 in the Virgo cluster, again using Chandra. Two different types of structures (bubbles and shocks), suggesting sound waves, were identified. The size of these image features suggests that M87* is creating notes 56 octaves below middle C and, even deeper still, notes at 58 to 59 octaves below middle C. These are the deepest known sounds in the universe (see chandra.harvard.edu/photo/2006/m87) (**Figure 2**) (Forman et al., 2007).

As an aside, there are "sonified" astronomical images by NASA (see chandra.si.edu/sound), including the image of the pressure wave in Perseus cluster. The Perseus sonification is not a simple frequency-shifted version of the notes one would hear ringing out in Perseus if they were to stand still and let the waves pass over them. Instead, these images are translations of the features of the image along radial slices converted into sound in the human hearing range. This kind of sonification can be performed on any image and is an interesting way to experience the data.

Gravitational Waves

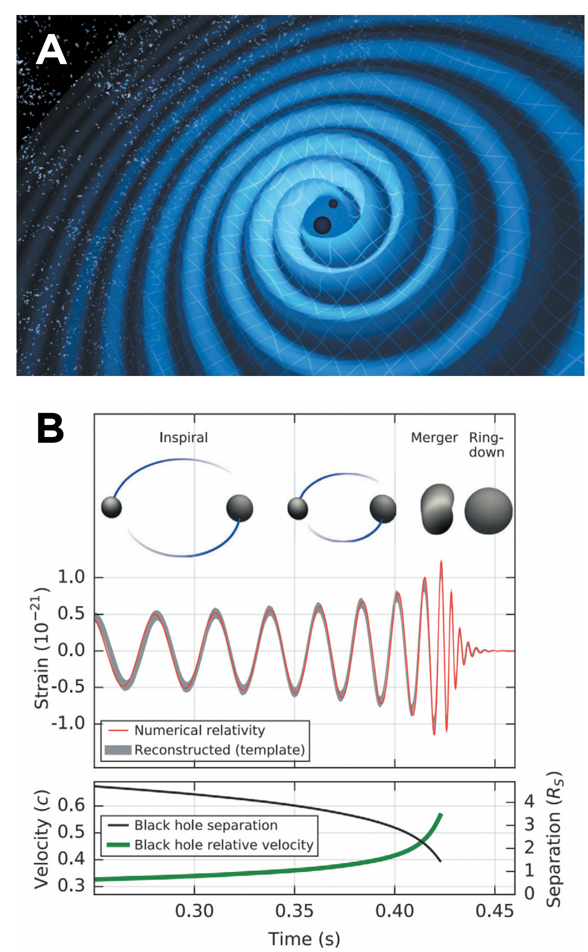
Although light has long been our "messenger" from the heavens giving us information about the wondrous astronomical bodies in the sky, general relativity opened the door for yet another way to detect objects in space: gravitational waves.

Gravitational waves are another prediction of general relativity described by Einstein (1918). Because general relativity describes space-time as a dynamical object that curves in response to the position of matter, it is naturally implied that moving masses should cause waves to ripple through the surface that is space-time, much like moving objects causing waves in water. Gravitational waves propagate at the speed of light and are transverse waves causing space to stretch and contract in the direction perpendicular to their direction of travel.

The gravitational waves caused by most objects are too weak to be detected, so only the most rapidly moving, strongest gravity objects can produce measurable disturbances. But such events do exist in our universe, one example being the merger of binary black holes.

Two black holes can get caught in each other's gravitational potentials, forming a binary. If they are close enough to one another, the black holes will spiral in on each other, gaining speed as their orbital period and the distance between them shrinks, giving off gravitational waves of increasing frequency and amplitude. When the black holes get close enough, they merge into a single black hole, which continues to give off gravitational waves as it vibrates, ringing as it settles down into a stationary state, much like a struck bell producing sound waves (**Figure 3**).

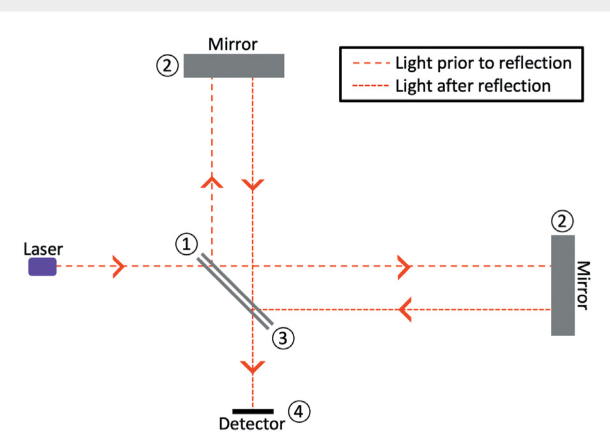
Figure 3. *Gravitational wave from a binary black hole system.* ***Top:*** *illustration of the gravitational waves emanating from binary black holes. Image credit: LIGO/T. Pyle, 2016.* ***Bottom:*** *detection of GW170817 in one of LIGO's detectors. The image shows the strain measured in the detector as the binary black holes go through inspiral (spiraling in on one other getting closer together), merger (where they combine into a single black hole), and ringdown (where the final black hole settles down). The separation and relative velocity of the binary black hole is also shown. Reproduced from Abbott et al. (2016, with permission of the American Physical Society.*



Even the gravitational waves from these violent mergers are extremely weak and measuring them is no easy feat. Still, black hole mergers happen frequently, and we humans on Earth never feel the effects of the passing gravitational waves. But just as small earthquakes unnoticed by humans are measured by seismometers, so too can the weak gravitational waves be detected by observatories like LIGO (see www.ligo.caltech.edu), Virgo (see www.virgo-gw.eu), and KAGRA (see gwcenter.icrr.u-tokyo.ac.jp).

The detectors of the gravitational wave observatories consist of L-shaped interferometers with kilometers-long arms. Laser light travels down the arms, hits a mirror, and travels back. The equipment is carefully stabilized and cooled so the mirrors are very still. When a gravitational wave passes the detectors, stretching or shrinking space, the mirrors move. Thus, the mirrors act like the eardrums of an animal being vibrated by a sound wave, allowing the detector to "hear" the gravitational wave. Motion in the mirrors changes the distance the light travels, which can be measured using changes in the interference pattern (**Figure 4**). LIGO can detect motion in its mirrors with a precision of one ten-thousandth the charge diameter of a proton.

Figure 4. *A simplified schematic of a laser interferometer. A laser is split in two by a half-silvered mirror; (**1**) the beams travel down the arms and encounter mirrors; (**2**) the reflected beams travel back along the arms and are recombined by the half-silvered mirror (**3**); and the recombined beam is shone on a detector (**4**). On recombination, the two beams will interfere. As the length of the arms change, the interference pattern changes.*



The first binary black hole merger detection (called GW150914) was made in 2015 (Abbott et al., 2016). Since the first gravitational wave detection, many more merger events have been found, including mergers whose initial constituents are neutron stars. Neutron stars are the most compact objects in the universe besides black holes. Binary neutron stars, which also result in black holes after merger, produce gravitational wave signals that the gravitational wave interferometers can detect. Observatories can discern between the different merger scenarios based on the waveform from the merger. The first binary neutron star merger detection in gravitational waves (GW170817) was in 2017 (Abbott et al., 2017a). The merger waveforms translated into sound are often called "chirps" because of their characteristic sound as they increase in frequency (see www.ligo.caltech.edu/video/ligo20160615v2)

Light from the first binary neutron star merger event was also seen in a telescope as a gamma ray burst (GRB170817A), marking the dawn of a new era of "multimessenger" astronomy (Abbott et al., 2017b). With ever-increasing advances in telescopes and gravitational wave detectors, including proposals for new larger ground-based detectors (see cosmicexplorer.org; www.et-gw.eu) and a space-based detector (see lisa.nasa.gov), the future of observational black hole astrophysics is both bright and loud.

Acknowledgment

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Uncertainty in Acoustical Modeling

Sheri L. Martinelli, D. Keith Wilson, Andrew S. Wixom, and Chris L. Pettit

Introduction

In acoustics, as in many fields, complex phenomena are often described with representations, or *models*. Unfortunately, all models are inherently imperfect representations of the real world. As the mathematician von Neumann (1947, p. 626) put it, "Truth is much too complicated to allow anything but approximations." Often, the models are highly idealized; for example, a fish may be represented as a cylinder in an acoustical scattering calculation. Similarly, a room may become a rectangular box and the ocean a homogeneous layer of water bounded above by air and below by sediment. Such simplifications can provide invaluable insights into acoustical phenomena, however. These idealizations allow us to express mathematically how sound waves interact with a fish, a room, or the ocean. The error incurred in making these approximations is called *model error* and is one component of the *error budget* (Pettit and Wilson, 2017) that all modeling efforts seek to balance against model fidelity.

Computers make it possible to create much more realistic models by translating the mathematical equations into computer code that can perform many more calculations than a mathematician can with a pencil. Increasing model fidelity (adding complexity to create a more detailed representation) can greatly reduce the model error. For example, the fish can have fins and a tail, the room can have balconies and seats, and the ocean can have a wavy surface and rocks in the sediment. The important acoustical effects arising from these examples would be intractable without computers. However, a computational model differs in important ways from a mathematical model. The mathematical model uses assumptions to simplify the physics. To solve the equations on a computer, they must be *discretized* for representation on a finite precision machine. For instance, integrals become weighted sums and derivatives become finite differences; this introduces error into the computational model that is not present in the mathematics. A second component of the error budget is the *discretization error*. It can be reduced by operations such as grid refinement or more advanced numerical methods.

Because models, whether computational or analytical, have these inherent errors due to simplifications, laboratory and field experiments remain essential for validating models and understanding acoustical phenomena. Real-world data are also needed as the model's input. Any data used to inform the model will have errors due to sensor calibration, resolution, and natural variability of the quantity being measured. This *measurement error* is another term in the error budget. For example, it is impossible to measure every grain of sand for input to an ocean acoustics model, and the action of taking a core sample disturbs the layered structure of the sediment, making any future description of this variable incorrect.

This article focuses on the final piece of the error budget, one that is perhaps the least often considered, *statistical error*. Indeed, most computational acoustics models are still constructed from a *deterministic* perspective, meaning that all parameters required to solve the mathematical expressions are specified as though exactly known. In contrast, experimentalists are usually aware that, even in highly controlled laboratory environments, measurement errors are always present and introduce *uncertainty* into observations, which must be captured by a suitable error analysis.

It is similarly important in computational modeling to assess how uncertainties in model inputs affect the outputs. An ocean acoustic propagation model, for example, needs information about seabed composition to compute the sound field in the water. But the seabed composition cannot be measured everywhere, and the measurements themselves are subject to error. Thus, the sediment properties can only be represented probabilistically. This, in turn, affects how much sound is reflected from and transmitted into the seabed. Characterizing the probability distribution of the output, in this case the sound field, is

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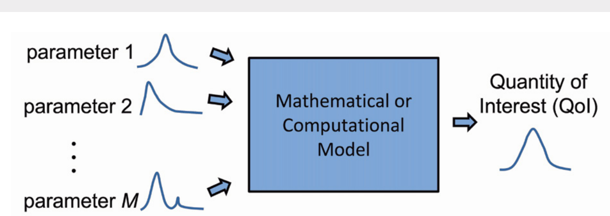
not necessarily straightforward. A common assumption is that each source of error is independent, and the uncertainty retains the same form in the model output. But this is inappropriate when the output depends on many complex nonlinear interactions. Misapplication of statistical information or failure to take uncertainty into account can undermine the utility and perception of the model itself.

To fully address the impact of uncertainties on the model output, modelers adopt the *probabilistic* perspective (**Figure 1**). The model is still a representation of a physical system, which relates a number of input parameters to an output quantity of interest (QoI). However, in the probabilistic perspective, *probability distributions* (which measure the likelihood that a variable takes on a particular value or range of values) are used to represent uncertainties in the parameters and QoI. Weather forecasting provides a familiar example. Forecast models are typically initialized with satellite and weather balloon data, which by nature imperfectly characterize the exact state of the atmosphere. The models then predict a QoI such as the path of a hurricane, as conveyed by the "cone of uncertainty" on the weather map used by emergency management agencies and the public to prepare for storms.

Considerations in Computational Modeling

Modelers use *uncertainty* in the general sense of a lack of knowledge. Uncertainties can be decomposed into two broad types, *epistemic* and *aleatory*. Epistemic uncertainty arises from *imperfect knowledge* of the parameter. Aleatory uncertainty is caused by actual *random variability*, for example, whether a coin toss lands on heads or tails. However, categorizing the types of uncertainty can be challenging because most practical uncertainties have elements of both types. For example, human or animal behaviors exhibit random variability because understanding of all factors driving such behaviors is extremely limited. As more is learned about biological drivers of behavior, uncertainty can be reduced (epistemic), but variables like the subject's motivation are necessarily aleatory. However, regardless of the type of uncertainty, they can be treated the same way mathematically, with probability distributions. For a more thorough discussion of the types of uncertainty, among other related definitions and techniques, see Smith (2013).

Figure 1. *Probabilistic perspective on modeling. The model is a mathematical or computational representation of a physical system. It relates a number of input parameters to an output quantity of interest (QoI). In the probabilistic perspective, the parameters and QoI are described by probability distributions.*



In this article, we focus on uncertainty describable with random variables or processes. For example, the location of an acoustic source in an experiment may be unknown and represented by a random variable that is uniformly distributed over some region. The size of the region could be reduced with more accurate measurement techniques (thus exemplifying epistemic uncertainty), whereas measurement errors that can be described only in probabilistic terms would be aleatory.

Computational techniques for incorporating uncertainty into a model can be classified into two types: intrusive and nonintrusive. An intrusive method's mathematical formulation changes the underlying model and thus requires reworking a computer program. Because a great deal of effort and resources go into developing and testing deterministic computer codes, we focus here on nonintrusive methods, which permit reuse of existing programs. For example, suppose a colleague has provided a complex code for calculating the reverberation time of a room given its dimensions and construction materials. Incorporating uncertainty, perhaps in the absorption coefficient of the wall paneling, in an intrusive manner would require modifying that code to handle the details of the uncertainty directly. However, a nonintrusive technique employs the code in a "black box" sense, only needing to evaluate the reverberation time using the existing code at certain values of its inputs.

Among nonintrusive methods, Monte Carlo simulation (MCS) is the most widely known. However, more recently, generalized polynomial chaos (GPC) expansions have gained ground as both an alternative and a complementary approach to MCS. GPC can be more efficient than MCS for certain problems and produces a stochastic representation of a computational expensive code, called a *metamodel*. And, importantly, in practice the metamodel is generally much less computationally expensive in terms of CPU time and memory to evaluate than the original code. Data-based approaches (e.g., Gaussian process regressions) can be combined with these methods to bridge the gap between equation-based models and experimental data. In this article, we discuss the MCS and GPC approaches and demonstrate their application using a classical problem in acoustics, namely the Lloyd's mirror, which, despite its relative simplicity, richly illustrates the hazards of neglecting uncertainties and how probabilistic approaches can address this problem.

What Is the Lloyd's Mirror Effect?

The Lloyd's mirror effect (named after Humphrey Lloyd, 1800-1881) is the pattern of constructive and destructive interference occurring when sound waves encounter a flat, reflective boundary. A previous article in *Acoustics Today* (Carey, 2009) described this effect and its history in detail. Although Carey's article focused on Lloyd's mirror in the context of underwater acoustics, it occurs in many other situations, such as in the atmosphere above the ground and indoors next to a wall. The geometry is illustrated in **Figure 2**. We have adopted the coordinate convention typical of atmospheric acoustics, with the vertical axis upward.

Although there is only one physical acoustic source in the Lloyd's mirror problem (the jet), the presence of the reflective boundary surface creates a pressure field consisting of the sum of two *apparent* sources, one representing sound from the actual source and the other from a so-called *image* source. The image source is located an equal distance from the true source on the other side of the reflecting boundary (**Figure 2**). In the present work, we assume a perfectly *rigid* boundary that occurs for propagation in air above a denser, harder medium such as water or rock. In this case, the image source is equal in magnitude and phase to the true source. However, if the reflecting surface has a different shape (such as a dome or wavy ocean surface), or different material properties (such as sound absorbing material), then the relationship between the source and image must also change. In Carey (2009), the reflecting boundary is "pressure release," meaning that the acoustic pressure is zero on the boundary (as for the water-air interface in underwater acoustics) and the image source is equal in magnitude and *opposite* in phase to the true source.

Examining **Figure 2** further, a few critical details of the Lloyd's mirror problem emerge. Given the horizontal distance from the source to receiver (the *range*) and both the source and receiver heights, different distances are traveled by sound along the *direct* and *reflected* paths (unless the receiver is on the reflecting surface itself). This means that the received signals from the actual and image sources can differ in phase and thus reinforce or partially cancel each other. This effect is compounded if the average sound speeds along the direct and reflective paths differ as well, as occurs in real environments where the sound speed depends on parameters such as temperature and salinity that vary in time and space.

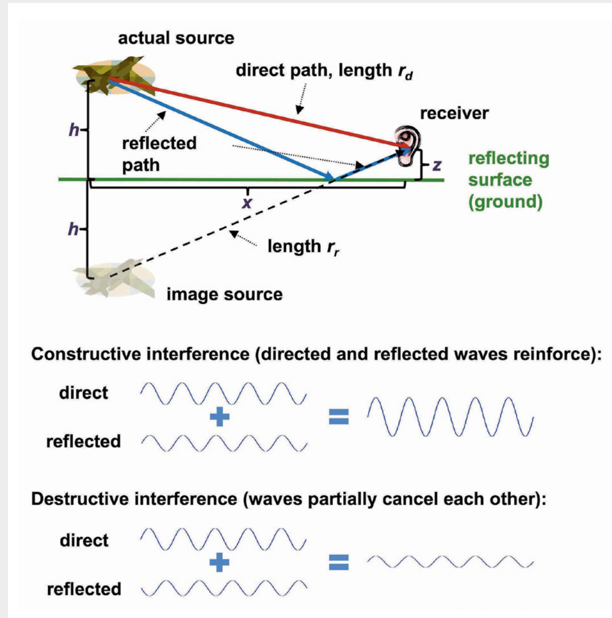


Figure 2. *Lloyd's mirror geometry and interference mechanism (**top**). **Red line:** direct path from the actual source to the receiver; **blue line:** path that reflects off the ground before reaching the receiver. The total length of the reflected path equals the length of a line drawn from an image source below the ground plane to the receiver (**dashed line**). In constructive interference (**center**), the sound along the direct and reflected paths are in phase and increase the amplitude when combined, whereas in destructive interference (**bottom**), they are out of phase, leading to decreased amplitude when combined. Here,* x *is the horizontal distance from the source to receiver,* z *is the receiver height,* r_d *is the length of the direct path (from the actual source to the receiver);* r_r *is the length of the reflected path (from the image source to the receiver); and* h *is the height of the source above the ground.*

Figure 3 shows examples of the Lloyd's mirror for propagation in air above a rigid surface, with a source height

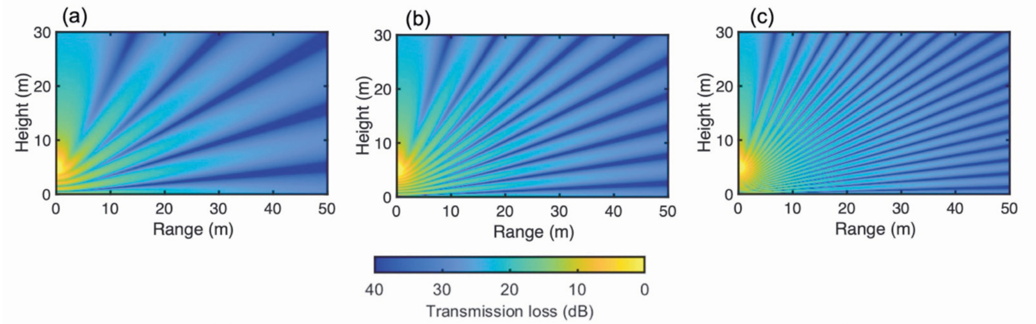


Figure 3. *Frequency dependence of the Lloyd's mirror transmission loss (TL) interference pattern.* ***a:*** *Wavelength (λ) = 0.5 m or 170 Hz;* ***b:*** *λ = 1 m or 340 Hz;* ***c:*** *λ = 2 m or 680 Hz. Darker regions indicate destructive interference (high TL), whereas lighter regions indicate constructive interference (low TL).*

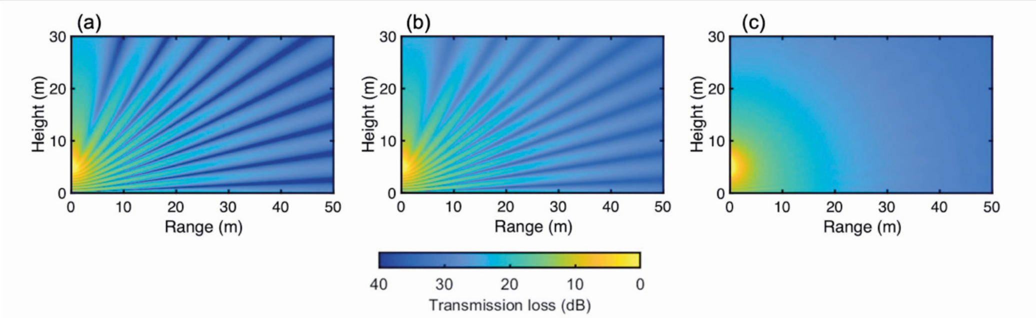


Figure 4. *Impact of uncertainties on the TL for the Lloyd mirror effect for various values of wavelength λ and variability.* ***a:*** *Small variability;* ***b:*** *medium variability;* ***c:*** *large variability. Note that increasing variability approaches the incoherent result.*

of 5 m and the same sound speed of 340 m/s along both direct and reflected paths. In **Figure 3**, we plot the transmission loss (TL), a measure of the signal loss between the source and receiver in decibels relative to the original source magnitude. TL is commonly used in propagation studies, being defined such that it equals zero at a distance of 1 m from the source in free space and increases with increasing *loss* in pressure amplitude. The frequency of the source was changed from 170 Hz (**Figure 3a**) to 340 Hz (**Figure 3b**) to 680 Hz (**Figure 3c**). These values correspond to wavelengths of 0.5 m, 1 m, and 2 m, respectively. The narrow, dark regions of **Figure 3** are receiver locations where the direct and reflected waves are very nearly out of phase with one another and thus destructively interfere. As the frequency is increased, the interferences become more closely spaced.

Impact of Uncertainty on Lloyd's Mirror

Although the mathematical description of the Lloyd's mirror effect is simple, the interference pattern can be difficult to predict accurately because it is extremely sensitive to the exact values of the model parameters. Thus, we would like to know how uncertainty in the model parameters influences the accuracy of sound field predictions.

In most practical experiments, both epistemic and aleatory uncertainties arise. Epistemic uncertainty is exemplified by not exactly knowing the range between the source and receiver or their heights. Random variations in the sound speeds, as occur from wind turbulence in the atmosphere or fluid mixing and other disturbances in a harbor, exemplify aleatory uncertainty.

Taking a probabilistic perspective, we wish to predict statistics of the sound field, in particular, the mean TL of the Lloyd's mirror problem in the presence of these uncertainties. We assume that there are five uncertain parameters: the receiver range and height, the source height, and the sound speed of the air along the direct and reflected paths.

Figure 4 plots the mean TL for three cases of increasing variability of the uncertain quantities. **Figure 4a** includes the least uncertainty and **Figure 4c** includes the most. The exact details of how the variability is specified is described later in the article, but first compare the results in **Figure 4** with those in **Figure 3b**. **Figure 3b** is the same case as **Figure 4** but assumes all model parameters are known; it is the *deterministic* result. Observe that as the amount of variability increases, the Lloyd's mirror interference pattern gradually vanishes. In fact, for the largest variability case (**Figure 4c**), the phases of the direct and reflected paths are nearly completely randomized relative to one another such that the pattern of constructive and destructive interference is averaged out. Therefore, the sound field is found simply by adding the direct and reflected energies together, in which case the two contributions are said to be *incoherent*. In ocean acoustics, coherence is diminished by scattering from ocean surface waves and bubbles (Cron and Sherman, 1962; Kuperman and Ingenito, 1980). In the atmosphere, coherence loss can be caused by turbulence (Daigle, 1979; Clifford and Lataitis, 1983). The important takeaway is that the details of the interference pattern depend on the uncertain parameters, and, therefore, the mean TL cannot be accurately predicted when these parameters are assumed to have exact, fixed values.

To further illustrate the impact of uncertainty on the interference pattern, **Figure 5** shows the TL computed at three sampled values of the sound speed from the high-variability probability density function (PDF). In **Figure 5,** *left,* the image corresponds to a sound speed of 335 m/s and the TL is between 20 and 25 dB all the way out to a 50-m range. In **Figure 5,** *center*, the image (340 m/s) has a region of high TL (a null) near the ground at a range between about 15 and 30 m. The near ground TL is important in noise applications. The image in **Figure 5,** *right* (345 m/s), has two smaller null regions near the ground. If the sound speed measurement has just a 1% error, the near-ground TL prediction at a range of 50 m could be off by as much as 15 dB!

Details of the Lloyd's Mirror Study

Probabilistic modeling requires deciding how to represent the unknown parameters with probability distributions. This is not a simple matter and very often assumptions must be made. These decisions are best informed by data, but in the absence of data, it is common to rely on expert opinions. A typical approach is to assume unknown parameters follow a *normal (Gaussian) distribution*; this simplifies the math for analytical calculations and is valid for measurements where the observed uncertainty is due to many independent, underlying random quantities. However, normal distributions are not appropriate for all situations and may, in fact, have undesirable features that preclude their use. Normally distributed random variables can take on both positive and negative values. Negative values are unlikely but still occur if the mean is positive

Figure 5. *Three evaluations of the TL for the Lloyd's mirror problem for different reflected wave sound speed: 335, 340, and 345 m/s, respectively. These sample points are also shown in relation to the probability density function (PDF) of the reflected sound speed random variable for the large variability case.* ***Colored lines and borders*** *indicate which input corresponds to which output.*

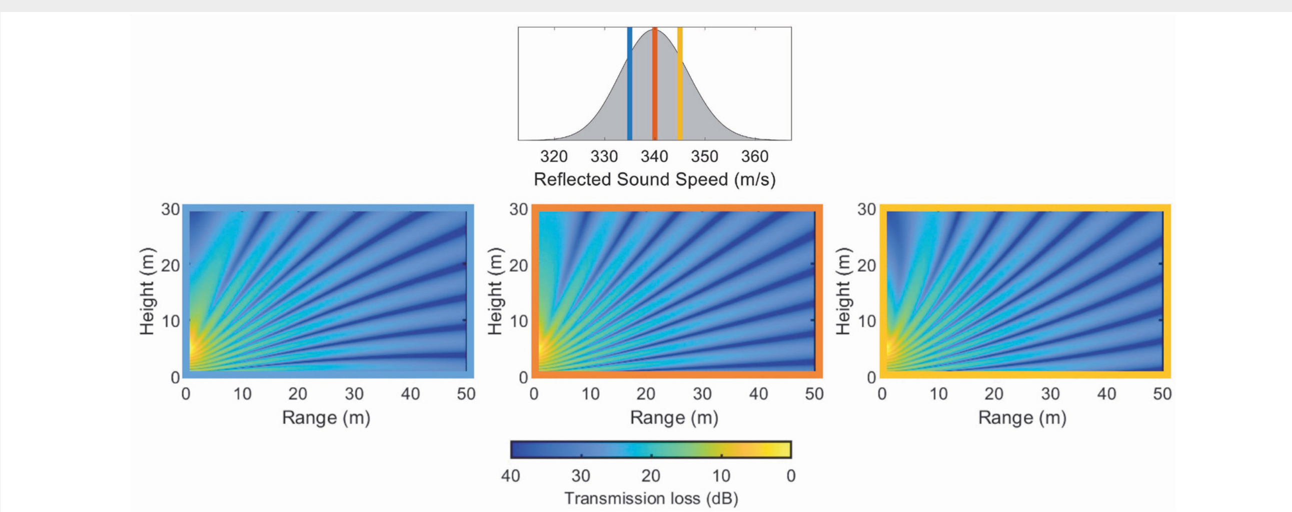


Table 1. *Mean and normalized standard deviations for the log-normal distributions, used in the cases involving small, medium, and large uncertainty*

Variability parameters used in Figures 4-6				
		Normalized standard deviation		
Variable	**Mean**	**Small**	**Medium**	**Large**
Direct sound speed	340 m/s	2×10^{-4}	2×10^{-3}	2×10^{-2}
Reflected sound speed	340 m/s	2×10^{-4}	2×10^{-3}	2×10^{-2}
Source height	5 m	1×10^{-3}	1×10^{-2}	1×10^{-1}
Receiver height	0-30 m	1×10^{-3}	1×10^{-2}	1×10^{-1}
Receiver range	0-50 m	1×10^{-3}	1×10^{-2}	1×10^{-1}

and the standard deviation is small. In the Lloyd's mirror example considered here, the uncertain parameters are all strictly positive quantities. If their assumed distributions do not share this property, negative values may lead to nonphysical results if not failure of the computer program.

The *log-normal* distribution is thus used for the Lloyd's mirror problem. This means that the *logarithms* of the parameters are normally distributed so that the parameters have the "strictly positive" property. If the mean is sufficiently large compared with the standard deviation, a log-normal distribution may appear to be very nearly the same as a normal distribution as observed in **Figure 5,** *inset*, that shows the PDF of the sound speed of the reflected path.

For the results shown in **Figure 4**, the mean (m) and normalized standard deviation (σ/m) (where σ is the usual standard deviation) for the log-normal distributions of each random variable corresponding to three different levels of variability are shown in **Table 1**. Because the source height and receiver location are uncertain, **Figure 4** was produced with the means of the receiver range and height corresponding to the position on the plot. The smaller standard deviation is used for the sound speed because the interference pattern is especially sensitive to variations in those parameters because they impact the signals' phases.

Methods for Quantifying Uncertainty in Computational Models

Two families of uncertainty quantification techniques are considered in this article to explore the impacts of uncertainty on the Lloyd's mirror effect. Both are nonintrusive. Each has a number of variants that are beyond the scope of this article. However, the following discussion provides the reader with a starting point for further investigation.

Monte Carlo Methods

Monte Carlo methods are attributed to Metropolis and Ulam (1949), who solved equations describing nuclear fission on a post-World War II computer using stacks of punch cards for input and output! They demonstrated that random sampling led to plausible results for as of then unobtainable solutions to a stochastic problem. MCS methods are well-known and used substantially in engineering studies.

MCS arose from the observation that an integral of a function of a single variable can be viewed as the probabilistic mean of the function when its argument is interpreted as a uniformly distributed random variable Thus, the integral may be computed by drawing samples from a uniform distribution, evaluating the function at those values, and calculating the sample average of the results. This approach is easily extended to multiple dimensions and straightforward to implement nonintrusively on existing codes for computing acoustic pressure fields. The primary drawback of ordinary MCS is that an impractically large number of samples are required for convergence in regions of low probability that can be important in applications where extreme values (e.g., threshold crossings) are of interest.

The errors for MCS theoretically decrease in proportion to $1/\sqrt{N}$ (Caflisch, 1998). This is slow! For the Lloyd's mirror example, using a strategy called Latin hypercube sampling (LHS), the observed rate appears closer to $1/N$, a significant speedup. If the goal is to approximately calculate the mean of the QoI (in this case TL) to within some percentage of the actual mean, and MCS achieves this with 10,000 computations of the TL, LHS can achieve the same accuracy using only 100 computations. LHS is designed to distribute the samples more evenly over the parameters than basic MCS, in which samples tend to cluster. The idea underlying LHS is to partition the domain for each random variable into N equally likely intervals, then to sample each interval just once. The order in which the intervals are sampled is random.

Generalized Polynomial Chaos

Generalized polynomial chaos (GPC) is an extension of *polynomial chaos* (PC), originally devised by Wiener (1938). PC specifically applies to expansions in terms of normal random variables, whereas Xiu and Karniadakis (2002) extended the method to accommodate a much a larger set of probability distributions, including the log-normal distributions used here. GPC involves computing the coefficients of a polynomial expansion, which turn out to be expectations of functions of the random parameters. Although the full details are beyond the scope of the present article, GPC can be approached either intrusively through derivation of a new system of equations and hence a new computer program to solve it or nonintrusively by computing the expectation integrals directly using quadrature or regression methods.

Under the right circumstances, GPC will exhibit spectral convergence (approximation error decreases exponentially fast as the number of samples is increased) and thus can solve problems with far fewer samples than MCS. For the example discussed in ***Monte Carlo Methods***, where 10,000 samples produce TL statistics accurate enough for the purpose at hand and 100 samples give the same accuracy if LHS is used, then GPC may achieve the required accuracy with only 5 samples!

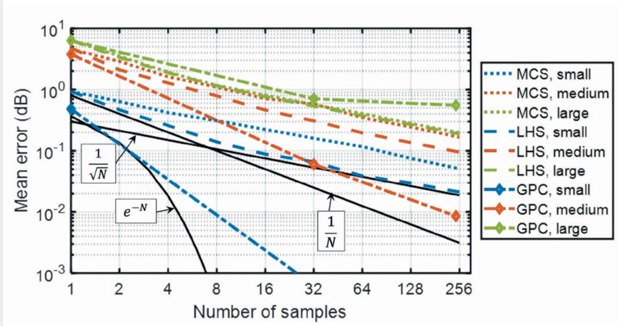
GPC is also not restricted to the estimation of statistical information; the coefficients, when combined with the polynomial basis expansion, yield a surrogate (or meta-) model, which can be evaluated rapidly. The surrogate provides a polynomial representation of the complicated physics in the original computational model, which can be useful for generating realizations in a larger simulation. For example, instead of integrating a Lloyd's mirror solver into a model of aircraft noise near the ground, a GPC surrogate could be used to speed the computation. The surrogate can support design decisions by rapidly assessing which parameters are the most important. Interested readers can find further information on GPC in Wixom et al. (2019).

Figure 6 shows the relative performance of three methods for the three levels of variability. Performance is measured by how well each method predicts the mean TL shown in **Figure 4** for a given number of input samples. The error in mean TL is spatially averaged over all considered ranges and receiver heights to compute a scalar error metric for plotting in **Figure 6**. The *solid lines* in **Figure 6** show theoretical convergence rates for reference. Such an "error-per-sample-point" metric is a common measure of performance for uncertainty quantification techniques. It is often the case that the underlying deterministic model (black box) takes a long time to evaluate. Thus, a method requiring fewer samples obtains probabilistic information on the QoI much faster. Observe that MCS results track well with its theoretical convergence rate. GPC outperforms MCS and LHS for small and medium variability, but MCS and LHS perform better for large variability.

Summary

Computational models are as ubiquitous in acoustics as they are in other areas of physics. In fact, computational modeling is rapidly expanding from acoustical applications where it has been common for decades, such as underwater and structural acoustics, to others such as biological acoustics and noise. Yet trust in these models relies on systematic and rigorous assessment, which is often challenging in itself. Neglecting uncertainty can lead to misinterpretation of model results, particularly when comparing against experiments. Experimentalists have learned to characterize measurement uncertainties, but for computational acousti-

Figure 6. *Comparison of performance of different uncertainty quantification methods using dependence of the spatially averaged error in mean TL of the predictions on the number of model samples used to estimate the TL.* ***Dotted lines:*** *ordinary Monte Carlo simulation (MCS);* ***dashed lines:*** *Latin hypercube sampling (LHS);* ***dash-dot lines with diamonds;*** *generalized polynomial chaos (GPC).* ***Red lines:*** *small uncertainty case;* ***blue lines:*** *medium uncertainty;* ***green lines:*** *large uncertainty;* ***black lines:*** *reference lines for* $1/N$, $1/\sqrt{N}$, *and* e^{-N} *convergence rates. The reference for error was a 16,384 sample LHS result.*



cians, this is often new territory. Nevertheless, characterizing uncertainties is a key aspect of the error budget for a given modeling effort.

We have used the Lloyd's mirror effect to demonstrate the impacts of varying degrees of uncertainty. Two popular techniques for propagating uncertainties from model input to predictions of QoI were described. It is important to note that these techniques are not "one size fits all"; the best approach is very much problem dependent.

Although we have only skimmed the topics of error analysis and uncertainty quantification in computational models, we hope the reader takes away their importance and is motivated to try incorporating the techniques presented here into their own analyses.

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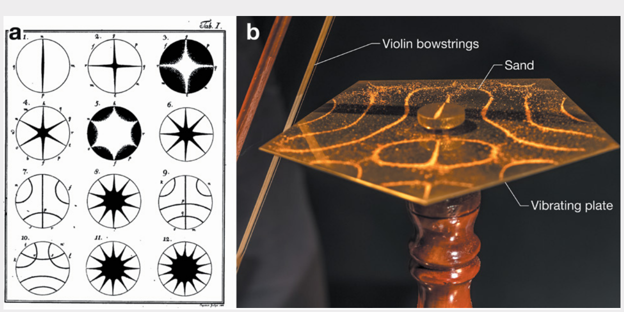
Acoustofluidics

Kha Nguyen, Lei Zhang, and James Friend

Introduction

From one of the first formally published works, Chladni (1787) became very well-known for his discovery of the patterns that now bear his name: sand organized into patterns on vibrating membranes (**Figure 1**). He toured European venues in the late 1700s to the early 1800s, demonstrating the curious phenomena to laypeople and trained scientists alike. The acoustic wave present in the membrane interacted with the sand, causing it to move away from regions that were vibrating, the antinodes, and to collect in regions that were quiescent, the nodes.

Figure 1. *In one of the first physical demonstrations of acoustics, sand spread on metal plates and membranes forms fascinating patterns called Chladni figures (**a**). Taken directly from Chladni's text (1787), it is composed of drawings of the patterns formed by the sand (**black**) on vibrating circular membranes at different frequencies. By mounting the plates and drawing a violin bow across the edge of the plate, the sand moves in response to the driven vibration into patterns (**b**). Chladni is often described as the father of acoustics for these figures and the work that arose from them by many researchers. It would likely have surprised him to learn that questions on how these patterns formed were still being asked in the past decade and that the discrepancies Savart found in Chladni's work would become so useful today. **a** from Chladni (1787); **b** licensed under CC-BY-SA 4.0 from Matemateca (IME/USP)/ Rodrigo Tetsuo Argenton. Available at bit.ly/3JfsrFS.*



Sound formed diaphanous pictures on the vibrating surface, changing with the sound before the audience's eyes.

Félix Savart was among the attendees at one of these events. He was an acclaimed scientist in his own right who came to be known for his work with the acoustics of violins. He later sought to replicate Chladni's work (1787) and found that not only would the sand sometimes collect at the nodes, but it would also occasionally collect at the antinodes. This phenomenon was not explained by Chladni's efforts. Savart hypothesized that air currents adjacent to the membrane were being driven by the vibration in the membrane and that these currents were responsible for the particle motion. The airflow and the transport of these particles were the genesis of the field of *acoustofluidics*, the physical effect of a passing acoustic wave on a fluid and particles suspended within it. Little did they know that the discrepancy Savart identified alongside Chladni's discovery would together eventually grow to define acoustofluidics as a new research discipline, let alone produce a crucial solution to one of the most vexing problems in modern medical diagnostics today.

The discrepancy in particle collection phenomena was one of several between the two men that sadly grew to become a rather vindictive relationship (Bell, 1991). It also attracted the interest of prominent scientists over the years and decades to follow. Thirty years later, Faraday (1831) conducted several simple experiments to clearly identify the existence of acoustic streaming, one of the key contributors to fluid transport and suspended particle manipulation responsible for the disagreement between Chladni and Savart.

Thirty years after Faraday's work, Kundt (1866) devised a simple hollow tube that became a popular platform to explain particle manipulation via acoustic streaming. Open on both ends and with a sound source at one end, Kundt's tube was originally devised to determine

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the speed of sound in gases. It was a simplification of Chladni's vibrating plates (1787) because the tube itself remained completely stationary. The particles in the tube were moved about solely due to airflow, which no doubt would have pleased Savart.

Like many topics, it drew the interest of the polymath Lord Rayleigh (Strutt, 1883) who offered the first explanation of the acoustic streaming phenomena. As acoustic waves passed through the air, they compressed and rarefied in the air. The viscosity of the air caused its velocity to be slightly out of phase with the density, leading to slightly denser air as it moved along the tube away from the source rather than in the other direction. Over time, this caused the air to flow slowly. Lord Rayleigh devised and solved a set of equations that explained why, the first of many attempts to explain the phenomena of acoustofluidics.

Over 60 years would then pass before acoustic streaming would be rediscovered in a significant way, this time in a completely different discipline: materials science. A class of materials, piezoelectric materials, was discovered to have the ability to usefully transform energy between mechanical and electrical forms. Vaguely known since ancient times, piezoelectric materials were vitally important with the advent of submarines in World War I. The submarines used sonar transducers formed from these materials to detect ships. The ships used similar transducers to detect the noise of submerged submarines. From the early 1900s, researchers sought to identify and improve piezoelectric materials from the easily dissolved and modestly performing Rochelle salt to quartz and, much later, ceramics like lead zirconate titanate and single crystal piezoelectric materials like lithium niobate.

Quartz is still found today as accurate oscillator crystals in watches, and lithium niobate is present in many telecommunication devices to handle signal-processing tasks, especially mobile phones. As the materials improved, so did the number of occasions that researchers observed odd air currents emanating from the surfaces of plates made with these new materials. Application of an oscillating electric field to the plates would produce vibrations in and on them, much like those observed by Chladni two centuries before (1787). However, this time there was no need for an external sound source because the piezoelectric plates themselves vibrated directly from applied electrical signals. Moreover, the air currents occurred without audible sound at all; the vibrations causing them were ultrasound waves at frequencies of 20 kHz and beyond. The ethereal air currents, "quartz wind," was another example of acoustic streaming reported by Eckart (1948), accompanying an analysis of the phenomenon.

Acoustic streaming had more secrets to proffer. Westervelt (1957) explained the most peculiar phenomenon of producing two completely different results from an analysis of Kundt's tube (1866). In one treatment, the analysis would suggest that there is no flow at all along the length of the tube. In another treatment, the analysis would suggest that there was a net flow after all toward the sound source. Neither prediction compared with experimental data that showed that the flow was away from the sound source. This odd result came to be named Westervelt's paradox and took some two decades and the discovery of a rare mistake made by Lord Rayleigh back in 1866 to properly explain.

In all that time, particles were used to track the flow of fluids driven by the passage of acoustic waves. In Chladni's original experiments (1787), the fluid was ignored as particles bounced about on vibrating surfaces to form the namesake patterns. Savart had demonstrated that the fluid's motion mattered, and in the years since, the question of what drives particles on vibrating surfaces to collect at the nodes or antinodes has been answered in many different contexts (Doinikov, 1996; Dorrestijn et al., 2007), producing a rich tapestry of individual solutions that together have produced a complex story and some interesting applications.

Indeed, in the modern era, Chaldni's techniques were used to verify the presence of vibrations in structures from aircraft wings to microdevices. In one example, the surface of an acoustic wave device was formed from a single crystal piezoelectric plate with an electrode deposited on it in the shape of interlaced metal fingers. These fingers form an interdigital transducer (IDT; see **Figure 2a**) that when driven with an oscillating electrical signal produces an acoustic wave in the plate that propagated across its surface. That wave is known as a Rayleigh wave, named after the same Lord Rayleigh who provided the early explanation of acoustic streaming. The wave formed patterns across its surface while being operated from 20 to 500 MHz, many orders of magnitude greater in frequency than in Chaldni's demonstrations.

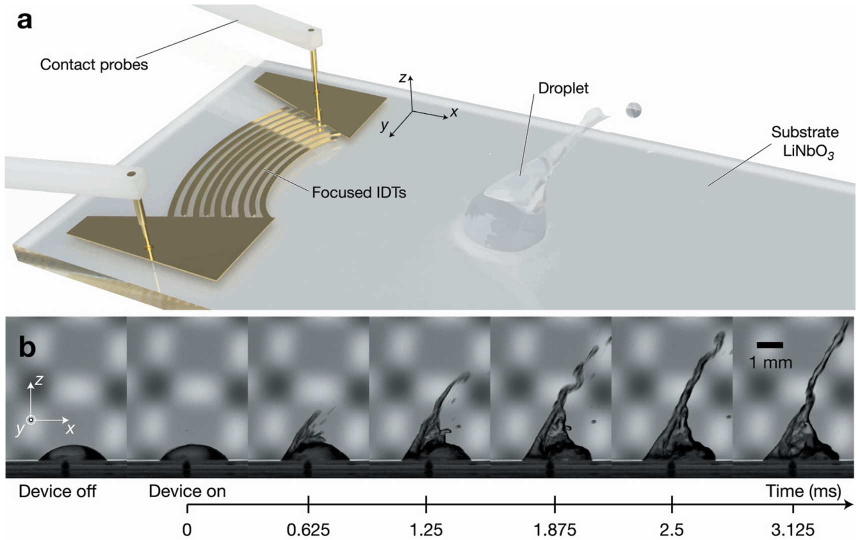


Figure 2. ***a:*** *Acoustic device made of single crystal piezoelectric lithium niobate ($LiNbO_3$) as a substrate, with an interdigital transducer (IDT) formed from a thin layer of gold deposited on it. Passing an oscillating electric field to the IDT via the contact probes (**left**), in this case at 40 MHz, causes an acoustic wave to be produced on the substrate. This Rayleigh wave propagates rightward along* x *and under a 6-µL fluid (water) droplet sitting on the surface. The fluid absorbs some of the energy from the passing Rayleigh wave, causing sound at the same frequency to be generated in the fluid. The sound propagates at a characteristic angle up and to the right in the* x-z *plane. This angle is the Rayleigh angle, 23° in this system.* ***b:*** *As the propagating sound is attenuated in the fluid, the fluid itself is being driven into motion, resulting in acoustic streaming. The velocity of the fluid is sufficient to cause it to jet from the surface. This result, first demonstrated by Shiokawa (1989), is one of the first demonstrations of acoustofluidics.*

The gateway to modern acoustofluidics was driven by research on these surface acoustic wave (SAW) devices by a seemingly minor discovery after swapping the particles with fluid. Shiokawa discovered how 20-MHz SAW devices the size of one's thumbnail would eject fluids nearly a meter away (Shiokawa et al., 1989), generating the Rayleigh wave across its surface (**Figure 2b**). Shiokawa, much like Chladni, toured laboratories in Japan and other locations overseas in the early 1990s demonstrating the curious physical phenomena of an ejecting droplet from a SAW device but with a limited explanation of what was happening and no connection to what would eventually become its principal application.

Microfluidics in Health Care

Acoustofluidics would have likely remained little more than a curiosity had there not been a profound need for fluid and particle manipulation methods in microfluidics for medical diagnostics. After Manz' demonstration of microfluidics in 1990 (Manz et al., 1990), its application drew the excitement of many researchers who recognized the potential of shrinking the laboratory to a single, handheld chip, a *lab-on-a-chip* (Stone et al., 2004). In their minds, microfluidics enabled the lab-on-a-chip to revolutionize the future of personal health care with rapid at-home point-of-care diagnostic tests that would lessen the burden on labs and physicians.

Indeed, microfluidics offered many advantages thanks to its short processing time, dynamic control, lower costs, and portability. From the beginning, however, the dual challenges of viscous drag and surface-dominated forces in microfluidics were seen as potential problems. The viscosity of the fluid in small scales resisted flow and made mixing difficult. Filling a microchannel with a fluid would stop at an intersection, forming a meniscus. To continue filling the channel required overwhelming this meniscus and the capillary forces responsible for it by coaxing the fluid along with extreme pressures. At the time, researchers were confident that these issues would eventually be overcome. Applications emerged from capillary electrophoresis (Swerdlow and Gesteland,

1990) for efficient DNA sequencing to polymerase chain reaction devices (Northrup, 1993), all of which needed effective methods to transport fluids at these small scales. Researchers searched for effective methods to transport fluids at these small scales (Laser and Santiago, 2004), using electric fields, large pressures, chemical and thermal gradients, and capillary forces. The trend continued even after the initial purpose of sequencing the human genome was completed in 2003, with the adoption of polydimethylsiloxane, a soft silicone polymer material closely related to the caulk used to seal windows and bathtubs, to produce devices (Friend and Yeo, 2010) at much lower costs, facilitating broad advances in the scope and utility of microfluidic devices.

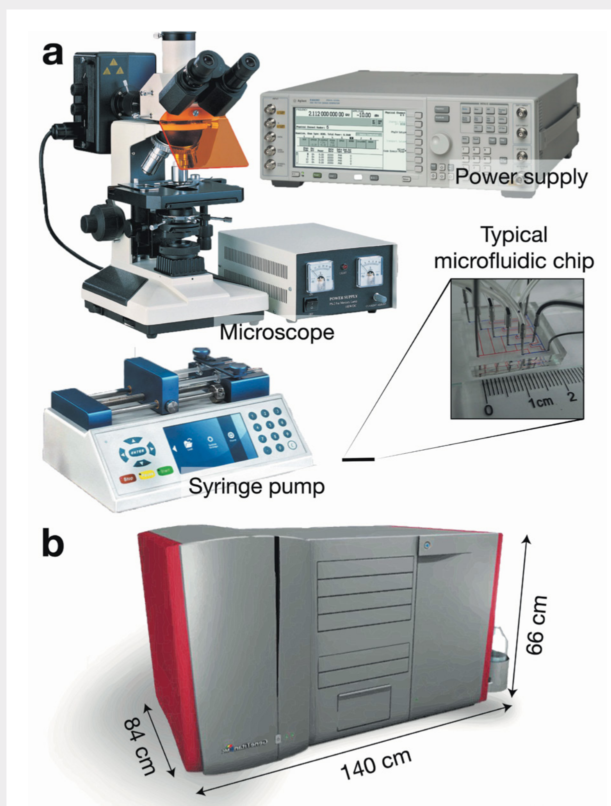
In some ways, microfluidics technology was devised and used many years before, using paper as the fluid transport medium. As anyone who has placed a coffee cup on a piece of paper and left a growing ring of coffee behind on the paper knows, liquid will absorb into and flow within the paper. The capillary forces responsible for flow of the fluid along the paper was used in everything from paper chromatography in the 1940s to pregnancy tests in the 1970s (Chard, 1992), but they also prevented anything more than simple device designs. It thus became clear that a combination of this method with fluid handling and chemical sensors devised in micro/nanofluidics research efforts would make the method nearly universally relevant for many diagnostics applications (Koczula and Gallotta, 2016). It has certainly made lateral flow assays instantly recognizable, with the nearly ubiquitous "Covid home test" enabled by engineered antibodies and having been used at one time or another over the past three years by so many of us around the world (Chu et al., 2022).

Chip in a Lab

The problem of fluid and suspended particle handling remained, particularly for more the complex processes that required more intricate control of fluids and particles. Some devices required continuous flow through a device to look for rare target cells or molecules in larger fluid samples. Other devices required fluid mixing; the manipulation of suspended cells; or the production of separations, mixtures, or suspended immiscible droplets. Researchers searched, somewhat fruitlessly, looking for methods to propel fluids, cells, particles, and mixtures through their microfluidics devices without the burden of all the equipment that kept them in the laboratory (Laser and Santiago, 2004). Many researchers and companies gave up on the heralded lab-on-a-chip concept, the idea that an entire laboratory could be shrunk to fit on a chip and used as a portable device. Instead, they returned their tiny microfluidics chips to the laboratory, surrounded again by large pumps and other equipment needed to make them work. The limitations in microfluidics technology remained, earning the discipline the derisive moniker "chip-in-a-lab" (**Figure 3**).

It took nearly a decade for researchers skilled in microfluidics and its application to recognize the potential of acoustic waves to solve the problems they faced. They

Figure 3. ***a:*** *The typical components needed in a laboratory benchtop setup to operate a microfluidic chip, alongside the relatively tiny chip itself. The microfluidic dream of "lab-on-a-chip" is tempered by the need for this equipment to operate the microfluidics devices, earning the derisive moniker "chip-in-a-lab." Modern commercial laboratory equipment is similar.* ***b:*** *A recent example is the ThermoFisher GeneTitan instrument, with small "genechips" alongside a very large benchtop instrument to process them (Chen et al., 2023). Adapted from Zhao et al. (2013).*



started to learn and adapt the curious phenomena of acoustic streaming and particle manipulation that had driven the curiosity and consternation of several generations of researchers from Chladni to Shiokawa.

Micro/Nano Acoustofluidics

Micro/nano acoustofluidics is the study of acoustic wave generation, propagation, attenuation, refraction, reflection, and other behaviors in fluids and across interfaces between fluids and solids at extremely small spatial and temporal scales. Although the study of acoustics and its wide range of applications have been around since Chladni's time (Friend and Yeo, 2011), micro/nano acoustofluidics is a relatively new discipline borne from the desire to solve the problems found in microfluidics with new fabrication methods for complex piezoelectric ultrasonic microdevices. Shiokawa's demonstration in the 1990s, discussed in **Introduction**, was but the first hint of the potential of the technology.

Before the 1970s, ultrasonic devices tended to be either large devices for high-power applications in sonar and medicine or very low power devices used in timing and telecommunications, generally operating at 20 kHz to a few hundred kilohertz. With the advent of practical single-crystal lithium niobate and tantalate alongside interdigital fingerlike electrodes in the 1960s (White and Voltmer, 1965), it became practical to generate and use powerful 10 MHz to 10 GHz SAW devices for telecommunications and timing and later for acoustofluidics.

The high frequencies are an important benefit in micro/nano acoustofluidics. First, the wavelength of the propagating acoustic wave needs to be on the order of the micro/nanofluidic channel size for there to be a gradient in forces at that length scale. These force gradients can produce mixing, particle motion, and all the other effects that render the previously laminar flow much more useful. Second, the acoustic wave attenuates as it propagates through the fluid. This causes the generation of fluid flow. The attenuation increases with the square of the frequency, and typically, such attenuation is useful over 5-10 wavelengths of the acoustic wave as it propagates in the fluid. Thus, to "fit" enough wavelengths into the micro/nanofluidic structure, the frequency must be high. Third, and most important, there is a fundamental limitation to the particle velocity that can be generated in the fluid, about one meter per second. Any higher and the acoustic wave will be rapidly attenuated. This also defines the vibration amplitude and acceleration limits; the amplitude is the particle velocity divided by the frequency, whereas the acceleration is the particle velocity multiplied by the frequency. At audible frequencies, one can often see the physical motion of a speaker as it produces sound near its maximum volume, and the acceleration of the speaker cone is perhaps two or three orders of magnitude greater than gravity. But at 2 GHz, for example, in devices reported by Wu et al. (2022), the maximum physical motion is only a few tens of picometers, an order of magnitude smaller than the diameter of a typical atom. However, accelerations over 10 billion m/s^2 are generated. It perhaps is little surprise, then, that the phenomena observed in using these devices is often surprising and new.

A typical example of an acoustofluidics device suitable for the laboratory bench or classroom (**Figure 2**) is similar to the one Shiokawa produced over 30 years ago (Shiokawa et al., 1989). A small fluid droplet placed on a SAW device fabricated from lithium niobate (Mei et al., 2020) can be made to jet from its surface as Shiokawa reported (1989): atomized, forming a mist of tiny droplets (Kurosawa et al., 1995; Collignon et al., 2018), or even driven across the surface to form patterns or thin fluid films that unveil the complex interactions between the acoustic wave in the substrate, the fluid, and the fluid interface (Rezk et al., 2014a). Over the years, other types of waves were rediscovered (Rezk et al., 2014b; Collignon et al., 2018), and the limits of the known useful frequency range continues to be explored all the way up to several gigahertz (He et al., 2021). Some of these fluid manipulations were performed for use in medical diagnostics, but some are finding use in printing, pulmonary drug delivery, producing thin films for coating surfaces, fuel atomization for engines, and many other applications.

The apparent simplicity of the device belies the many phenomena that may arise from acoustic wave propagation within. A combination of acoustic streaming within the fluid bulk and acoustic radiation pressure on the droplet's free interface will arise, and, if there are particles suspended in the fluid, acoustic radiation pressure can also appear on those particles to force them into patterns or rapid motion. These forces can cause selective concentration and separation of cells in microliter droplets stuck on surfaces (Zhang et al., 2021b) and in fluids in channels (Wu et al., 2022). These effects extend into enclosed microfluidic and even nanofluidic systems, with the recent discovery of a new type of acoustic streaming in a nanofluidic channel reliant on the channel's deformation from a passing acoustic wave (Zhang et al., 2021a) and the rapid flows that can be generated around sharp-tipped structures (Ovchinnikov et al., 2014) and bubbles (Doinikov and Bouakaz, 2010; Marin et al., 2015).

These effects are often several orders of magnitude greater than what is possible using electric fields, chemical gradients, thermal effects, or even high pressures in microfluidics and nanofluidics devices. The many ways they may be used to produce useful diagnostic devices is only now being identified (Rufo et al., 2022), and a significant barrier to broader use of acoustics in micro/nanofluidics is the same challenge that faced Chladni so many years ago: the complexity of the underpinning phenomena, particularly acoustic streaming and particle manipulation.

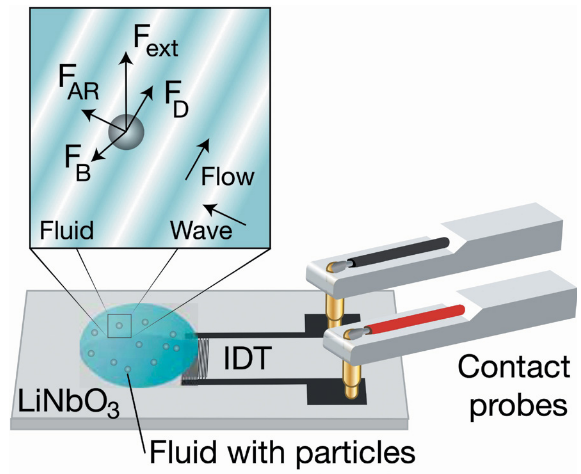


Figure 4. *A simple experiment where a sessile droplet with suspended particles is placed on a surface acoustic wave device. When turning on the device, the acoustic wave generated in the fluid via the Rayleigh wave absorption from the substrate interacts with the suspended particles. Some common forces that particles in a fluid droplet experience from the passage of these acoustic waves include the acoustic radiation (F_{AR}), drag (F_D), Bjerknes (F_B), and externally applied (F_{ext}) forces. Most externally applied forces are insignificant, although some experiments have used buoyancy and electrically applied forces in concert with the three acoustically driven forces to move the particles. All these forces appear on the particles to define their behavior, a complex arrangement that collectively suggests why it has taken over 250 years to begin to explain their motion.*

Acoustic Streaming

Acoustic streaming relies on the generation of gradients in the fluid's density and motion that, coupled together, produce momentum acting to transport the fluid in a desired direction. Typical sounds propagating through the air or a fluid are insufficiently powerful to cause the necessary density changes. However, using intense ultrasound, it becomes possible to drive uniform fluid flow as the ultrasound propagates and is attenuated. The analysis of the phenomenon is difficult, attracting interest from researchers since Lord Rayleigh to offer a variety of mathematical analyses to represent it as either a phenomena with the acoustics independent of the acoustic streaming (Strutt, 1883), a one-dimensional phenomenon driven entirely by attenuation (Eckart, 1948), a means to transport vorticity (Nyborg, 1965), a rapid flow within the viscous boundary layer adjacent a vibrating substrate (Schlichting, 1932), much like the phenomena that disrupted Chladni's patterns, or a spatiotemporally varying phenomenon (Orosco and Friend, 2022).

Particle Manipulation

The original discovery of patterns of vibration by Chladni (1787) relied on the presence and manipulation of particles. In the modern context, particles are rarely left to reside on the vibrating surface. There are some notable exceptions, however. It is possible to disassemble carbon nanotube bundles (Miansari et al., 2015) through bouncing the bundles until they split and stick on the vibrating surface to charge and toss out carbon nanotubes. Cigarette smoke has even been allowed to collect on vibrating surfaces to identify the shape of these vibrations and the acoustic streaming they generate (Tan et al., 2007). Typically, however, particles are present as suspensions or colloids and can be anything from cells to bubbles depending on the application.

Particles experience forces from passing acoustic waves in two ways: drag from acoustic streaming and the force imposed directly on the particle from the acoustic wave (Marston, 2006) and any acoustic waves scattered from nearby objects (e.g., **Figure 4**) (Marston and Zhang, 2016). The acoustic wave can interact with a particle by reflecting from it or by being diffracted around it. In most cases, even in modern acoustofludics with its use of ultrasound at 1 MHz and up, the particles tend to be much smaller than the wavelength of the passing wave, becoming so-called Rayleigh particles, implying that the acoustic waves scatter from the particle as a combination of monopole and dipole effects.

Even so, the analysis of the interaction is complicated (Doinikov, 1996) and researchers often resort to remarkable simplifications for the surrounding fluid and the characteristics of the particles to produce tractable approximations. King (1934), in one of the first complete analyses of acoustic forces present on particles, assumed that the particles were not compressible. He also assumed that the surrounding fluid was incompressible and lacked any viscous effects.

The analysis was later improved with relaxation of these assumptions, with compressible particles (Yosioka and Kawasima, 1955), viscous fluids (Zhang and Marston, 2014), symmetrical (Nadal and Lauga, 2016) and asymmetrical (Zhang and Marston, 2014) particles, and the inclusion of the energy conservation equation (Karlsen and Bruus, 2015). Indeed, in Europe USWNet was established to determine how particles could be manipulated, principally via standing acoustic waves in numerous configurations. Many of the modern uses of acoustofluidics in lab-on-a-chip applications rely on live cell manipulation, from sorting (Laurell et al., 2007; Rufo et al., 2022) to separations (Ding et al., 2014; Zhang et al., 2021) and patterning (Melde et al., 2023).

Where the Discipline Is Going

Into the future, acoustofluidics will continue to grow and play an important role in the establishment of true lab-on-a-chip devices and technologies and help establish new disciplines, from batteries (Huang et al., 2022) to drug delivery (Xu et al., 2023) and tissue engineering (Melde et al., 2023), enabled through its unique capabilities of producing large, controlled accelerations at micro- to nanometer scales without contact nor risk of compatibility problems.

However, the burgeoning discipline, as always, relies on a thorough understanding of the underpinning phenomena. From Chaldni's time to Faraday, Rayleigh, Eckart, Westervelt, Shiokawa, and onward to today, the mystery of acoustofluidics has puzzled researchers and the promise it offers, these mysteries are worthy of exploration and elucidation. More questions have been answered in the discipline in the last 10 years than in the past 200. We look hopefully forward to the rapid development of the field over the next few years toward reaching vastly smaller scales, higher powers, and greater utility.

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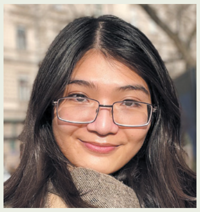

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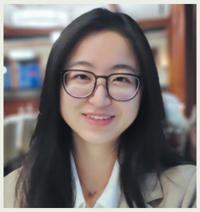

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Hearing Aids Can't Solve the Cocktail Party Problem—Yet

Marina Salorio-Corbetto and Brian C. J. Moore

The Cocktail Party Problem

It is Saturday and you look forward to dinner at your favorite restaurant. The evening is perfect, and you walk through the candlelit garden to join your friends inside. The menu looks exciting and the wine choices are exquisite. What could go wrong? You find out as soon as the restaurant starts filling up. The hubbub around you becomes overwhelming and stops you from conversing with your companions. This failure to solve the "cocktail party problem" (Cherry, 1953) is a common consequence of hearing loss.

What Hearing Loss Is Like

Most young people with normal hearing cope remarkably well in a noisy restaurant or at a cocktail party. They can selectively listen to the person they want to hear (the "target") and ignore the background sounds, and, in essence, solve the cocktail party problem. However, the functioning of the auditory system tends to worsen with increasing age (Anderson et al., 2018) and with exposure to noise and certain chemicals, and this is associated with greater difficulty at the cocktail party.

The most common measure of hearing function is the audiogram, which is the minimum sound level required to detect sinusoids with different frequencies, usually ranging from 0.125 to 8 kHz. The thresholds are specified relative to the average threshold at each frequency for young people with no known hearing problems and have units of decibels hearing level (HL) (Le Prell, 2018). Thus, a person with normal hearing would have thresholds close to 0 dB HL at all frequencies. The most commonly used overall measure of hearing is the pure-tone average (PTA) threshold across 0.5, 1, 2, and 4 kHz, which are the frequencies that are most important for speech perception. The boundary between normal and impaired hearing is usually taken as a PTA of 15 or 20 dB HL, although hearing losses of less than 15 dB are associated with deficits in the ability to understand speech in noise (Smoorenburg, 1992).

There are several methods of classifying the severity of hearing loss. A common one in the United States, based on the PTA, is slight (16-25 dB HL), mild (26-40 dB HL), moderate (41-55 dB HL), moderately severe (56-70 dB HL), severe (71-90 dB HL), and profound (>91 dB HL) (Clark, 1981). However, the descriptors do not accurately reflect the degree of difficulty experienced in everyday life (Clark, 1981). Because of this, self-reported listening difficulty is also important. About 10% of people who go to a clinic complaining of hearing problems turn out to have "normal" audiograms (Parthasarathy et al., 2020).

In 2019, about 20% of the world's population had a PTA >20 dB HL (Haile et al., 2021). This percentage is increasing as a result of longer life spans and greater exposure to recreational noise (Olusanya et al., 2019).

Hearing and Types of Hearing Loss

Hearing loss can result from dysfunction of several parts of the auditory system. **Figure 1** shows the structure of the peripheral part of the human auditory system.

Transmission of Sound to the Cochlea and Conductive Hearing Loss

Sound travels down the auditory canal and causes the eardrum to vibrate. These vibrations are transmitted through the middle ear by three bones, the malleus, incus, and stapes, to the oval window, a membrane-covered opening in the bony wall of the inner ear. The part of the inner ear concerned with hearing is the spiral-shaped cochlea. The stapes lies on top of the oval window. When the oval window moves inward, a second

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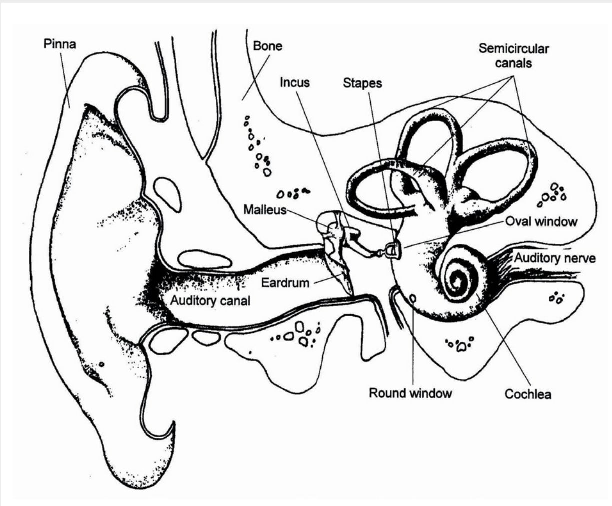


Figure 1. *Schematic illustration of the outer, middle and inner ears. Reproduced from Moore (2012), with permission.*

membrane-covered opening, the round window, moves outward, and vice versa. The middle ear ensures the efficient transfer of sound from the air to the fluids in the cochlea by acting as an impedance-matching device.

"Conductive" hearing loss occurs when sound is not conducted effectively to the cochlea because of wax in the ear canal, infections of the outer or middle ear, or the growth of bone in the middle ear. Conductive hearing loss is similar to an attenuation of the sound. It is often treated with medicines or surgery, usually with good hearing outcomes.

Analysis of Sound in the Cochlea and Sensorineural Hearing Loss

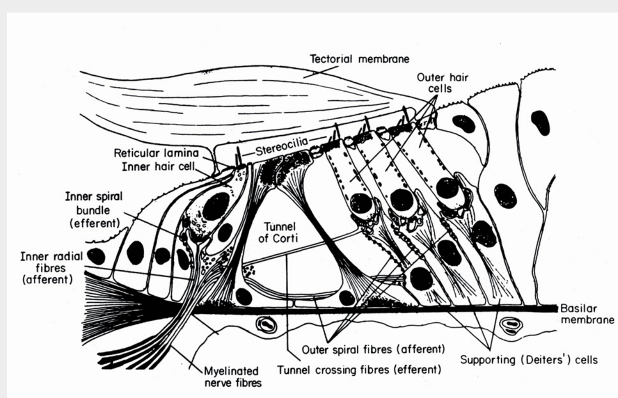
The most common type of hearing loss, sensorineural hearing loss, is caused by dysfunction of the cochlea or the auditory nerve. This can lead to several types of perceptual deficits, only some of which are compensated by hearing aids. **Figure 2** shows a schematic cross section of the cochlea. The cochlea is filled with almost incompressible fluids and has bony rigid walls. It is divided along its length by the basilar membrane (BM). Two types of sensory hair cells run along the BM, the outer hair cells (OHCs) and inner hair cells (IHCs), both of which have tiny hairlike tufts at their tops called stereocilia. The tectorial membrane runs along the tops of the OHCs and IHCs. The region bounded by the BM, OHCs, IHCs, and tectorial membrane is called the organ of Corti.

The end of the cochlea near the oval window is called the base and the other end is called the apex. When the oval window moves, a pressure difference is applied across the BM, causing it to move. The response to sinusoidal stimulation is a wave that moves along the BM from the base toward the apex. The amplitude of the wave increases at first and then decreases. At the base, the BM is narrow and stiff, whereas at the apex, it is wider and much less stiff. Consequently, high-frequency sounds produce maximum displacement of the BM near the base, whereas low-frequency sounds produce maximum displacement toward the apex. The frequency that evokes the maximum response at a given point on the BM is called the "characteristic frequency" (CF).

Each neuron of the auditory nerve is connected via a synapse to a specific IHC. When the BM vibrates, there is a sideways movement of the stereocilia of the IHC that depends partly on vibrations on the top side of the organ of Corti (Altoè et al., 2022). As a result, an electric current flows through the IHC, leading to release of a neurotransmitter at the synapse and the initiation of "spikes" in the auditory nerve. Each neuron also shows tuning and has a CF. In a normal healthy ear, each point on the BM and each neuron are sharply tuned, responding with high sensitivity to a limited range of frequencies. The sharp tuning and high sensitivity depend on an active mechanism involving movements of the OHCs (Robles and Ruggero, 2001).

Dysfunction of the OHCs is common following noise exposure or with increasing age (Wu et al., 2021; Wu

Figure 2. *Cross section of the cochlea, showing the basilar membrane, the tectorial membrane, and the organ of Corti. Reproduced from Moore (2012), with permission.*



and Liberman, 2022). This impairs the operation of the active mechanism, with three main consequences. First, it reduces the amount of BM vibration around the peak of the vibration pattern, especially for low-level sounds, resulting in an elevation in the pure-tone threshold as measured by the audiogram.

A second consequence of OHC dysfunction is reduced frequency selectivity. This is the ability to "hear out" or resolve the sinusoidal components of complex sounds. For example, if you simultaneously strike two tuning forks tuned to different frequencies, such as 256 and 440 Hz, you hear two separate tones, each with a distinct pitch. This ability depends on the tuning that occurs on the BM; each point can be regarded as a band-pass filter. In a normal ear, these filters, often called the auditory filters, have bandwidths at medium and high CFs that are 12-13% of the CF (Glasberg and Moore, 1990). Dysfunction of the OHCs causes the filters to broaden by a factor up to four (Moore, 2007), thereby reducing the ability to determine the spectral shape of sounds, which is important for distinguishing speech sounds and for understanding speech in background sounds (Baer and Moore, 1994). It also reduces the ability to hear out individual musical instruments or groups of instruments in a mixture (Madsen et al., 2015).

A third consequence of OHC dysfunction is related to the fact that, in a normal ear, the response on the BM is a compressive function of the input level for frequencies close to the CF. For example, a 10 dB increase in input level may produce only a 2.5 dB increase in response on the BM (Robles and Ruggero, 2001). This compresses the large range of sound levels encountered in everyday life (about 120 dB) into a much smaller range of responses on the BM, reducing "saturation" of the responses of the neurons in the auditory nerve. This allows us to hear over a wide range of levels, from the rustling of dry leaves to a loud rock band. OHC dysfunction reduces or abolishes the compression on the BM, and this reduced compression is thought to contribute to an effect called loudness recruitment (Moore, 2004). Once the sound level exceeds the detection threshold, the loudness grows more rapidly than normal with increasing sound level. At high-sound levels, the loudness for an ear with OHC dysfunction "catches up" with the loudness for a normal ear. Consequently, a person with OHC dysfunction can only hear comfortably over a small range of sound levels; this is described as having a reduced dynamic range.

There may also be dysfunction of the IHCs, the synapses that connect the IHCs to the neurons of the auditory nerve, and of the neurons themselves. Synaptic dysfunction, called synaptopathy, is associated with noise exposure (Kujawa and Liberman, 2009; Wu et al., 2021) and increasing age (Wu et al., 2021). Following synaptopathy, the auditory nerve may degenerate, although in humans, this can take many years. Unless the dysfunction is extreme, it has little effect on the audiogram because only a few nerve spikes are sufficient for a sound to be detected (Lobarinas et al., 2013). This type of dysfunction has been called "hidden hearing loss" (Schaette and McAlpine, 2011) or "hidden hearing disorder" (Moore et al., 2019) because its effects are not apparent in the audiogram. Synaptopathy reduces the number of neurons conveying information from the ear to the brain, leading to a more "noisy" representation of sounds, and this may result in a lack of clarity of speech, especially in noisy places.

One aspect of perception that may be especially affected by IHC/synaptic/neural dysfunction is sensitivity to "temporal fine structure" (TFS). The output of each auditory filter can be thought of as an envelope, the slow changes over time in the amplitude of the vibration of the BM, superimposed on the TFS, the rapid fluctuations in instantaneous amplitude (Moore, 2014). The TFS is reflected in neural phase locking; the nerve spikes are synchronized to a specific phase of the waveform on the BM, at least for frequencies up to 4-5 kHz. When the number of neurons conveying phase-locking information is reduced, this may impair the ability of the central auditory system in the brain to "decode" the TFS information. In addition, OHC dysfunction can change the tuning of a given place on the BM in such a way that the patterns of TFS information become distorted (Henry and Heinz, 2012), making it harder to discriminate speech sounds, especially in background noise (Moore, 2014). Information about TFS may also be important when trying to focus on one talker in a multitalker background (Hopkins and Moore, 2009). Finally, TFS information can be compared across ears, which contributes to the ability to localize sounds and to understand speech in the presence of spatially distributed interfering sounds. This ability worsens with increasing age and increasing hearing loss (Moore, 2021).

Near-complete IHC/synaptic/neural dysfunction results in a "cochlear dead region" (DR) (Moore, 2001). No information is sent to the brain from a DR. However, a sinusoid that produces maximum BM vibration in a DR may be detected if the sinusoid produces sufficient vibration in an adjacent functioning region, something called "off-frequency" or "off-place" listening. A hearing loss of 70 dB or more at a given frequency is often associated with a DR at the place on the BM tuned to that frequency, but a DR cannot be reliably diagnosed from the audiogram (Vinay and Moore, 2007). An extensive DR is associated with a very poor ability to understand speech, even in quiet situations, and is also associated with a limited benefit from hearing aids (Vickers et al., 2001; Baer et al., 2002).

How Hearing Aids Work

Hearing aids usually contain the following components (Moore and Popelka, 2016):

(1) One to three microphones to pick up the sound;
(2) Each microphone is connected to a preamplifier followed by a low-pass filter;
(3) An analog-to-digital converter that periodically samples the voltage at the output of each filter and converts it into a numerical value. The number of samples per second (sampling frequency) needs to be at least double the highest frequency that it is desired to transmit (i.e., the low-pass filter cutoff frequency). In modern hearing aids, the sample frequency is usually about 20,000 samples per second;
(4) A miniature computer that processes the digitized sound;
(5) A miniature loudspeaker, confusingly called a "receiver," that converts the digital output of the computer to sound;
(6) A battery; and
(7) A casing to accommodate the components that fits behind the ear or in the ear canal.

Figure 3. *Illustration of the main styles of hearing aids.* ***a:*** *In the ear;* ***b:*** *completely in the canal;* ***c:*** *behind the ear;* ***d:*** *receiver in the ear canal. From Moore and Popelka (2016), with permission of Springer Cham.*

Styles of Hearing Aids

Figure 3 shows the common hearing aid styles. When all of the components are housed in a single case, this is called in the ear (ITE) if the case is partly in the bowl of the pinna (**Figure 3A**) or completely in the canal (CIC) if the case fits completely in the ear canal (**Figure 3B**). The most common style is behind the ear (BTE) (**Figure 3C**), where the case is placed behind the pinna. For this style, the microphones are just above the pinna. In the "receiver-in-the-ear" (RITE) style, the case is also behind the pinna, but the receiver is inside the ear canal (**Figure 3D**). The RITE style does not generally require a custom-made earmold or shell, whereas the ITE and CIC styles usually, but not always, involve a custom-made shell.

What Do Hearing Aids Do?

Compensation for Threshold Elevation and Loudness Recruitment

Hearing aids incorporate signal processing to compensate for reduced sensitivity to soft sounds and loudness recruitment. Usually, this is done by filtering the sound into several frequency bands or "channels" and applying independent automatic gain control (AGC) to the signal in each channel (Kates, 2005). This allows for the fact that the amount of hearing loss of an individual varies with frequency, often being greater at high than at low frequencies. With AGC, weak sounds are strongly amplified to restore their audibility, but the amplification is progressively reduced as the sound level increases. This partially compensates for the effects of loudness recruitment.

The amplitude compression produced by the active mechanism in a normally functioning cochlea is very fast acting (Cooper and van der Heijden, 2016), in that the amplification changes rapidly with changes in the input sound level. It might be expected that the AGC in hearing aids would be most effective if it was also fast acting. However, despite many research studies, there is no clear consensus as to whether fast or slow compression is preferable (Moore, 2008). Indeed, based on the subjective judgments of hearing-impaired people, it appears that slow AGC is slightly preferred over fast AGC for listening to music but preferences for speech are less clear (Moore and Sęk, 2016).

Multichannel AGC does not compensate fully for the effects of threshold elevation and loudness recruitment. The amplification of soft sounds is usually not sufficient to fully restore their audibility, and slow-acting AGC does not compensate adequately for rapid fluctuations in level, such as can occur in music. Hence, dynamic changes in music can appear exaggerated, and users of hearing aids still complain that some sounds are too loud (Madsen and Moore, 2014).

The number of compression channels does not have a strong influence on the ability to understand speech in quiet or in noise (Salorio-Corbetto et al., 2020). However, the filtering of the input signal into channels is also used for other forms of signal processing, such as noise reduction, as described in the section ***Partial Compensation for Reduced Frequency Selectivity and Other Deficits***. For such processing, it can be beneficial to have many channels. The filtering is often done using the fast Fourier transform (FFT) to process the signal in short overlapping time frames (Allen, 1977). The longer the time frame, the greater the sharpness of filtering. However, long time frames involve greater time delays and if the delay is greater than about 10 ms, it can have deleterious effects on speech production and perception (Stone et al., 2008). In practice, the time delay of modern hearing aids is in the range 0.5 to 10 ms. This limits the sharpness of the filtering that can be achieved and also limits the number of channels.

Partial Compensation for Reduced Frequency Selectivity and Other Deficits

Hearing aids do not compensate directly for reduced frequency selectivity or for the effects of IHC/synaptic/neural dysfunction. At best, they achieve partial compensation for these effects by improving the speech-to-background ratio. This is done in two main ways: (1) using directional microphones and (2) using noise-reduction algorithms (NRAs).

Directionality is often achieved using the two microphones within one hearing aid. The signal picked up by one microphone is delayed and combined with the signal from the other microphone. Manipulation of the delay leads to different patterns of directionality (Launer et al., 2016). In addition, signals can be transmitted wirelessly between bilaterally fitted aids, and all four microphones of the two hearing aids can be used to create high directional selectivity (Launer et al., 2016). Such systems are called binaural beamformers, by analogy with a beam of light that is pointed at an object of interest.

Usually, it is assumed that the user of hearing aids will face toward the target so the beamformer is pointed toward the front. However, people do not always want to listen to someone directly in front of them and so some beamformers can steer the beam in different directions. Additionally, because background sounds and targets can move, *adaptive* beamformers have been developed that change their directionality patterns, usually so as to select the most prominent talker (Launer et al., 2016; Kollmeier and Kiessling, 2018). Adaptive directional systems improve speech understanding and/or ease of listening in a range of situations, but the benefits vary depending on the type of environment, the technical implementation, the type of background, and the auditory skills of the individual (Best et al., 2015).

NRAs are most effective when the background is dominated by noise (e.g., from ventilation or machinery) rather than by people talking. NRAs attempt to estimate the signal-to-noise ratio (SNR) in each channel using information such as the amount or pattern of amplitude modulation of the channel signal (Launer et al., 2016; Kollmeier and Kiessling, 2018). In one approach, the gain is maintained for channels with a high estimated SNR but is reduced for channels with a low SNR (Holube et al., 1999). Alternatively, the estimated noise signal is subtracted from the speech plus noise in each channel (Kollmeier and Kiessling, 2018). Such NRAs have been shown to make the sound more pleasant, but they have not been clearly shown to improve speech intelligibility.

Applications of Deep Learning

NRAs are currently being transformed by advances in machine learning, based on deep neural networks (DNNs). DNNs require training. For example, if it is desired to improve the SNR, the DNN is trained by providing as input many samples of noisy speech and the corresponding clean speech (without noise). The clean speech is the "training target." After training, the DNN can process noisy speech to extract clean speech. To ensure that the DNN is effective in practice, it must be trained using many talkers, types of background, and SNRs. DNNs have been shown to be effective for speech in noise (Healy et al., 2013; Keshavarzi et al., 2018), speech in the presence of a single competing talker (Healy et al., 2017; Bramsløw et al., 2018), and even for separating talkers in a multitalker background in reverberant environments (Lesica et al., 2021). Of course, in multitalker environments, it would also be necessary to select the target talker, and this is a difficult task. Although much current research is aimed at "cognitively controlled" hearing aids, where the target talker is selected based on sound-evoked brain electrical potentials, this research is still far from practical application.

The DNNs used in many laboratory studies require more memory storage and processing power than is currently available in hearing aids, and some involve time delays exceeding 10 ms. For implementation in current hearing aids, the architecture must be simplified and the time delay reduced. We are aware of only one manufacturer that incorporates a DNN to process speech in noise in some of their hearing aids. This DNN was trained to attenuate nonspeech background sounds while preserving speech sounds from all directions (Andersen et al., 2021).

Sound Classification

Many hearing aids incorporate methods of classifying the sound environment, for example, speech in quiet, speech in noise, music, or low reverberation versus high reverberation. In some cases, this is done via simple DNNs. The signal processing in the hearing aid is then adapted to suit the specific environment. For example, an extended low-frequency response may be beneficial for listening to music (Moore et al., 2016), whereas a highly directional response with strong noise reduction may be beneficial for listening to speech in a noisy situation. The benefits of such classification methods require further evaluation.

Dealing with Acoustic Feedback

When a person has a hearing loss that requires considerable amplification, the sound output from the hearing aid may be picked up by the microphones, leading to a squealing sound called acoustic feedback. Nearly all hearing aids incorporate systems for reducing acoustic feedback (Kates, 1999), but these can degrade sound quality and introduce artifacts of various kinds (Madsen and Moore, 2014; Zheng et al., 2022). A DNN for reducing such artifacts has been described but has not yet been implemented in hearing aids (Zheng et al., 2022).

Other Features of Modern Hearing Aids

Bluetooth streaming of sound from mobile phones, remote microphones, or TVs to hearing aids is becoming more frequent. This can be beneficial in delivering a relatively clean signal to the hearing aids, with little background noise or reverberation.

Most modern hearing aids provide sufficient amplification to partially restore audibility for frequencies up to about 5 kHz for people with mild-to-moderate hearing loss (Moore et al., 2001). However, for severe hearing losses, the maximum audible frequency can be much lower. For this reason, some hearing aids shift the high frequencies of the input to lower frequencies where the user's hearing thresholds are lower (Launer et al., 2016; Salorio-Corbetto et al., 2017). The lower frequency components of the input signal remain intact. Although frequency lowering of various types is an option in many hearing aids, evaluations of its benefits have given conflicting results.

Summary of What Hearing Aids Do

In summary, hearing aids partially compensate for threshold elevation and loudness recruitment, but they only compensate indirectly and to a limited extent for the other perceptual effects of hearing loss. Thus, hearing aids help, but they by no means restore hearing to "normal" and they have not yet solved the cocktail party problem. This may be one of the reasons why less than 20% of those with hearing difficulties in the United States regularly use hearing aids (Humes, 2023). Other reasons for the limited uptake include cost, perceived stigma, the "bother" of looking after hearing aids (e.g., the receivers can get clogged with wax), and discomfort produced by the part in the ear canal.

Recent Developments

The incorporation of biosensors into hearing aids is blurring the boundary between hearing aids and other gadgets used in everyday life. Some hearing aids can count your steps, track your heart rate and even detect a fall and send an alert to a close contact. These features are changing public perception about hearing health and hearing aids. Current hearing aids are being integrated into modern lifestyles as an additional way of promoting health and well-being. This phenomenon is further promoted by the approval of over-the-counter instruments in some countries, including the United States and Japan, and by the use of "hearables" as hearing aids.

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Innovative Solutions for Acoustic Challenges in Tall Slender Skyscrapers

Bonnie Schnitta and Sean Harkin

Introduction

During hurricanes, news stations broadcast astonishing live scenes, with a meteorologist showing the dramatic and often devastating effects of the wind. As the storm approaches, images of trees swaying due to these conditions are shown to illustrate the force of that wind speed. If you have ever sheltered from a windstorm in your home, you are likely to be familiar with the sounds the structure begins to create as it is moved by the force of the wind. Fortunately, for those in tall skyscrapers, these structures are designed to move with not only the force of the wind but also with the force of earthquakes. However, although these building designs keep their occupants safe, if the interior partitions, such as walls, floors, and ceilings, are not designed to be adaptable to the motion of the skyscraper, then the language of building sounds at higher floors associated with weather conditions, particularly on windy days, can be unsettling.

Today, skyscrapers not only are taller than their twentieth-century predecessors, but advances in structural engineering have made it possible for architects to achieve soaring heights with a remarkably small base area on the ground. Most people are familiar with the Empire State Building in New York, New York, which is 1,250 feet tall. Comparably, buildings of this new class of tall skyscrapers are as tall as 1,776 feet, as is the case of the new One World Trade Tower (NY). The Empire State Building has a height-to-base ratio of 3:1. The typical height-to-base ratio of these tall slender buildings is 10:1, although buildings built in the last decade have included such ratios as 13:1 and greater for height-to-width ratio. There were buildings completed in 2022 that have a ratio of 24:1 (Dreith, 2022), challenging what many would have ever conceived to be possible. An example of one such building can be found in **Figure 1**.

As the base-to-height ratio increases, the impact caused by the wind on the building's interior partitions and the potential for partition sounds also increases. This article explores the movement of these new tall skyscrapers and the potential disruptive noises that can occur during high winds unless careful design considerations are made and innovative solutions are engineered and implemented.

Tall Skyscraper Sounds

All buildings are designed to endure the impact of environmental phenomena. The motion of a tall building in high-wind conditions produces movement where the top of the structure moves more than its base. This simple law of physics then tells us that if the top of a building is moving more than its base, then the ceiling of a room will move more than the floor. This movement in tall

Figure 1. *Photograph of a tall slender skyscraper in New York City. Courtesy of Victor Salcedo of Gerb USA.*

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skyscrapers can create a vibratory response within the partitions of a building that then become airborne sounds, much like the vibrating strings of a guitar creating sound. The science to solve this problem is fascinating and is presented in this article.

An Overview of the Solution

Ultimately, the goal is to determine a solution to create a quiet environment within a building. Once the potential noises are understood, the next step would be to analyze the movement of the building and how that movement will impact an individual floor. Ideally, each floor of a building should be analyzed because each is different in how it will respond to building movement. If untreated, this wind impact causes exterior motion and interior movement of the partitions, which, in turn, generates audible sounds of what we call "snap, creak, and pop" in standard construction. The three main steps taken to mitigate the potential sounds are to (1) determine the acceptable noise level for the client, who could be the architect, building owner, or individual residence owner; (2) measure the baseline motion and sounds of the building; and (3) engineer and finalize the solution set to bring the noise levels down to acceptable levels.

Although it is well-documented and researched that the senses are a key factor in how one feels in a room from sounds and vibrations in general (Harris, 1998; Tamura et al., 2006; Keith, 2008; Kwok et al., 2009; ANSI/ASA, 2012; Waddington et al., 2014; Kowalska-Koczwara and Stypula, 2020), the reverse is also true. That is, if someone categorizes an auditory or vibratory experience as unpleasant, then the space with those auditory or vibratory sounds will also be considered unpleasant. This was expanded on in Heshmati's PhD dissertation (2022). A summary of the experiments performed and his thesis is the question: "What vibrations outweigh the amazing and breathtaking view of a city skyline and make the residence feel unpleasant?" With this research in mind, we ask and answer in this article "What acoustic treatment is required and confirmed to work in the construction of a room, apartment, or home to make the space feel as wonderful as the majestic city views?"

The acoustic treatment solution set used to bring a residence in a tall skyscraper that is subject to high winds to a state of quietude requires thorough acoustic testing and analysis. This testing and analysis generate construction specifications for consideration during the design phase of the building. Actual testing to date shows that wind tunnel tests have the potential to be a good estimate, but there is nothing that leads to a more successful solution set as the actual site vibration and airborne readings. Also, it is critical to remember that each floor often has a different movement and therefore a potentially different solution set to the building noise.

Some of the basic solution sets to address building movements provide important guidelines and are presented in this article. The procedure of measuring sound and vibration in tall slender buildings during high-wind conditions is also included because it is critical to engineering a solution with optimum efficacy. After a building is constructed, a very critical point is that airborne acoustic readings alone typically do not provide sufficient data that will lead to the correct solution set. Vibration readings must also be taken. Case studies are provided in this article to provide some examples of how novel techniques and solution sets have successfully been installed in even the most challenging environments.

Gaspar (2017) of the Brewer Smith Brewer Group, Abu Dhabi, United Arab Emirates, identified that, in strong winds, building movement can be nearly three feet on each side during strong winds. Gasper went on to state that despite this building movement, the building is structurally fine.

To address wind-induced movement of the structure, a tuned mass damper (TMD), or "harmonic absorber" is

Figure 2. *Photograph of a tuned mass damper installed in a tall slender skyscraper. Courtesy of Victor Salcedo of Gerb USA.*

commonly included in the building design. Frahm (1911) received a United States patent for a Dynamic Vibration Absorber, which today is known as a TMD. The TMD helps reduce the perception of the movement, although it does not eliminate the movement entirely. An excellent overview of how a TMD works in skyscrapers is provided by Gasper (2017). The full video is found on the Practical Engineering YouTube channel (Hillhouse, 2016). An example of a TMD installed in a skyscraper can be seen in **Figure 2**.

The engineering to specify the TMD that is used to create this counterweight is performed by a structural engineer. It is a beautiful sight to see a multi-ton object move in response to environmental conditions. With that TMD dance comes sounds from the TMD movements. Although minor sounds, readings of these sounds must be taken by the acoustic engineer to ensure that sounds from the TMD movement do not travel through the partitions where the TMD is located or through other possible conduits, such as HVAC ducts. This could result in acoustic issues in any space connected through shared ductwork.

Next Step: Treating Interior Sound Sources in a Residence of a Tall Skyscraper

Acoustic and Vibration Readings for Design-Phase Acoustic Engineering

After the TMD has done its magic, there remains the critical step in the solution set: treating the remaining sounds and vibrations that result from building movement. These remaining sounds must be addressed by acoustically treating the interior partitions with an innovative solution set because standard construction typically fails to meet the demand of the structure movement. Additionally, the movement of the building systems, such as the pipes or the ducts for the heating or cooling, and those movements against rigid clamps or surfaces, such as the drywall, also contributes to the movement sounds and must be addressed.

There are examples that easily demonstrate how rigidity where movement is needed create acoustic problems and give a hint to the solution set. The first example of how the rigid wall contributes to the noise source is to think of children making a telephone using two cups and a string. When a cup is placed to their ear, the voice of their friend on the other end can be heard if the string is taut. If there is slack to the string, the only sound heard is that of frustration because the "phone" did not work. This illustrates that the solution for this rigid wall noise is "loosening" these taut lines or making the partitions resilient. This same analogy will help for understanding later sections.

The other important fact to remember in the solution set is that sound travels much further than its point of origin when given the right set of circumstances. This is easily explained by how the earth's motion from an earthquake in one part of the world will register on seismic graphs in the United States. A fascinating article with further detail on this phenomenon is "The Unheard Symphony of the Planet" (Morley, 2023). If a vibration can travel from Los Angeles, California, to New York, a vibration can also easily travel along the walls of a building. Therefore, the solution set needs to "cut the string of the telephone cup" wherever possible.

Indeed, although it may seem like the building sounds are from the movement of the building and nothing can be done, a successful solution set comes from addressing standard rigid construction. The ground movement and the typical and maximum winds that influence the building movement contribute to engineering the solution set.

It is critical to understand the amount of sound created within the building during windy conditions as well as the natural frequency response of the partitions creating noise while impacted by building movement. This can be accomplished by monitoring both airborne noise levels with a spectrum analyzer and simultaneously vibration levels with an accelerometer attached to a partition within the room.

Depending on the building, wind speeds that induce noise can be as low as 10-15 mph sustained winds at ground level to create meaningful building noise the interior partitions are not acoustically treated. Moreover, it is imperative to know that this can vary from floor to floor. That is, even if readings are used to engineer a successful innovative installation on one floor, those readings and that solution set may not work as well for another floor. Fortunately, once the solution set has been engineered for one floor, it can be used in any future renovation at that specific floor. Also, if there are changes to the buildings around the new tall skyscraper, they typically create a buffer and may reduce the wind effects. Furthermore, there is enough of a margin in the design for each floor that if one nearby building comes down, it will not cause a problem.

Acoustic Readings of Building Noise with Typical Construction

Acoustic readings were taken in a residence that was built using conventional construction methods of rigid walls, preventing them from moving with the building structure so that a solution could be determined. Results of the airborne acoustic readings showed that wind events generated sound levels from the partitions that were significantly above ambient sound levels. Ambient and building movement noise data are provided in **Figure 3.**

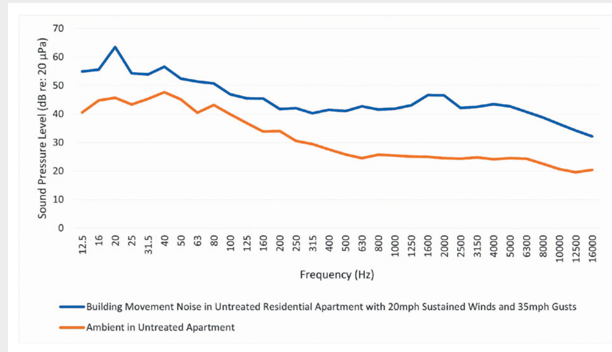


Figure 3. *Acoustic data collected within an untreated apartment showing background sound levels, and sound levels due to building movement.*

The data collected showed that ambient-sound levels were exceeded by as much as 20 dB in select one-third octave bands around 2,000 Hz. To put this into perspective, speech frequencies typically range from 125 to 2,000 Hz.

Engineering a Quiet Space on a Floor or Room of a Tall Building

With data collected for airborne and structure-borne vibrations, solution sets can be engineered. Just as tall needle buildings are novel in some aspects of their design, the construction that results in a quiet and comfortable space for typical weather as well as in high-wind conditions must include some novel acoustic engineering and construction. This is true for residences as well as for office spaces. As these are explained, remember the analogy of the two cups with the string in-between. The string needs to be cut or loosened to minimize the movement of the building from transferring into the partition. Consequently, it is now clear that successful installations have all included the following:

- Resilient connections (remember the two telephone cups with the string in-between)
- Eliminating metal-on-metal connections and structure selection
- Expansion joints; and
- Increasing the transmission loss of partitions to contain any residual noise.

These additions may initially appear to be significant additions to the construction strategy. However, they are not that different from the requirements for an acoustically correct home or workspace. The difference in construction requirements is only a few novel acoustic materials and installation requirements with diligent construction administration.

As noted in the **Introduction**, an acoustic consultant starts the architectural design and associated construction process first with an interview or survey of the client's noise sensitivities (Schnitta and Carter, 2017) and vision of the acoustic outcome. After the engineering is performed, it is followed by a discussion of the recommended acoustic treatment and associated costs. Whether the client is the architect, the owner of the building, or the individual residence owner, decisions are made based on the interview and survey. In the case of the tall skyscraper, some of the requirements are not optional for an ideal living or working environment (Cerrato and Goodes, 2011). It has been stated by professionals in the construction field that even when evaluating simple improvements to the acoustics of a project that sound treatment can have a minimal impact on the budget at the early design stages. As construction begins, the cost to make those same improvements can be significant and is often done with compromises due to other design constraints. This is a fact that permeates into every aspect of construction but especially for acoustics.

Resilient Connections

In concrete buildings, the walls, ceilings, pipes, ductwork, and any building materials within the apartment are typically attached to the concrete at the top and bottom, typically referred to as the top slab and bottom slab. Resilient connections of building elements that are connected to the concrete at the ceiling and floor of a residence in the building are essential. Including resilient connections not only allows the partitions and mechanical equipment to have a small amount of travel movement but also allows for the movement in the resilient component to be spread out evenly over the partition rather than showing an immediate deformation or shift that is characteristic of a rigid connection. Remember the two cups with the string in between. We do not want a taut or rigid connection.

Further emphasis on the importance of engineering the specifications for these resilient connections and allowing movement is that there is some torque in the building movement. Although it is not the intent of this article to explain these movements, it should be noted the importance of knowing that (1) these movements occur and must be part of engineering the solution set and (2) they put emphasis on the importance of airborne and vibration readings. The resilient connection of floors and ceilings is necessary to inhibit tall skyscraper sounds on a windy day. These resilient connections also help reduce sound transmission between apartments of people talking/listening to TV as well as people walking around. Resilient connections of ductwork and piping are just as essential. The solution set includes acoustic resilient underlayments under the floors to be installed as well as using a decoupler or resilient clips within the ceiling construction.

Because the walls connect the top and bottom concrete slabs, which move in different amounts, thoughtful selection of the attachment methods is critical. One solution is to use resilient bushings with elastomeric materials. An example of one of the bushing assemblies creating a connection between the wall and bottom slab is shown in **Figure 4**. This type of assembly is critical to allow the structure to move ever so slightly with the building without resistance.

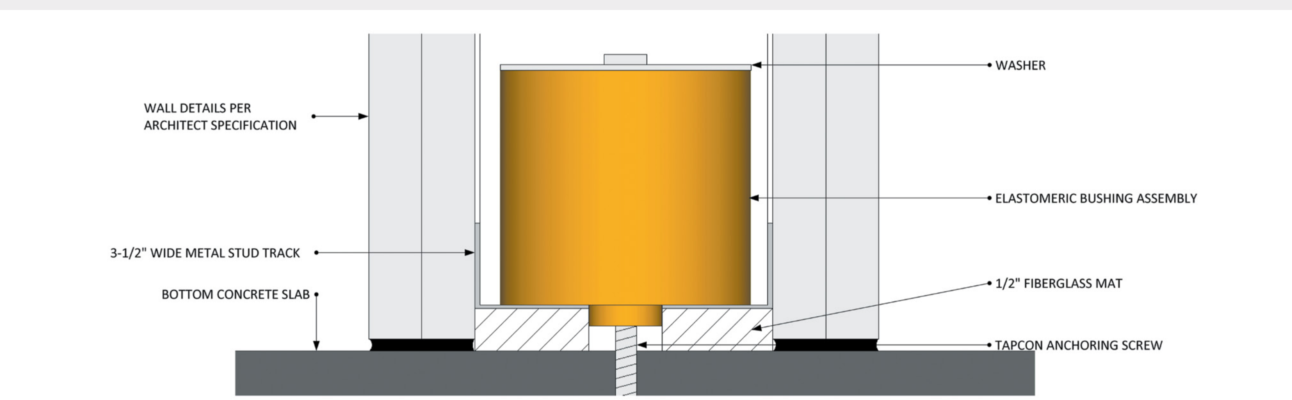
Although the bushing assembly shown in **Figure 4** functions similarly to readily available rubber products, it is a custom-engineered component that must be tailored to the application. Although the same or similar bushing designs have been able to be used in multiple floors of the same building or in a couple of different buildings, it is unknown if they can be used across all slender building applications. It probably would not provide the optimum efficacy. This is why acoustic testing for each application is critical so that the design can be reevaluated to determine if the same dimensions and stiffness of elastomeric materials are acceptable or if a different design is necessary.

To isolate ductwork and piping, rubber or elastomeric hangers are used when connecting ductwork and piping to a concrete slab. For example, resilient clips or equivalents could be used instead. A typical application of a resiliently hung pipe is shown in **Figure 5**.

Elimination of Metal-on-Metal Connections and Structure Selection

During building movement, the framing for the partitions and their connections will shift against one another, causing any metal-on-metal connections to create noises. This type of movement is necessary within the dynamics of the building but needs to be appropriately treated so that additional noise is not created from metal rubbing against metal. Thus, any metal-on-metal connections should be eliminated. This can be accomplished through several different means, including introducing layers of

Figure 4. *Example of an elastomeric bushing assembly for wall connection.*



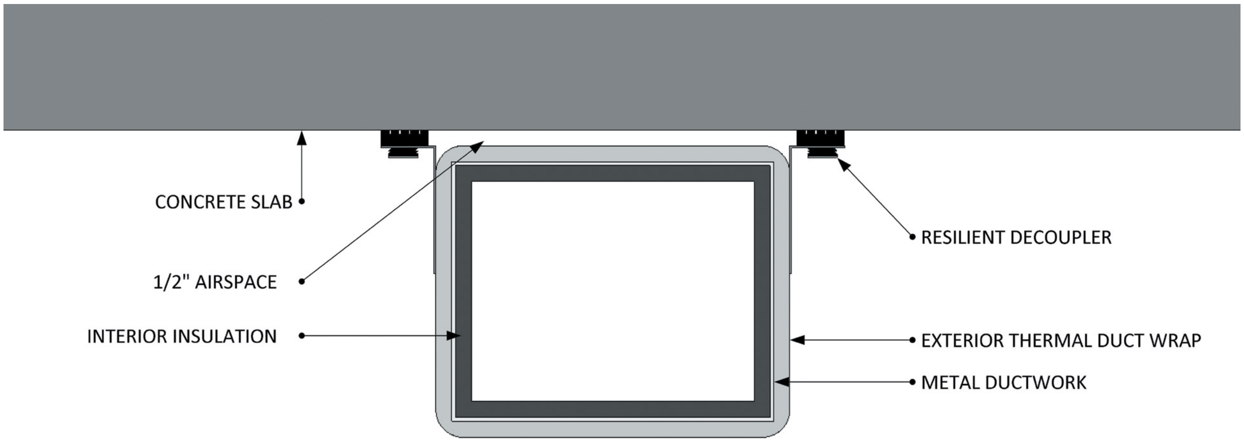


Figure 5. *Example of a resilient ductwork connection to a concrete slab.*

materials between the metal. Some companies have also developed products to break up these connections.

In addition to the connections of the framing to each other as well as the structure, it is important that the framing of the wall be thoughtfully selected so that it can remain strong even under the motion of the building while also providing resiliency and freedom of motion where possible. In addition to the elastomeric bushings described in ***Resilient Connections***, the metal studs of the wall normally sit in a rigid track. Using a track in which the studs reside allows for vertical movement between the stud and the track, or a slip track, at the top track of the structure, allowing for some movement between the wall and top concrete because, as mentioned in **Tall Skyscraper Sounds**, the ceiling of an apartment moves more than the floor. Although the actual dynamics of the situation are more complicated, the motion can be likened to an object under a force that creates torque. The differential of movement between the top and bottom slab of each floor provides the torque, whereas strengthening the wall assembly helps to increase the wall's "moment of inertia." Since the original applications of this work, some manufacturers have come up with additional solutions, allowing for drift in multiple axes, not just one.

Expansion Joints

Along the same lines as using framing assemblies to allow for drift, expansion joints are also a key component of successful solutions. Using an expansion joint, particularly at the ceiling, allows for some movement of the wall relative to the ceiling, which helps to reduce the risk of cracking finishes during movement as well as deformation at these connections. The installed expansion joints can be covered with molding details and a small gap.

Transmission Loss Increase on Each Side of a Wall

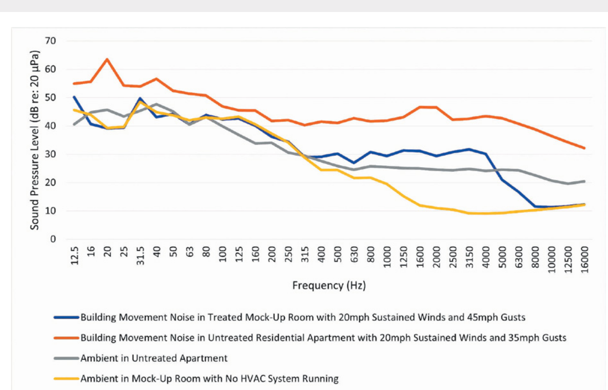
During design, it was assumed that some noise on the interior of the wall could still be possible. Therefore, the transmission loss on each side of the wall was increased. Because this had to be done in as little space as possible, mass-loaded vinyl was included in wall configurations to be able to provide an airtight acoustic barrier into the wall cavity while also providing a break between the metal studs and gypsum board that introduced a small amount of resiliency.

Mock-Up Testing with Solutions Installed

In most instances, mock-up testing is critical to ensure that the solution set will meet the satisfaction of all project stakeholders, even if the building is being designed from the start of construction instead of a renovation. During one project that was associated with the data collected in an untreated unit presented in ***Acoustic Readings of Building Noise with Typical Construction***, the outlined solutions provided there were implemented to measure the residual sound levels within the mock-up room. A significant amount of flanking or acoustic leakage was observed because of unsealed ductwork penetrations and no acoustic gaskets on the temporary doors installed into the room. These paths were identified and tested through visual inspection as well as utilizing a recently patented device, the dB Focus Tube (Schnitta and Israel, 2018), to test and identify the severity of such acoustic leakage paths. This led to conditions that were corroborated by the project team where noise was occasionally slightly audible within the mock-up room but was clearly emanating from a wall outside the room and sound was entering through the doorways. Although it was not a perfect environment for full evaluation, it was the best that could be achieved at a minimal cost and built expeditiously.

Over the course of three months, noise and vibration measurements were collected within the mock-up room. The sound level meter was configured to capture audio recordings for sound levels higher than the background sound level of 38 dB(A). Any recordings reviewed during the monitoring were inaudible until one sample recorded in the third month of monitoring. This sound above 38 dB(A) was attributed to something within the room instead of to noise outside the room. The results of this sample can be found in **Figure 6,** which shows the data collected in the untreated portion of the building presented in ***Acoustic Readings of Building Noise with Typical Construction*** as well as inside the mock-up room. It should also be noted that since the heating, ventilation, and air conditioning (HVAC) equipment was not operational in the mock-up room, ambient-sound levels were extremely low and lower than what would occur after project completion. Therefore, the ambient-sound level with an operational HVAC system has also been provided as a point of reference.

Figure 6. *Measured sound levels in the mock-up room and untreated apartment.*



The results of the mock-up testing showed that, in similar wind conditions, a 10-15 dB reduction was observed. Compared with the ambient-sound levels measured within the untreated apartment with an operational HVAC system, sound levels were only 5-7 dB above ambient levels, which is a significant reduction.

Despite the known acoustic leakage into the room as described at the beginning of this section, the lack of any absorptive finishes within the mock-up room and the low ambient sound, there was no or minimal audible sound during typical wind conditions. The apartment was built using the mitigation measures implemented in the mock-up room. The emphasis in the construction ensured that all acoustic leakage points were resolved in each room being constructed.

Sound will travel through any weak or incomplete junctions of a partition. For example, the sound through a wall can be 10 dB greater when there is something as seemingly minor as a 1-inch square gap, such as a 1/8-inch space between the bottom of a wall where the wall meets the floor (Gover and Bradley, 2006), or a lack of complete caulking at partition perimeters. For this reason, acoustic leakage paths such as doors, outlets, plumbing penetrations, shared chases, conduits, ceiling/wall, or floor/wall points of intersection in construction should be addressed so the wall or other partitions perform up to their engineered ability to stop sound.

More importantly, the partitions for tall skyscrapers contain some residual noise from building movement. Just like perimeter seals keep the cold from coming into a warm house, acoustic leakage treatment of partitions will keep the residual sounds in a wall, ceiling, or floor from entering a room. The locating and treating of acoustic leakage is a significant step in a successful solution set. This can be performed with products such as an ultrasound camera or dB Focus Tube.

In addition to resolving acoustic leakage, addressing reverberation was a key component to the project moving forward. Excessive reverberation reduces the intelligibility of speech, corrupts the music within a room, or can amplify sounds in a room. This becomes problematic when a slight sound (1-2 dB above ambient) from building movement becomes amplified to 4-5 dB or more due to a high reverberation time within the room and results in a disturbance. Acoustically absorbing or diffusive surfaces were integrated where possible because they should be in any home, office, or hospital.

In addition, HVAC systems were specifically designed so that they would provide a small amount of sound masking to ensure that ambient sound levels were not too low so that a larger differential between ambient and residual noise did not present itself. A true sound-masking system was proposed to be integrated into the speaker system of the residence. Due to the success of the innovative solution set, this was never installed.

Conclusion

Although noises in buildings, and especially in skyscrapers, are normal due to the motion of the buildings, they can create disturbance to occupants, whether in a residence or an office space. With careful structural and acoustic design as well as treatments such as elastomeric bushings, framing selection, resilient partition connections, elimination of metal-on-metal connections, expansion joints, and mass-loaded vinyl, builders can help to mitigate these noises. Although the noises during high-wind conditions may not be able to be eliminated in all circumstances, thoughtful selection of target background noise levels, mock-up testing, reverberation analysis, and construction administration help bring the solution set to a successful outcome. All of this helps to create a reduction in noise to ensure the quietude of these amazing apartments will be as pleasurable and exciting as the views afforded by the advances in structural technology.

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For author bios, please go to acousticstoday.org/bios-19-2-6

Conversation with a Colleague: Jordan Cheer

Jordan Cheer
Conversation with a Colleague Editor:
Micheal L. Dent

Meet Jordan Cheer

Jordan Cheer is the next acoustician in our "Sound Perspectives" series "Conversation with a Colleague" (see bit.ly/ATC-CWC for previous essays). Jordan is currently an associate professor in the Institute of Sound and Vibration Research (ISVR) at the University of Southampton, Southampton, United Kingdom. He received his BMus in music and sound recording from the University of Surrey, Surrey, United Kingdom, and his MSc in sound and vibration from the University of Southampton. He worked with the Signal Processing and Control Group in the ISVR for his PhD. We asked Jordan 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.

In everyday life, we are exposed to examples of sounds that we want to hear, such as our favorite music playing on our hi-fi system, and noise that we don't want to hear, such as the aircraft flying over our homes. Throughout my career, my research has focused on both how we can reduce unwanted noise and vibration and enhance or manipulate wanted sound. Early in my research career, I focused on how active sound control systems could be used to reduce unwanted sound, such as the road noise inside a car, or to generate spatially focused zones of audio reproduction to allow the driver in a car to listen to different audio than the passengers. Although seemingly distinct technologies, both rely on the same physical principles and utilize loudspeakers to generate carefully designed sound fields via constructive and destructive interference. My research has since expanded to consider how similar active approaches can be used to control vibration in structures, often with the ultimate aim of controlling the sound field radiated by the structure. Although the active technologies that much of my research has focused on have significant performance advantages at low frequencies, physical limitations occur at higher frequencies. Therefore, over the last few years, I have also begun to explore how the active control systems can be effectively integrated with passive systems to augment performance and capabilities in various ways; this has seen my team explore the integration of active control systems into passive acoustic and vibration-based metamaterials and acoustic black holes, leading to the unifying concept of intelligent structures for low-noise environments.

What inspired you to work in this area of scholarship?

My interest in sound stems from my background as a musician, but my curiosity about the technical side of acoustics grew during my undergraduate studies on the Tonmeister program at the University of Surrey, which covers both music and sound recording. This led me to join the ISVR at the University of Southampton for a masters, during which I completed my dissertation under the supervision of Steve Elliott and began my research in the field of active sound control. Initially, I focused on the realization of directional loudspeakers for audio reproduction, remaining consistent with my background in audio, but as my understanding of sound field control increased, I developed an interest in how the same physical principles can be exploited to control noise. Under the supervision of Steve Elliott, my PhD focused on combining these two areas within the context of the automotive environment, exploring how active control

https://doi.org/10.1121/AT.2023.19.2.61

can be used to reduce road noise, manipulate engine noise, and generate multiple independent listening zones within a car. This period of training in research under Steve's mentorship inspired my future research focus as well as my decision to pursue an academic career, where I have been motivated by being able to work in multiple industries including automotive, aerospace, maritime, and telecommunications.

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

In terms of research, I am probably most proud of my work on the active control of acoustic scattering. Having spent several years working on active sound field control with Steve Elliott at the ISVR during my PhD and first postdoctoral position, my work on the active control of acoustic scattering was my first work as an independent investigator. Around that time, there were several groups exploring the use of passive metamaterials for the control of acoustic scattering, with the aim of acoustically cloaking an object. My work, however, focused on the application of active strategies to control scattering.

This approach uses additional acoustic sources to generate a secondary field that is tuned to interfere with the unwanted primary sound field destructively, which in this case is the scattered field. Typically, active control strategies work well at low frequencies because the number of acoustic sources required to achieve control increases rapidly with frequency and so quickly becomes impractical. My initial research into active acoustic-scattering control, or active acoustic cloaking, explored how well-established insight into the physical limitations of active noise control and sound field reproduction could be used to build an understanding of the corresponding limitations for active acoustic cloaking.

This initial study into active acoustic cloaking was purely simulation based but provided a number of new insights that were critical in extending the work to practical applications. First, it provided a common framework for formulating the related sound field control problems of active noise control, sound field reproduction, and active scattering control. This common framework demonstrated that active acoustic cloaking is mathematically equivalent to actively canceling the primary sound field produced in the presence of the scattering object and then reproducing the primary sound field that would occur in the absence of the scattering object. However, more practically, and probably more intuitively, active cloaking must directly cancel the scattered component of the sound field.

Following the insight provided by the consistent formulation of the three sound field control problems, I used numerical simulations to investigate the physical limitations on active acoustic cloaking. In particular, the change in performance with frequency and both the number and position of the acoustic control sources were investigated. This highlighted the importance of locating the control sources close to the scattering object to maximize the control performance and also the frequency range over which effective cloaking could be achieved. Consistent with active control in general, increasing the number of control sources was shown to increase performance. However, from a practical perspective, it was interesting to show that relatively high levels of cloaking performance can be achieved with a relatively small number of acoustic control sources if they are located in close proximity to the scattering object.

The initial simulation-based study into active cloaking focused on the classical problem of scattering from a rigid sphere, but as a first step in taking the fundamental insights to a more practical application, the control strategies were also applied to the less straightforward problem of scattering from a rigid cuboid. These results showed similar physical limitations but also further highlighted the challenges to practically implementing an active acoustic cloak. This work consequently led to a number of follow-on research programs that focused on the experimental investigation of active acoustic cloaking, alternative active control strategies, combined passive-active cloaking strategies, various approaches to actuating control, and approaches to sensing the scattered acoustic field using remote-sensing techniques. As always, this subsequent research has probably raised more questions than it answered, but for me, finding out what you don't know is one of the most motivating things about research.

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

During my PhD, I was financially supported to work on active noise control for green city cars. However, my background and personal interest in audio systems led me to explore how similar sound field control techniques could be used in the automotive environment. This led to the investigation of how we can generate independent listening zones in a car cabin that allow, for example, the driver to listen to navigation while the rear seat passengers listen to music without disturbing each other. We developed the first system, at least publicly, that was able to generate independent listening zones in the front and rear of a car cabin, and this relied on a combination of headrest-mounted loudspeakers operating at high frequencies and the standard door-mounted car audio loudspeakers at low frequencies. The low-frequency performance relied on active sound field control approaches while the high-frequency performance relied on the proximity and directivity of the headrest-mounted loudspeakers. Although the performance of the system was some way from commercial exploitation, it seemed either to be quite timely or to motivate many other researchers and companies to explore the potential of in-car zonal audio.

More recently, I have become involved in research into acoustic black holes. The concept of acoustic black holes was established quite some time ago and generally relies on tapering the thickness profile of a structure to reduce the structural wave speed. The decrease in wave speed massively enhances the effect of damping treatments, and acoustic black holes thus provide a very weight efficient vibration control treatment. However, this only works well at frequencies above some cut-on frequency, but the performance is limited at lower frequencies. This limitation led my group to explore and make some useful contributions to the concept of active acoustic black holes. Our research in this area has demonstrated how combining the active and passive concepts into the acoustic black hole design can broaden the frequency range over which they can provide effective vibration control but also reduces the electrical and computational power requirements compared with straightforward active vibration control. This approach thus provides a very high level of vibration control performance and, in fact, reduces the weight of the structure.

Outside of my research contributions, I am extremely proud of my contributions to the supervision of graduate students. Helping to support and encourage their development is extremely rewarding, and helping them to fulfill their potential beyond their PhD studies feels like the most effective way of creating impact from my work.

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

Active control of noise and sound field control for audio reproduction are now both relatively well-established technologies. However, what is perhaps less well-established is how the two technologies interact from a subjective perspective and how they should be optimized in combination to best improve user experience in various scenarios. I find this challenge particularly interesting because it requires an understanding of active sound control to come together with psychoacoustics, user experience, and, most likely, some form of artificial intelligence. Therefore, there is not only the opportunity to make interesting contributions to the field but also to learn and collaborate more widely, which I find particularly motivating.

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Sounds Like Research: More Graduate Student Stories

Megan S. Anderson

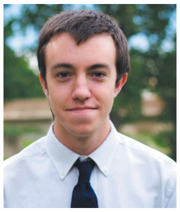
The Acoustical Society of America (ASA) is fortunate to have many talented student members from diverse academic backgrounds who are actively contributing to fields ranging from human health to animal ecology. The purpose of this essay is for the ASA Student Council to highlight some of these outstanding student members, with a particular focus on those who have recently completed their graduate studies or are nearing graduation. This is the second installment in our "Sounds Like Research" series (see bit.ly/3m6gdY0). The Student Council hopes that these articles will serve not only to showcase the innovative research being conducted by young ASA members but also to provide an opportunity for readers to "meet" members of the next generation of leaders in acoustics.

Victoria V. Doheny

(vdoheny@bu.edu; see bit.ly/VictoriaDoheny) graduated in May 2023 with a PhD in mechanical engineering from Boston University, Boston, Massachusetts. She has always been fascinated by how complicated medical problems can be solved using sound, and she gained early exposure to research in this area during an undergraduate Oak Ridge Institute for Science and Education (ORISE) research fellowship at the Food and Drug Administration (FDA). During this internship, Victoria studied the heating of bone and surrounding tissue due to ultrasound. This work inspired Victoria to apply to graduate school and pursue a PhD in biomedical acoustics. Her graduate advisor, R. Glynn Holt, introduced her to the added therapeutic effects that can be obtained using microbubbles in the presence of ultrasound.

> "Peritoneal adhesions develop from almost all deep abdominal surgeries. They can bind adjacent organs together, constrict or obstruct intestines, and cause chronic pain. Currently, there is no way of either diagnosing or treating adhesions without the patient undergoing a second surgery. This is counterproductive because a second surgery can cause more adhesions to form. Therefore, there is a critical need for imaging and removing adhesions noninvasively without causing additional adhesion formation. My research is on the detection and treatment of adhesions using targeted microbubbles. When exposed to ultrasound, these microbubbles oscillate and have the potential to break up soft, early-stage peritoneal adhesion tissue formed in the first 48 hours postsurgery. My dissertation focuses on characterizing the dynamics of these microbubbles under ultrasound exposure and determining the mechanism of nascent adhesion break up" (Victoria V. Doheny).

After graduation, Victoria hopes to continue in the field of therapeutic ultrasound as a postdoctoral researcher, deepening her knowledge of the applications for microbubbles under ultrasound exposure.



Daniel Guest

(daniel_guest@urmc.rochester.edu; see guestdaniel.github.io) graduated in May 2022 with a PhD in psychology from the University of Minnesota, Minneapolis. He summarizes his path into acoustics as a kind of domino effect in which "each research interest I've had has naturally led me in new directions, always orbiting around the broad themes of language, communication, information, and acoustics." His undergraduate studies in speech, language, and psychology led to a research opportunity studying the ways that voice pitch impacts our perception of speech. This research opportunity led to his interest in the fundamentals of how pitch is perceived by the human auditory system, which then led him to do graduate work in Andrew Oxenham's Auditory Perception and Cognition Laboratory (see apc.psych.umn.edu).

> "Pitch, which is the attribute of sound that maps onto the concept of 'low' and 'high' in speech and music, is

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important to how we experience the auditory world. Pitch perception is generally less accurate at high frequencies (above 4-8 kHz) than at low frequencies. My PhD sought to investigate the origin of this difference by combining behavioral techniques (measuring the sensitivity of human listeners to small changes in pitch, amplitude, and other features of sound at high frequencies) and computational techniques (building and analyzing computer models of how the auditory system responds to high-frequency sounds). My work suggested that differences in pitch perception at high frequencies likely do not originate in the early auditory system (e.g., cochlea, auditory nerve) but may originate instead in later stages (e.g., auditory subcortex)" (Daniel Guest).

This finding increased Daniel's interest in the auditory subcortex, leading him to his current position as a postdoc at the University of Rochester, Rochester, New York. As he dives deeper into speech communication research, Daniel hopes to continue cultivating cross-disciplinary relationships and finding new perspectives on classic problems in the study of the human auditory system.

Colin Malloy

(malloyc@uvic.ca; see bit.ly/ColinMalloy) will graduate in late 2023 with a PhD in interdisciplinary studies (music/computer science) from the University of Victoria, Victoria, British Columbia, Canada. As a musician, his entrance into programming was motivated by the desire to create custom audio effects. He soon realized that many of the existing audio effects did not work well for one of his favorite instruments, a type of drum known as the steelpan that originated in Trinidad and Tobago. In an effort to improve these audio effects, Colin began the acoustics studies that led to his PhD research with George Tzanetakis (see webhome.csc.uvic.ca/~gtzan).

"My thesis covers many topics surrounding the steelpan and music technology. The core of the work is the acoustical analysis of the steelpan, with studies ranging from the timbres produced using different types of mallets to the effectiveness of different pitch detection methods. More recently, I developed an AI-based steelpan pitch detection system that outperforms the available state-of-the-art methods. I view what I do as a holistic approach to analysis, processing, and application in musical performance. Acoustics starts the process and informs everything downstream while the issues I encounter in sound design and performance determine what aspect of the acoustics I will study" (Colin Malloy).

Colin's accomplishments include original steelpan compositions (see colinmalloy.com/crushed-atmos) as part of his PhD work as well as a 2022 Artist-in-Residence position at Ocean Networks Canada. Additionally, thanks to the skills he gained as a graduate student, Colin works as a contract digital signal-processing engineer. He plans to continue in the music technology industry after graduation, applying his acoustics knowledge to the design of new instruments and audio effects.

Christopher Pacia

(pacia.christopher@gmail.com; see bit.ly/ChristopherPacia) graduated in April 2022 with a PhD in biomedical engineering from Washington University in St. Louis, St. Louis, Missouri. He entered graduate school with a passion for acoustics as "the next frontier of innovative biomedical technology." His experience in Hong Chen's laboratory (see chenultrasoundlab.wustl.edu) affirmed this time and time again as he worked with others who were also dedicated to understanding disease diagnosis and treatments. Inspired by the new devices and the ways of thinking he witnessed, he pushed the boundaries of ultrasound techniques in the application of brain disease diagnosis.

"Brain cancer severely threatens human health due to its disruption of neurological function, poor prognosis, and substantial reduction in quality of life. Advances in patient care have suggested that the accurate diagnosis of molecular subtypes is critical for individualized targeted treatment and improving survival outcomes for brain cancer patients. This work provided evidence that combining focused ultrasound and microbubbles can release brain tumor-derived biomarkers into the blood circulation to improve the sensitivity for noninvasive molecular characterization of brain cancers (i.e., sonobiopsy). This enhanced capability could have an important impact throughout the continuum of patient care from brain disease diagnosis and treatment monitoring to recurrence detection. In addition, sonobiopsy could also support the investigation of disease-specific molecular mechanisms and accelerate the development of targeted therapy" (Christopher Pacia).

As his research and understanding of patient care progressed, Christopher's career goal became clear: *drive innovation and deliver solutions to patients in need.* He now uses his technical expertise as a life sciences consultant with the Triangle Insights Group, providing biotech and pharmaceutical companies with data-driven, patient-focused recommendations and helping deliver novel technologies that can transform patient's lives.

Morgan Ziegenhorn

(maziegenhorn36@gmail.com; see bit.ly/MorganZiegenhorn) graduated in August 2022 with a PhD in oceanography from the Scripps Institution of Oceanography, University of California (UC) San Diego, La Jolla. She first learned about acoustics as a method for studying animal behavior during her undergraduate studies at UC Berkeley, Berkeley. Morgan appreciated the large amount of information that could be obtained without disturbing the species of interest. She pursued graduate school with the goal of using acoustics to inform the conservation efforts surrounding marine mammals.

"My PhD research focused on using an existing passive acoustic monitoring (PAM) dataset to study toothed whales at several sites in the Hawaiian Islands region. PAM is an incredibly useful tool for studying these species because it provides us with cost-effective, continuous monitoring that's relatively noninvasive. However, this can result in a *lot* of unlabeled data. In my work, I leveraged machine learning tools to label over 10 years of near-continuous acoustic recordings for toothed whale species. This allowed for spatiotemporal analyses and habitat modeling that led to valuable ecological insights. I found that species' temporal behavior differed between sites even within the relatively small region of the Hawaiian Islands. I also linked longer term patterns in marine mammal presence to variations in climate indices. These insights expanded our current knowledge of toothed whale behavior in Hawai'i and beyond" (Morgan Ziegenhorn).

Morgan completed her PhD work under the supervision of Simone Baumann-Pickering (see sbaumann.scrippsprofiles.ucsd.edu) and John A. Hildebrand (see jahildebrand.scrippsprofiles.ucsd.edu) and then worked as a postdoctoral researcher at the Scripps Institution of Oceanography. She hopes that the research she has done on marine mammals will be useful to future researchers and species' managers, and she looks forward to contributing more to ecologically focused acoustic research in the future.

Conclusion

Through the introduction of these young researchers and their work, the ASA Student Council offers a glimpse into the future of acoustics research and the impact that these emerging leaders may have. We hope that this essay will inspire readers to learn more about both the exciting developments in acoustics research and the people behind those developments, perhaps even leading to future collaborations or job offers. We also invite you to say hello to these individuals if you see them at future ASA meetings! Connections between members of the ASA at all career stages enriches the acoustics community of today and prepares it for the innovations of tomorrow.

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Alan Lomax and Equality Through Recording

AJ Lawrence

Alan James Lomax was one of (if not) the foremost ethnomusicologists of the twentieth century. Lomax was a tireless promoter of folk music, discoverer of some of the musicians most influential to modern American music (see bit.ly/3Swh8gB) and was a campaigner for racial equality (see bit.ly/3XYkryt). His influence on American music is often unknown, but to those who know his story, it is crucial. Nobel Laureate and great American folk singer Bob Dylan said it best when, during a concert in August 1997, he paused and turned the spotlight to one man in the crowd.

> "There is a distinguished gentleman here (...) named Alan Lomax (...) Alan was one of those who unlocked the secrets of this kind of music. So if we've got anybody to thank, it's Alan. Thanks, Alan" (Greenberg, 2003).

Alan Lomax was born on January 31, 1915, in Austin, Texas (Szwed, 2010), and grew up in the then-wilds of central Austin's creeks and hills. His father, John Avery Lomax, was already a noted ethnomusicologist of Mexican and Texan cowboy songs. Precocious, Alan studied at both Harvard and the University of Texas (UT) at Austin. In 1933, the morning after he finished his junior year, Alan and his father got into the family's Ford Model A and embarked on their first trip, one fabled trip that would change their lives and American music at large. (Alan later graduated from UT Austin in 1936.)

This trip, backed by a small grant for collecting folk music from the U.S. Library of Congress, would bring the Lomaxes to all 11 southern state penitentiaries (Lomax, 2017), backwoods bars, sharecropped fields, and forestry camps, where they would record folk music in its environment for an entirely archival and noncommercial purpose. Jailhouse blues or labor songs, French-Creole *juré* music, and "sinful" songs coaxed out of their singers (songs with themes forbidden by their church) (Szwed, 2010) were all captured on their trip. Few of them were the traditional English ballads that dominated academic folklore collection and study at the time (Szwed, 2010).

In contrast, the specter of slavery was omnipresent on this 1933 trip. In some places, Alan and his father were denied entry once their aim was understood, and they resented when penitentiary hosts forced inmates to sing at gunpoint (Szwed, 2010). Race was not, however, considered by the Lomaxes when they were looking for songs to collect. Rather, they found that the most incredible music, the music they most wanted to preserve, was made by the most marginalized and downtrodden, the ones who would use song to keep the rhythm while laying railroad tracks with a team (see bit.ly/3Zq1HZG), keep the morale in punishing conditions, or keep the faith every Sunday in a black spiritual or hymn (a style that John later claimed had created the best songs America had, a style that held "no vestige of self-consciousness or artificiality"; see bit.ly/3Zqv1PR) (Lomax, 2017, p. 106).

The Lomaxes were not the first to record folk music in the field. A few others had, but it was still new and a technological marvel in portability (Lomax, nd). One goal in their trip was to find pockets of cultural isolation that may still hold folk music uninfluenced by urban culture and where most performers had never been recorded.

In their 1933 trip, the bulk of the recording was done on a custom machine acquired by the Library of Congress (Szwed, 2010). It took up the entire rear seat and trunk of their Ford, weighed over 315 pounds, and embossed (not cut!) a groove with a steel needle at 78 rpm in a blank aluminum disc. It required an AC motor and 75-pound Edison batteries to record for fewer than 8 minutes per side of aluminum disc. Recommended playback was with a sharpened wooden or bamboo needle or cactus thorn; the steel recording needle would ruin the record on playback. The sound quality was poor, limited in bandwidth (not helped by their carbon RCA public address microphone), and warbling (the AC motor driving the disc platter had no speed governor) (Lomax, nd; Szwed, 2010). The equipment also frequently broke down (Lomax, 1934), which was indubitably not helped by eventually traveling "16,000 miles" (Lomax, 2017 p. 96) in their car.

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Figure 1. *Lead Belly at the Washington Press Club between 1938 and 1948. Photograph of Huddie "Lead Belly" Ledbetter, courtesy of the Lead Belly Estate. Image available at the William P. Gottlieb/Ira and Leonore S. Gershwin Fund Collection, Music Division, Library of Congress, www.loc.gov/item/gottlieb.13561.*

They reached the Angola State Prison Farm near Baton Rouge, Louisiana, in July and found an inmate who, in Alan's later words, "performed with an incredible fire (...) Even in a world where there were hundreds of other great singers, (he) would be noticed" (Santelli et al., 2001). They wanted to record but were stymied by the equipment, having recorded only two sides with the then-unknown Huddie (*hew-dee*) Ledbetter, popularly known as Lead Belly (**Figure 1**).

My interest in this story began when, with my colleague Kyle Spratt, we discovered that the founder of our university-affiliated research center, the Applied Research Laboratories at UT Austin (ARL:UT), fixed Lomax's troublesome recording equipment in May 1934 and refused any payment (Lomax, nd). C. P. Boner, a prodigious researcher, an early member and former president (1963–1964) of the Acoustical Society of America (ASA), and a professor of physics at UT Austin, gave a laundry list of problems with the Lomaxes' equipment in a letter digitized by the Library of Congress (Lomax, 1934). A schematic found in the Lomax family papers at the Briscoe Center for American History, Austin, Texas, likely documents the new amplifier Boner built (Lomax, 1933). The schematic depicted a three-stage push-pull vacuum tube amplifier with transformer input, output, and interstage coupling that was remarkably like a schematic that can be found in the prior year's RCA Radio Handbook (RCA Radiotron Company Inc,. 1933). John soon wrote that they were now making "the best (sounding) records" in all their travels, the equipment being "far more durable," and their new recordings will "please even the most sensitive ear" (Lomax, 1934). This information was published, but ARL:UT's link to this cultural watershed was not known to anyone within the laboratories.

In July 1934, Alan and John Lomax returned to the penitentiary with the new equipment and Alan captured Lead Belly in his finest recordings (Lomax, nd). Lead Belly was soon released on good behavior and worked for the Lomaxes, unhappily driving their car and doing other menial tasks (Wolfe and Lornell, 1999). His story as a singing, double murderer was sensationalized by the press on their arrival in New York, New York, but his fame quickly faded. John took him on romanticized folklore lecture tours, forcing Lead Belly to perform for an audience in striped prison garb (Szwed, 2010), and their relationship soon soured. Alan remained on better terms with Lead Belly and got him performances in concerts and on radio.

Having published only six songs, Lead Belly died in 1949 (Wolfe and Lornell, 1999). The following year, the world-famous quartet The Weavers (including Pete Seeger) released a #1 hit single with a recording of Lead Belly's "Goodnight Irene" (see bit.ly/3Z2ljTY). Numerous remakes by other artists, including Creedence Clearwater Revival, Frank Sinatra, Nirvana, and the Beach Boys among them, followed, most of them traditional songs but in the performance style of Lead Belly (see bit.ly/3KDLuvZ turned into bit.ly/3y3C6Kw; bit.ly/3ZrKW0g turned into bit.ly/3KLVa7s).

After graduation, Alan continued recording in Florida, Haiti, and the Georgia Sea Islands (see bit.ly/3IFoVV8) among other locales. He noted commonalities between folk styles in these separated cultures that could be traced to African roots. He made it a principle to pay musicians their normal hourly wage and get them proper royalties despite the personal labor and often not having money for his own rent (Szwed, 2010).

Before, during his service in, and after the Second World War, Alan produced radio plays and pioneering documentaries, notably the first broadcast documentary that featured person-on-the-street reactions recorded the day after the attack on Pearl Harbor (see bit.ly/3EHcsyK) (Szwed, 2010). With CBS Radio, Alan produced a series of radio programs featuring Woody Guthrie and Lead Belly for the classroom that were centered on folk music were heard by an estimated 10 million listeners (Szwed, 2010).

Alan also played a part in the origins of the 1960s folk revival by organizing acclaimed multicultural concert series in Manhattan featuring folk musicians brought in from across the country. He also found sporadic work producing folk music albums from choice recordings in vaults of the big record companies. Some of these releases would also influence the folk revival, but the revival's darling Bob Dylan later claimed to be less influenced by the recordings because he hung around Alan's apartment and heard it firsthand from the performers themselves (Szwed, 2010).

One later and particularly successful collecting trip to Francoist Spain yielded the record that Gil Evans brought to Miles Davis and inspired the Grammy Award-winning album *Sketches of Spain* (see bit.ly/3kASrmT) (Szwed, 2010). A weeks-long recording session of oral history with a then-underappreciated Jelly Roll Morton yielded maybe the best account of the New Orleans, Louisiana, birth of jazz (see bit.ly/3maKfdb).

Later, Alan Lomax was asked by the American astrophysicist Carl Sagan to join the steering committee for the Voyager Golden Record, and almost half of the final choices were originally by Lomax. Reputedly, Debussy was left off in favor of folk music (Sagan, 1978) from the Navajo Nation, Bulgaria, Japan, Azerbaijan, and other cultures and were thus elevated in status next to Bach and Beethoven. During the 1960s civil rights movement in the United States, Alan Lomax worked with the Student Nonviolent Coordinating Committee (SNCC), a youthful wing of the movement formed to mobilize voters and demand constitutional protection of civil rights, to produce documentary albums as well as to bring folk musicians to play at rallies in Washington, DC (Szwed, 2010). Alan Lomax died in 2002 in Florida.

Alan Lomax was a tireless advocate for cultural equity, having found that it is often the marginalized who influence the urban culture, then the urban commercialism reflects and dominates the nation with their newfound performer. Throughout his life, Lomax argued that folk music is the property of the poor (Cohen, 2010; Szwed, 2010) and that they should be given their due equity in society in return. Alan intuitively grasped that folk music is a product of generations of isolation, hard work, survival, and spiritualism and joy and that those creators (or re-interpreters) are stakeholders in society, not because of their social status but because of the beauty of their music.

Acknowledgments

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Studying Acoustics in the United States: Exciting Opportunities for Young Acousticians

Erik Alan Petersen

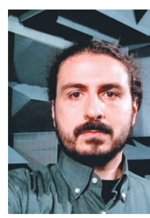
I am the 2022 *Acoustics Today* intern, and this is the second of two articles about the experiences of early-career acousticians who complete some portion of their training (master's, PhD, postdoc) in a foreign country. The first article (Petersen, 2022; see tinyurl.com/2t8recs3) focused on students from the United States who trained in other countries. This article centers on those who came to the United States to study. These articles are meant to provide helpful information to students who are considering such a move and highlight some of the difficulties faced by foreign students to foster a more empathetic academic environment.

Motivations and Initial Impressions

In preparation for this article, I spoke with early-career acousticians from a wide variety of cultural and academic backgrounds. Equally varied were their reasons for leaving home to study in the United States. Although everyone I spoke with faced unique challenges, all expressed positive sentiments and highly recommend the experience of studying in the United States to prospective students. I began by asking each person to describe their academic trajectory leading them to the United States.

Mourad Oudich (assistant research professor, Graduate Program in Acoustics, Pennsylvania State University, State College; see tinyurl.com/4rfa4zex) responded that "most of the time, you don't get choose the career you wish for," continuing "it often depends on the opportunities that come up." Originally from Morocco, Mourad studied in France and taught at the University of Lorraine, preceding a postdoc in metamaterials at the North Carolina State University, Raleigh. He remarks on the mentorship culture in the United States, commenting that there are ample opportunities for meeting other students/postdocs, professional development, grant writing workshops, and networking.

In contrast, **Agudemu Borjigin** (postdoc, University of Wisconsin, Madison; see tinyurl.com/nhkwap7x), who is from Inner Mongolia, China, and works on cochlear implants, had difficulty making friends with Americans during his master's program. He suggests forming study groups to interact with colleagues, although he notes that these friendships may be fragile and not continue when the course ends.



Although many foreign students are drawn to US institutions for their prestige and perceived greater opportunity, **Danilo Lombardo** (PhD student, City University of New York Graduate Center, New York) emphasized that the fit between student, advisor, and department is his top consideration. Born in Italy, Danilo moved to France, where he met his future advisor at a conference in Paris. Danilo comments that "many Europeans have roots in more than one country. Moreover, it is possible to meet a potential US advisor at international research events in Europe." As he prepared his application for the Speech-Language-Hearing Sciences program, he discovered additional barriers for foreign students such as needing notarized translations of transcripts and financial guarantors for the visa application. He advises prospective students to dedicate sufficient time while planning an international move within higher education.

Fernando del Solar Dorrego (PhD, Graduate Program in Acoustics, Pennsylvania State University, State College; see tinyurl.com/47wu4ed3) noticed that the family culture in the United States is different from his native Argentina, where he owns an architectural acoustics consulting

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firm and teaches at the Buenos Aires Institute of Technology, Buenos Aires, (www.itba.edu.ar). While a master's student at Penn State, he noticed that "in Latin America, multigenerational families are common, undergrads often live at home, so moving to the United States and living with housemates for the first time as a master's student may be very different from most Americans' experience."

Finding a suitable arrangement sometimes requires negotiation. Fernando, whose wife's career prohibited relocating to the United States, returned to Penn State to complete a PhD with an agreement with his advisor that he would conduct research on-site for the first several years and finish remotely from Argentina. Although not always possible, these atypical agreements do exist and do not emerge spontaneously; one may have to ask advisors or administrators for special arrangements.

It is important to choose one's advisor carefully. Although this is arguably good advice for all prospective students, **Miad Al Mursaline** (see tinyurl.com/mrxb4v28), a PhD student from Bangladesh working in underwater acoustics at MIT, Cambridge, Massachusetts, comments that if an "international student has a toxic relationship with an advisor and he or she is unable to find another advisor, the student cannot switch to another job in the United States." Before committing to a particular advisor, Miad recommends contacting current and previous students to learn about the professional environment.

Bertan Kurşun (PhD student, Department of Speech and Hearing Sciences, University of Washington, Seattle; see tinyurl.com/57vhxz98) is from Turkey and studied in Italy and Germany. He comments that furnished apartments are less common in the United States compared with some Europe countries, so he had a lot of unanticipated initial expenses. Furthermore, rental apartments often require a minimum salary that is higher than a PhD stipend. He emphasizes that it is essential to research the economics of higher education in the United States, especially regarding health insurance requirements in the United States and potential tax laws requiring filing in both countries.

Location

Although Fernando intended to return to Argentina, many students, such as Indian PhD student **Pratik Ambekar** (University of Washington, Seattle; see tinyurl.com/2xtwkaa4), arrive without plans postgraduation. Initially enrolled in a master's program, Pratik continued into doctoral studies with the same advisor. Although some students know where they want to go after graduation, more than one commented that they will decide based on the job market. Some, however, have specific considerations. Pratik is not considering a non-English-speaking country to avoid the complications of launching a career while learning a new language.

Mark Rau (Canadian PhD student, Center for Computer Research in Music and Acoustics, Stanford University, Stanford, California; see tinyurl.com/ykt9779t) had another important consideration: after years apart, living in the same location as his long-distance partner is an important factor determining his next move. Indeed, navigating long-distance relationships can be particularly challenging for foreigners, whose partners may not be able to obtain visas to visit or live in the United States. Even for those who receive long-stay visas, it may not be financially viable to support two adults on one graduate stipend.

However, long distances are not exclusively international; Mark comments that the distance between California and his home in Canada is not much further than the distance to New York. Indeed, the East and West US Coasts are geographically farther apart than Dhaka to Seoul or Buenos Aires to Quito.

Bertan was amazed by the variation of cultures within the United States, musing that perhaps domestic students may experience a similar degree of culture shock in a new city or state. Prospective international students should consider geography when applying to universities; a college town in the Midwest may be very different from a metropolitan campus.

Immigration and Citizenship

Acquiring a student visa can be challenging for citizens of certain countries. Although Mark was able to obtain a visa with minimal effort, Pratik and Miad described challenging visa interviews and assembling lengthy dossiers of supporting documents. Because the procedure varies between nationalities, it is important to understand the regulations pertaining to one's citizenship, including not just what is required to study in the United States but also what immigration and employment options are available on completion of the degree.

Not everyone has equal access to higher education. Higher foreign tuition and the expense of international travel to visit family are additional barriers that are not experienced by US students. Miad comments that foreign students who want to settle in the United States must work harder because they do not have the privilege of staying after graduation without a job to support their immigration status.

Another consideration is that access to certain funding sources, such as training grants issued by the National Institutes of Health, have citizenship or permanent residency requirements. Additionally, topics relating to national security may not be an option for foreign students who do not qualify for a security clearance and who may find themselves excluded from certain meetings or access to secured facilities. Foreign citizenship may rule out certain funding sources that are integral to the work of many in this profession.

Cultural Expectations

Ellen Peng (researcher, Boys Town National Research Hospital, Omaha, Nebraska; see tinyurl.com/45juczyz) is from China and trained in architectural acoustics in the United States and Germany. She found it difficult to understand culturally appropriate expectations. Once, in Germany, she was told sternly to leave the office when she had a cold. Going to work with a cold would have been acceptable, if not expected (pre-Covid), in her previous laboratories so being sent home was a shock.

As another example, Ellen mentioned a foreign student colleague who was asked by her advisor to complete personal errands, such as picking up dry cleaning. This student suspected it was an inappropriate task but did not know if it was culturally acceptable to challenge their advisor and how to approach a confrontation.

Ellen comments that it took time to learn how to fit into the professional community as a foreigner. As a young trainee, she was advised by several mentors to "mold herself in a certain way," although without providing any specific direction. This being an impossible task, she instead found that it was best to be herself, listen carefully, and try to always understand other people's perspectives. Her experiences adapting to new cultural environments have trained her not only for a career in research but also honed her interpersonal skills.

Foreign students often navigate microaggressions. Agudemu remembers vividly when colleagues would comment that, because he is Chinese, he must be good at math. Feeling self-conscious, Agudemu says these comments trigger imposter syndrome.

Communication

Communication, both verbal and nonverbal, was a challenge expressed by nearly everyone I spoke with. Agudemu warns that English in the United States is very different from his textbook instruction and more complicated than the Test of English as a Foreign Language (TOEFL) exam. During his first semester, he struggled to understand lectures and was challenged by different accents. However, he adapted quickly, and the second semester was much easier.

Despite these early challenges with English, Agudemu observes another microaggression: people still comment that he speaks English very well. Although at first, he would have been happy for this compliment, he wonders why people are still commenting on his language skills after so many years in the United States.

However, communication is not limited to language and varies between cultures. In Boston, Miad found that verbal communication is less direct than in Bangladesh. Early on, a faculty member asked if he would *like* to spend time on a particular problem. Interpreting this as a question, Miad prioritized another task, although in retrospect believes that the question was intended as a directive.

In the beginning, Miad struggled to interpret the emotional nuances of his American colleagues and occasionally found himself wondering what intentions they meant to convey. Similarly, Ellen comments that it can be challenging to "read the room" or understand the emotional atmosphere in a group of people when in a new culture. Clues that are obvious to some people, such as word choice, tone of voice, or body language, may not come easily to someone in an unfamiliar place.

As an example, Ellen imagines a foreign student at a conference, surrounded by new people. Someone makes an offensive joke and the student wonders "Should I laugh along?" In navigating these types of scenarios, Ellen developed strategies to listen and observe carefully, traits that have become part of her professional and personal communication style.

Summary

Over the course of writing these two articles, I had the opportunity to interview early-career acousticians from the United States and all over the world, covering a wide range of academic disciplines. Although I found a large diversity in motivations, experiences, and challenges, I am surprised by the communalities across this group of people. Most striking was the overwhelming positive reactions, both for those who left the United States and for those who came. In some intangible way, training abroad changes how we navigate the world and may have a lasting impact on our careers and lives. To those for whom it is possible, the people I interviewed (and myself), suggest considering a foreign country while planning their next career move.

Key Lessons

As I review these two essays, certain key lessons emerge that are applicable to both trainees who leave the United States and those who come from abroad. Although these suggestions arise from conversations about foreign training, many of them are applicable for early-career acousticians at all institutions. The key points are summarized here.

- It is important to find a good fit for a mentor/advisor/student relationship, a point that is especially true for international students who may need extra support navigating a new country. It is important to keep in mind, however, that just because an advisor has a great scholarly reputation, they may not necessarily provide the best training!
- Campus/departmental/laboratory cultures vary widely, so contact current and former students from the laboratory that interests you to learn what to expect before deciding to join. It is important to know if you will be supported by your future colleagues both academically and in social integration.
- Research the local culture. Even within a single country, there may be considerable differences in, for example, politics, diversity, and cultural expectations that may have a significant impact on the quality of life. Early-career training is an investment of time, so make sure you choose a place where you actually want to live.
- Cultural understanding and communication may be difficult, especially in the beginning. If applicable, devote sufficient time to learn a new language through classes and constant practice. Also, pay attention to nonverbal communication cues that may be different from what you are used to.
- Don't be shy to ask for help form your colleagues and mentors. There is often a community of foreign students who have gone through similar experiences and are willing to provide guidance.
- You may find peers through official international student organizations and informal groups, which are sometimes hosted as online forums or messaging apps.
- Organized extracurricular activities such as sports teams or music ensembles are a great way to make friends, meet locals, and learn a new language.
- Country-specific bureaucracy often poses significant challenges that will take time away from more important tasks. Learn about hurdles such as visas, bank accounts, health insurance, and tax laws early.
- Plans can, and often do, change; that is okay. Be compassionate with yourself and others and embrace mistakes.

Despite these challenges, everyone interviewed for these articles recommends the experience of training abroad — but know that it will likely change your perception of the world around you.

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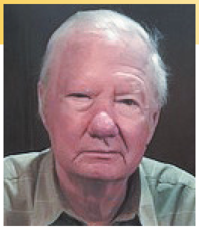
Obituary

Bryant Edward McDonald, 1944–2022



Bryant Edward (Ed) McDonald, a Fellow of the Acoustical Society of America (ASA) with a profound expertise in nonlinear physics and acoustics, passed away on August 6, 2022. Ed was born in Kentucky, grew up in Mississippi, and studied physics at Utah State University, Logan, receiving a BA in 1966. He received a MS in 1968 and a PhD in 1970 from Princeton University, Princeton, New Jersey. Starting in his undergraduate years, his signature style for approaching physics problems was his intuitive formulation with front-loaded physics to simplify the solution process.

Ed spent most of his career in Washington, DC, starting in 1970 at the Naval Research Laboratory (NRL) Plasma Physics Division; in 1980, he transferred to the Naval Ocean R&D Activity and then joined NRL's Acoustics Division in 1990, retiring in 2011. From 1997 to 2000, he was at the NATO Supreme Allied Commander Atlantic (SACLANT) anti-submarine warfare (ASW) Research Centre, La Spezia, Italy. His research trajectory intersected astrophysics, fluid dynamics, plasma physics, numerical analysis, oceanography, and ocean acoustics, including a sojourn into Jovian acoustics.

When Ed started his acoustics research, linear ocean acoustics models for *arbitrary* ocean parameters were plentiful. However, nonlinear equivalents only emerged when Ed took on the problem of ocean acoustic shock propagation. Because shocks have discontinuities, his derivation of the nonlinear progressive wave equation (NPE) was formulated as a pulse following process to eliminate, up-front, any subsequent requirement of a large, very fine grid and an irrelevant propagation timescale. Flux conservation methods to deal with the remaining numerical complexities had already been dealt with in his earlier research. The NPE became a standard tool in the Department of Energy Laboratories such as Los Alamos, Los Alamos, New Mexico. Ed continued this work, focusing on ocean boundaries, sediments, and shock propagation in the atmosphere.

Possibly motivated by his early-career work in astrophysics (his PhD thesis was on *Meridian Circulation in Rotating Stars*), he gravitated toward studying very long-range, global-scale acoustics. By including the distortion of the Earth's shape caused by rotation and the horizontal gradient in the ocean's acoustic index of refraction caused by the pole-to-equator temperature gradient, he was able to quantitatively explain the two received arrivals of a 1960 classic experiment in which sound from a 300-pound TNT explosion in the waters off Perth, Australia, reached Bermuda in about 13,000 seconds. He then applied his methods to explaining the long-range results of the Munk and colleagues' Heard Island Feasibility Test (HIFT) in 1991, the forerunner of ocean acoustic tomography to study global warming. His results agreed with the vertical structure received off California (18,000 km) and the pulse arrival structure received at Christmas Island (5,500 km). Subsequently, his acoustic research contributions included extracting signals from reverberation and nonlinearities of sediment acoustics, time-reversal acoustic-array processing, and surface and bubble acoustics.

On a personal note, Ed was an avid outdoors person, but the most rewarding part of his life was centered around his family. He is survived by his wife of 54 years, Kathleen; their two daughters, Leah and Esther; and four grandchildren.

Selected Publications of Bryant Edward McDonald

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