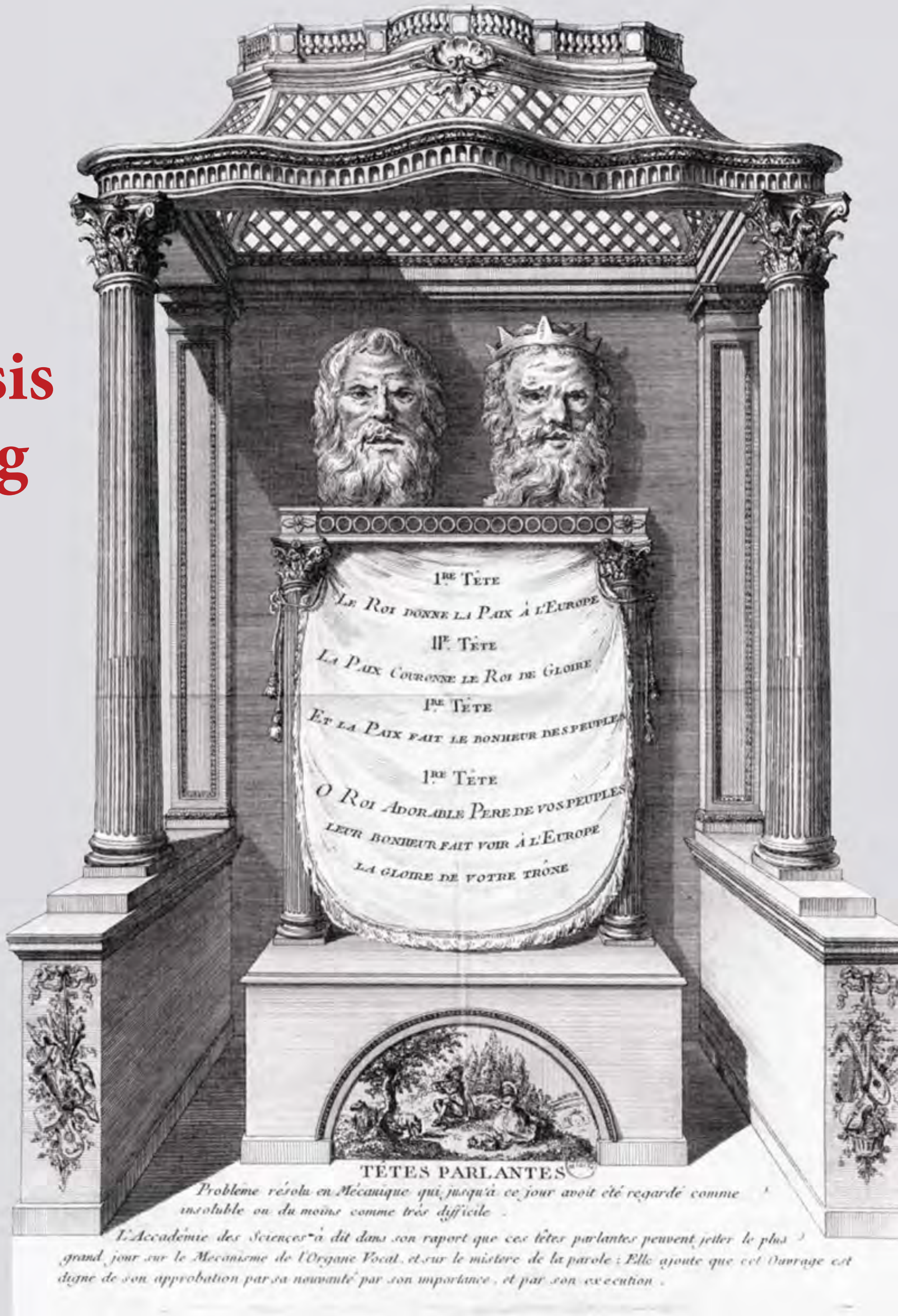
Volume 15 | Issue 2 Summer 2019

Acoustics Today

ASA A Publication of the Acoustical Society of America

Mechanical Speech Synthesis in Early Talking Automata



ALSO IN THIS ISSUE

- Satisfying Hunger, Thirst, and Acoustic Comfort in Restaurants, Diners, and Bars… Is This an Oxymoron?
- The Peculiar Acoustics of Rocks
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From "Mechanical Speech Synthesis in Early Talking Automata" by Gordon J. Ramsay. The "talking heads" of the Abbé Mical, exhibited in Paris in 1783. Illustration reproduced from the Bibliothèque Nationale, Paris, France, with permission. Copyright Bibliothèque Nationale, Paris, Gallica, ark:/12148/btv1b8410437r.

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Acoustical Society of America

The Acoustical Society of America was founded in 1929 "to increase and diffuse the knowledge of acoustics and to promote its practical applications." Information about the Society can be found on the Internet site: **www.acousticalsociety.org.**

The Society has approximately 7,000 members, distributed worldwide, with over 30% living outside the United States.

Membership includes a variety of benefits, a list of which can be found at the website:
www.acousticalsociety.org/asa-membership

All members receive online access to the entire contents of the *Journal of Acoustical Society of America* from 1929 to the present. New members are welcome, and several grades of membership, including low rates for students and for persons living in developing countries, are possible. Instructions for applying can be found at the Internet site above.

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From the Editor | Arthur N. Popper

One of my "pet peeves" is the increasing sound levels in restaurants. Dining out, with a rare exception, has become a hearing challenge: a challenge to hear the server and a challenge to hear your tablemates. Indeed, my wife and I have "discovered" that a much more pleasant evening is dining at home with friends because conversation does not involve shouting to be heard, not hearing much of what is said due to acoustic masking, and possibly developing temporary threshold shift (hearing loss) over dinner. And so, at a recent meeting of the Acoustical Society of America (ASA), when I heard a talk by Kenneth Roy, I immediately invited him to contribute to this issue of *Acoustics Today* (*AT*), an article he wrote with Keely Siebein. The article gives fascinating insight into the basis for high sound levels in restaurants and an appreciation of the fact that even if a restauranteur wants to lower sound levels, the challenges are great. I trust that most (if not all) members of the ASA will "relate" to this article, as did I. Indeed, I invite you to download copies and provide it to the manager of your favorite restaurants; maybe they will "get the message."

The first article also comes from a talk at an ASA meeting. There, Gordon Ramsay discussed the history of machines that produce speech. Although I was not at the talk, I heard about it from several colleagues and am delighted to have this fascinating article.

Our third article, by James TenCate and Marcel Remillieux, discusses the acoustics of rocks. This is an area I had not much thought about, but I think readers will find, as did I, that the acoustical properties of rocks are not only fascinating but also very revealing. And I suggest that readers also check out the Marcel's BioSketch and do a search for his French bakery. I wonder if it is quiet!

The fourth article by Bradley Treeby, Jiri Jaros, Eleanor Martin, and Ben Cox is another in what has become an informal series in *AT* that deals with use of ultrasound in biomedicine. In this fascinating article, the authors talk about how one predicts the path of ultrasound in the body, and it becomes apparent that the path is not simple to predict and is affected by many different aspects of the body tissues.

The "Sound Perspectives" pieces in this issue of *AT* are quite diverse. "Ask an Acoustician" features my old friend Sam Ridgway. Sam, who is often referred to as the "Dolphin Doctor," was the world's first marine mammal veterinarian. He continues to have a fascinating career that mixes medicine and extraordinary research on the biology of marine mammals.

Another essay is by another old friend of mine, Ed Walsh. Ed chairs the ASA Public Policy Committee, something I knew nothing about but which has the potential to hold great importance for all ASA members.

We also have an essay by a young friend of mine (no, I do not only ask friends to write essays, but it just happens that there are three such essays in this issue), Laura Kloepper. Laura is involved in a number of important ASA committees, but the focus of this article comes from a talk she gave at a recent ASA meeting on communicating science to non-scientists. Laura teaches this subject in very creative ways, and because it is an area that I think is very important and one relevant to all of us, I asked her to share her approach so that others might give some thought of adopting similar courses elsewhere.

The other two essays reflect support for the ASA Student Council and for the ASA Women in Acoustics committee. In a report from the Student Council, Kali Burke and William Doebler discuss ways that students can get more involved in ASA and the value of getting involved for developing networks that will be useful now and in the future. The idea of networking and its value is very much the theme of the essay from Tracianne Neilsen, Lauren Ronsse, and T. Christina Zhao from the Women in Acoustics group. This essay, which really applies to all ASA members, reflects on the need to develop networks and mentors throughout one's career.

Finally, I am pleased to announce that this issue of *AT* is the first with our new production team, Opus Design. The firm is located in the United States (Boston) and Germany, and it has exceptional experience in creative design. We don't anticipate much change in the design right now (though there are a number of subtle changes to improve the readability and look of the magazine), but down the road, as we and Opus get to know one another, we look forward to perhaps enhancing *AT* in interesting ways.

From the President | Lily Wang

Planning for the Next Chapter of the Acoustical Society of America

I have often referenced the 2015 Acoustical Society of America (ASA) Strategic Leadership for the Future Plan (acoustic.link/SLFP) in my From the President columns (acoustic.link/AT-Sp19-PC; acoustic.link/AT-W18-PC; acoustic.link/AT-F18-PC) when discussing the progress we have made in the four goals outlined in that plan. In my opinion, it has been tremendously beneficial for the ASA to have that map of where we wanted to go so that the leadership could make decisions that navigate the Society toward those goals. Time has passed, and it's now almost 2020, so the ASA leadership team felt that it was time to revisit our priorities for the coming three to five years. Since the fall of 2018, we have worked to define what the ASA should focus on next.

We hired a firm to guide the strategic planning process, and they began by interviewing 30 key stakeholders in September 2018 from diverse backgrounds, employers, and career stages, all of whom were ASA members. This was followed by a survey sent in October 2018 to all current and former ASA members and nonmembers who had attended meetings in recent years. We received survey responses from 2,635 persons, corresponding to a 36.4% response rate. Next, approximately 60 members spanning diverse technical areas, backgrounds, career paths, and career stages (**Figure 1**) met in Tucson, AZ, in February 2019 for a focused Strategy Summit. This group reviewed the gathered input, defined an ideal future for the ASA, and brainstormed potential strategic initiatives that could help us to achieve that vision.

In April 2019, the ASA Executive Council and staff convened at ASA headquarters in Melville, NY, to further prioritize the strategic initiatives developed in Tucson. The four areas of focus that the leadership synthesized from the gathered data, each of which is discussed below in detail, are

(1) identification and promotion of emerging scientific areas related to acoustics and its applications;
(2) better engagement with industry and practitioners in acoustics;
(3) improved communication, marketing, and public relations on the importance of acoustics; and
(4) continued member engagement, with a special focus on those who do not regularly attend biannual meetings.

Figure 1*. Attendees at the 2019 Strategic Summit in Tucson, AZ.* ***Top row:*** *D. Bouavichith, D. Farrell, F. Gallun, J. Lynch, L. Crum, A. Jaramillo, W. Murphy, V. Sparrow, M. Buckingham, E. Reuter, J. Phillips, T. Hoover, B. Moore, L. Kloepper, A. Piacsek, A. Morrison.* ***Row 3:*** *K. Jones, B. Schulte-Fortkamp, M. Vorländer, Y. Jing, S. Maruvada, C. Naify, T. Porter, B. Anderson, W. Coyle, S. Dosso, P. Nelson, M. Hamilton, W.-J. Lee, K. Gee, V. Keppens, M. Haberman.* ***Row 2:*** *A. Diedesch, T. Jerome, C. Holland, S. Fox, N. Blair-DeLeon, T. Bent.* ***Bottom row:*** *A. Lee, J. Gladden, M. Vigeant, D. Kewley-Port, E. Bury, K. Wilson, P. Gendron, L. Wang, S. Sommerfeldt, B. Reeder, J. Miller, J. Dubno, J. Ehl, D. Feit, P. Davies, J. Colosi.* ***Not shown:*** *M. Isakson, E. Moran, T. Smyth, C. Struck, P. Wilson.*

The qualitative and quantitative responses received from stakeholder interviews and the surveys were clear: the *top* priority of the ASA must be to stay true to our mission of generating, disseminating, and promoting the knowledge and practical applications of acoustics. The Society can better position itself to achieve this mission by proactively identifying and promoting emerging scientific discoveries and their applications in acoustics, more so than we have in the past. The challenges we face in achieving this are varied, including the difficulty predicting what emerging areas will have a long-lasting impact on our field. Also, the existing structures under which the ASA Technical Council is organized and operates may limit scientific cross-fertilization and the ability of the Society to integrate emerging areas nimbly. Although specific tactics toward achieving this goal have not been decided on, potential ones include

- hosting regular workshops on emerging technologies and issues related to acoustics;
- defining a number of interdisciplinary grand challenges in acoustics, similar to those announced by the National Academy of Engineering (engineeringchallenges.org); and/or
- dedicating more time to cross-disciplinary interactions and discussions at the biannual meetings.

We considered this strategic initiative to be most important and will be aggressively moving forward on tactics toward achieving this goal.

The second strategic initiative is to improve engagement with people who do not work in academic institutions, particularly practitioners, consultants, and those in industry. Currently, about 38% of ASA members are employed at a college or university, whereas 32% are consultants or work in industry, 9% are employed by government or government-related institutions, followed by other employer categories with smaller percentages. Responses from the gathered data clearly indicated that those who are not at an academic institution had different perceptions about the role and benefits of the Society than do academic members. Better engagement of those working in the practical applications of acoustics, while continuing to provide great value to those from academic institutions, will help the ASA to stay truer to its mission, as stated above, and can help position the Society to better accomplish the first goal of identifying and promoting emerging scientific areas and their applications. Multidisciplinary in all areas of the ASA is something for which the leadership believes the ASA should strive for because diversity of backgrounds, training, career paths, and career stages brings many voices to the table, making the Society stronger. Potential tactics in support of this goal could be

- offering technical sessions or workshops in partnership with industry and practitioners, focused on practical applications of acoustics;
- hosting a well-advertised career fair; and/or
- increasing the number of papers that the ASA publishes on the practical applications of acoustics.

The third priority initiative relates to one from the 2015 Plan on Awareness of Acoustics: we seek to improve communication, outreach, and public relations in all areas related to acoustics. We cannot be relevant if no one outside of our Society knows about what we do. The research revealed several key focus areas: communication and outreach to K-12 pipelines, funding agencies, governing bodies that oversee public policy, and society at large. Potential tactics toward this goal could be

- creating a proactive communication and marketing plan aimed at building and sustaining recognition of the relevance of acoustics;
- helping members to become more adept at science communication; and/or
- developing more standards, policy statements, and guidelines in acoustics that are relevant to our communities at large.

Finally, although the ASA has made improvements as to how we approach member engagement and diversity since the last strategic plan (acoustic.link/AT-F18-PC), continued member engagement is still a priority and has been identified as the fourth primary initiative. In particular, the data highlighted the fact that the ASA could improve the engagement of members who are unable to regularly attend the its biannual meetings. (A majority of members do not attend meetings!) Tactics to explore in support of this goal could be

- strengthening the regional chapters program so that members have an opportunity to engage with the Society at a more local level;
- offering more on-line professional development or continuing education opportunities for members at all levels; and/or
- sponsoring pop-up events in between meetings.

I am so grateful to all of you who engaged in the interviews and surveys. Your input has been invaluable in helping the leadership to outline these priority initiatives for the next three to five years. At the Spring 2019 Louisville Meeting, the Executive Council plans to approve the new strategic plan with these four primary goals, and then we will begin defining and implementing tactics to get this done. Your input and engagement is certainly welcome and needed for this next stage. What tactical ideas do you suggest toward achieving each of the above goals? As with the last strategic plan, we anticipate holding an open "Strategic Champions" meeting at each of the biannual ASA meetings. Please join us at these sessions to help prioritize, implement, and review tactics aimed at achieving these new goals.

If you do not regularly attend meetings, please do still send your ideas and consider engaging in the strategic initiative task forces or ad hoc committees tasked with moving these priority initiatives forward. These groups have typically met via teleconference between meetings, and I expect they will continue to do so. If you're not sure how to become a member of the task forces or ad hoc committees, please contact me (lilywang@unl.edu) or any other Executive Council member, and we will make sure to include you.

The ASA is a great Society, but we must not become stagnant, imagining that we will remain great in the long term without any effort or proactive initiatives. The strategic planning process helps to guide how we move forward, and I have confidence that we will have as much success with the coming plan as we did with the 2015 plan.

Finally, by the time this issue of *Acoustics Today* is published, my term as ASA president will have come to an end, and I will have passed the presidential baton on to Victor Sparrow. I look forward to remaining active in the Society, helping to achieve its ideal future as an engaged member. I encourage all of you to become more engaged as well. Send your ideas on potential tactics or participate actively on task forces and groups working toward these strategic initiatives! Visit the "Get Involved" web page (bit.ly/ASA-GetInvolved) to learn more about how to volunteer for other ASA administrative and technical committees. Donate to the Campaign for ASA Early Career Leadership to support a new recognition and leadership development program for early-career members (acoustic.link/CAECL). I'm looking forward to looking back with all of you in 10 years when the ASA celebrates its centennial anniversary and feeling proud about all that the ASA has accomplished in its first 100 years and how it has positioned itself well for the next 100.

From the Editor in Chief | James Lynch

The Journal of the Acoustical Society of America and _The Journal of the Acoustical Society of America Express Letters_ Update

I thank *Acoustics Today* (*AT*) Editor Arthur Popper for asking me to contribute a brief update about *The Journal of the Acoustical Society of America* (*JASA*) and its special section *JASA Express Letters* (*JASA-EL*) to supplement the editorial that appeared in the March 2019 issue of *JASA* (see doi.org/10.1121/1.5095417). One large function of the ASA Publications Program is to advertise the Acoustical Society of America (ASA) and its activities, including our journals, proceedings, and magazines. *AT* reaches a different audience than *JASA*, and so this extra communication will help us reach a much wider audience overall.

There is no need to reproduce the *JASA* Editorial here because it is freely available at the *JASA* site. However, before reading the *JASA* Editorial, I ask the reader for the patience to read further for a minute or two and then circle back.

The March *JASA* Editorial had two main aims: (1) to give a periodic progress report about what has transpired regarding *JASA* and *JASA-EL* over the past year and (2) to give the reader an idea of some of the coming changes in ASA Publications. I will let the *JASA* Editorial speak for itself on those topics but will also note that even in the brief months since that editorial, much has happened that will affect *JASA*, and I mention those particular things here.

The second "Summit" meeting of the Society in Tucson, AZ, in February 2019 (see From the President in this issue of *AT*), followed by a smaller meeting in Melville, NY, in April, were very noteworthy events because they will be very influential in charting the course for the Society and thus for ASA Publications. The first Summit (in Austin, TX, in 2015) had a profound effect on ASA Publications (see References in the March editorial), and the second Summit promises to do so as well.

Although the final reports were not available when this was written (April 25, 2019), there are (at least) two areas where we see major changes that will affect ASA Publications. The first is the plan of the Society to look carefully at possible new technical areas of scholarship and interest to supplement the areas that we already currently encompass. Keeping the Society up-to-date regarding technical foci is a must, and we fully expect that this will be reflected in the technical area headings that will be found in our publications in future years.

A second topic was increasing the emphasis of the ASA on "practice" in addition to its academic component. Toward this, we are already initiating a new section heading in *JASA* (tentatively) called "Acoustic Standards and Practice," where practice means the application(s) of acoustics as opposed to acoustical theory. We need the practice of acoustics to be represented in our journals, meetings, and other activities, and this new section heading is a first step as far as ASA Publications is concerned. By the time you read this, a separate, brief *JASA* editorial should appear on this topic, authored by *JASA* Editor in Chief James Lynch and Standards Director Chris Struck.

Another direction being pursued that wasn't mentioned in the *JASA* Editorial is that we will be exchanging overview articles with Chinese acoustics journals as a part of increasing our international outreach and presence. Chinese authors submit the second highest number of articles to *JASA* after US authors, and so China seems a very good starting point for this international initiative.

A final topic is the "changing of the guard" at the American Institute of Physics Publications (AIPP) regarding the journal manager for ASA Publications. For the past three years, Dr. Frederick Kontur has been our AIPP point of contact and did an absolutely fantastic job for us as well as being a pleasure with whom to work. Fred left the AIPP on April 19 for a job closer to his family in Pittsburgh, PA, and all of us at ASA Publications wish him the best! Succeeding Fred is Dr. Matthew Kershis. We welcome Matt aboard and look forward to working with him in the years to come.

I'll leave things here but with one small further note. Please don't forget to read the March *JASA* Editorial because there are some good bits in that as well!

Mechanical Speech Synthesis in Early Talking Automata

Gordon J. Ramsay

Address:
Spoken Communication Laboratory
Marcus Autism Center
1920 Briarcliff Road NE
Atlanta, Georgia 30329
USA

Email:
gordon.ramsay@emory.edu

Early attempts at synthesizing speech using mechanical models of the vocal tract prefigure modern embodied theories of speech production.

Introduction

Three centuries of scientific research on speech production have seen significant progress in understanding the relationship between articulation and acoustics in the human vocal tract. Over this period, there has been a marked shift in approaches to experimentation, driven by the emergence of new technologies and the novel ideas these have stimulated. The greatest advances during the last hundred years have arisen from the use of electronic or computer simulations of vocal tract acoustics for the analysis, synthesis, and recognition of speech. Before this was possible, the focus necessarily lay in detailed observation and direct experimental manipulation of the physical mechanisms underlying speech using mechanical models of the vocal tract, which were the new technology of their time. Understanding the history of the problems encountered and solutions proposed in these largely forgotten attempts to develop speaking machines that mimic the actual physical processes governing voice production can help to highlight fundamental issues that are still outstanding in this field. Many recent embodied theories of speech production and perception actually directly recapitulate proposals that arose from early talking automata.

The Voice as a Musical Instrument

By the beginning of the seventeenth century, the anatomy of the head and neck was already well understood, as witnessed by the extraordinarily detailed illustrations found in many books of the period (e.g., Casserius, 1600). An example of a mid-sagittal cross section of the vocal tract from the first anatomy textbook published in color (Gautier d'Agoty and Duverney, 1745), correctly reproducing all of the major anatomical structures, is shown in **Figure 1**. However, the exact function of the many different structures within the vocal tract and the origin of the human voice were still an active topic of discussion. From the earliest definition of the science of acoustics in the landmark article by Sauveur (1700) and even before, analogies were drawn between speech and music that drove much of the debate.

The first clear understanding that the geometry of the vocal tract directly shapes the timbre of speech was published by Marin Mersenne in his book *Harmonie Universelle* (Mersenne, 1636). In the sixth volume of that remarkable tome, Proposition XXXVI "explains how to construct a set of organ pipes, to pronounce vowels, consonants, syllables, and utterances," correctly inferring that appropriately manipulated tube shapes excited by a reed would produce corresponding speech sounds. Later, the focus shifted to the function of the larynx, with much heated argument about how the vocal folds were able to create sound. Dodart (1700) proposed that the glottis acts as a wind instrument, blown by air flowing over the edges of the hole between the vocal folds, whereas Ferrein (1741) claimed instead that the vocal cords vibrate like a string instrument, bowed by the air from the lungs. Reviewing the evidence from

https://doi.org/10.1121/AT.2019.15.2.11

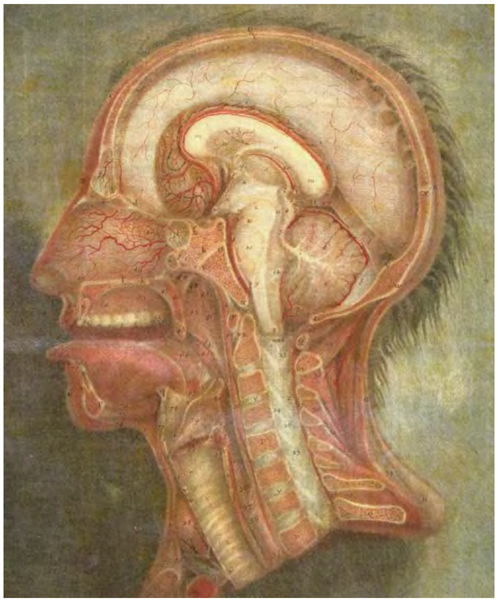

Figure 1. *Midsagittal section of the vocal tract from the first color anatomy book of the head and neck. All of the structures of the respiratory, oral, and nasal tracts are accurately labeled in exquisite detail, including the trachea (x), vocal folds (85), jaw (p), tongue (65), palate (54), velum (45), and lips (L, M). The flow of air from the trachea through the vocal folds into the oral and nasal cavities was clearly understood as was the vibration of the vocal folds; the shaping of the oral cavity by the jaw, tongue, and lips; and the action of the velum in closing off the nasal cavity during speech. Reproduced from Gautier d'Agoty and Duverney (1745).*

these apparently contradictory viewpoints, Ferrein himself, and later Vicq d'Azyr (1779), concluded that the vibration of the vocal folds, the shape of the glottis, and the glottal airflow could not be meaningfully separated and were all responsible for sound generation, in many respects predicting the modern myoelastic-aerodynamic theory of vocal fold vibration (van den Berg, 1958). By the middle of the eighteenth century, the analogy between the vocal tract and a very special kind of musical instrument was no longer in doubt. The open issue was how to "play" the vocal instrument to produce speech.

Mechanical Reproduction of the Voice

It took until the late eighteenth century for all of these early ideas by Mersenne, Dodart, and Ferrein to be fully explored and implemented. The basic component mechanisms underlying speech production were by now understood: a pair of lungs to create an aerodynamic flow, a pair of vocal folds vibrating under tension and blown by the glottal air flow to create sound, and a tube shaped like the vocal tract to form sound into speech.

Mechanical analogs were proposed, drawing again on comparisons with musical instruments: a pair of bellows for the lungs, a vibrating reed or membrane for the vocal folds, and organ pipes for the mouth and nose. Only the control mechanism and the confidence that a mechanical speaking machine could actually be built were lacking. These were provided by Vaucanson (1738), who constructed an automaton flute player that played tunes by blowing into a real flute. Drawing on a long history of mechanisms used in musical clocks and chamber organs (cf. Kircher, 1650), dating back to before the middle ages, Vaucanson ingeniously employed a revolving cylinder studded with pins to coordinate the timing and activation of a set of levers moving the articulators of his automaton, leaving physics to do the rest. Generalizing the same idea, Engramelle (1775) later published a monograph detailing how individual musical performances could be systematically transcribed onto pinned cylinders, as in a modern music box, and used to drive a mechanical organ for playback. These were the first examples of programmable musical instruments and also the first examples of musical automata designed to reproduce the actions of human musicians. It did not escape the imagination of contemporaries of both Vaucanson and Engramelle that the same mechanism could also be used to synthesize human speech (Doyon and Liaigre, 1966; Séris, 1995).

Kratzenstein's Vowel Tubes and Kempelen's Speaking Machine

The first instantiation of Mersenne's original proposal appeared in 1780, when Christian Gottlieb Kratzenstein, a professor in Copenhagen, won first prize for a competition proposed by Leonhard Euler at the Imperial Academy of St. Petersburg in 1777. Euler asked whether it might be possible to construct a set of organ pipes similar to the traditional *vox humana* stops, which would perfectly imitate the vowels *a, e, i, o,* and *u*. Kratzenstein (1780) responded by making five tubes of metal and wood (**Figure 2**) that he shaped by trial and error to produce approximations of the different vowel sounds when blown with a free reed. Notably, none of these bore any recognizable resemblance to the shape of an actual vocal tract.

At around the same time, Wolfgang von Kempelen spent 20 years making several attempts to create a mechanical speaking

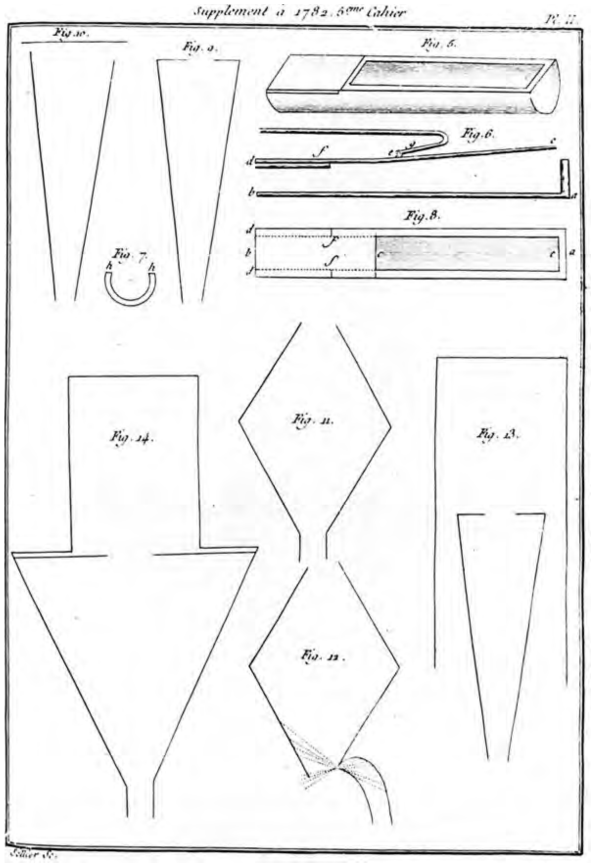

Figure 2. Kratzenstein's five vowel tubes for the vowel sounds a (two cross sections in Figs. 9, 10), e (Fig. 11), i (Fig. 12), o (Fig. 13), and u (Fig. 14), excited by a free reed (Figs. 5-8). Kratzenstein remarks that the passage from o (Fig. 13) to u (Fig. 14) is achieved by the stricture of the upper cavity. Reproduced from Kratzenstein (1780).

machine, as summarized in his famous book (Kempelen, 1791). After working on various pipe models like Kratzenstein, Kempelen eventually returned to analogies between music and speech. Inspired by a rustic bagpipe, he adopted the familiar model of wooden bellows, counterbalanced by a weight, to blow air through a vibrating ivory-and-leather reed mounted inside a box and venting through a flared gutta-percha tube, respectively simulating lungs, larynx, and mouth (**Figure 3**). In the process of developing his model, he thought carefully about the relationship between the detailed articulations of all the different parts of the vocal tract and the phonetic contrasts that he found to be important in different languages, realizing that many speech sounds can be compared and discriminated based on voicing, aspiration, frication, or nasality as well as the shape of the vocal tract. Accordingly, to the basic model he added nostril tubes that could be opened or closed; a means of damping the vibration of the reed to cut off voicing; an extra smaller side bellows that would inflate and then rapidly deflate as the mouth opening was closed off and released to create air puffs for plosives; two side tubes of different lengths bypassing the reed for fricatives; and, finally, a metal wire that could be pushed onto the reed to create a rattle resembling a trill. The bellows were pressed with the right elbow, and the levers and openings on the top of the main box were operated with the right hand to control the secondary modifications, while the left hand was partially inserted into the mouth tube and manipulated empirically to create the primary articulation of the sound. Modern reconstructions have shown that, in the hands of a skilled operator, unrestricted whole sentences can be produced intelligibly on demand, but the perceptual quality is far from natural, as everyone remarked at the time (Liénard, 1967; Brackhane, 2011).

These first two vocal tract models have been described in detail elsewhere many times (e.g., Chapuis and Gélis, 1928; Dudley and Tarnóczy, 1950) and are the most well-known but perhaps the least interesting of all the mechanical speaking machines. Kratzenstein's tubes reproduce isolated vowel sounds acoustically but fail to accurately simulate even the geometry of the vocal tract, let alone the underlying physics. Kempelen's speaking machine captures many of the physical mechanisms responsible for sound production in the vocal tract, albeit crudely, but totally sidesteps many of the crucial issues of articulatory timing and control by reducing the model to a passive musical instrument that needs to be harnessed back to the actions of a human musician. The shaping of the mouth tube, for example, is largely provided by the operator's hand and can only be learned through a great deal of practice and listening. The next two models ultimately resolved these problems.

The "Talking Heads" of the Abbé Mical

An almost exact contemporary of Kempelen, the Abbé Mical was an impecunious cleric, the younger son of a wealthy family from the Dauphiné in France who ran away from the church to pursue mechanics. From 1776 to 1785, he exhibited across Paris first one, then two, carved wooden "talking heads" that produced not only single speech sounds and syllables but also whole sentences and even an entire dialogue (**Figure 4**). On his request, his invention was examined by the Académie des Sciences, which appointed a committee of notable scientists, including Vicq d'Azyr, Laplace, and Lavoisier, to produce a report (de Milli et al., 1784; Chapuis and Gélis, 1928; Hémardinquer, 1961).

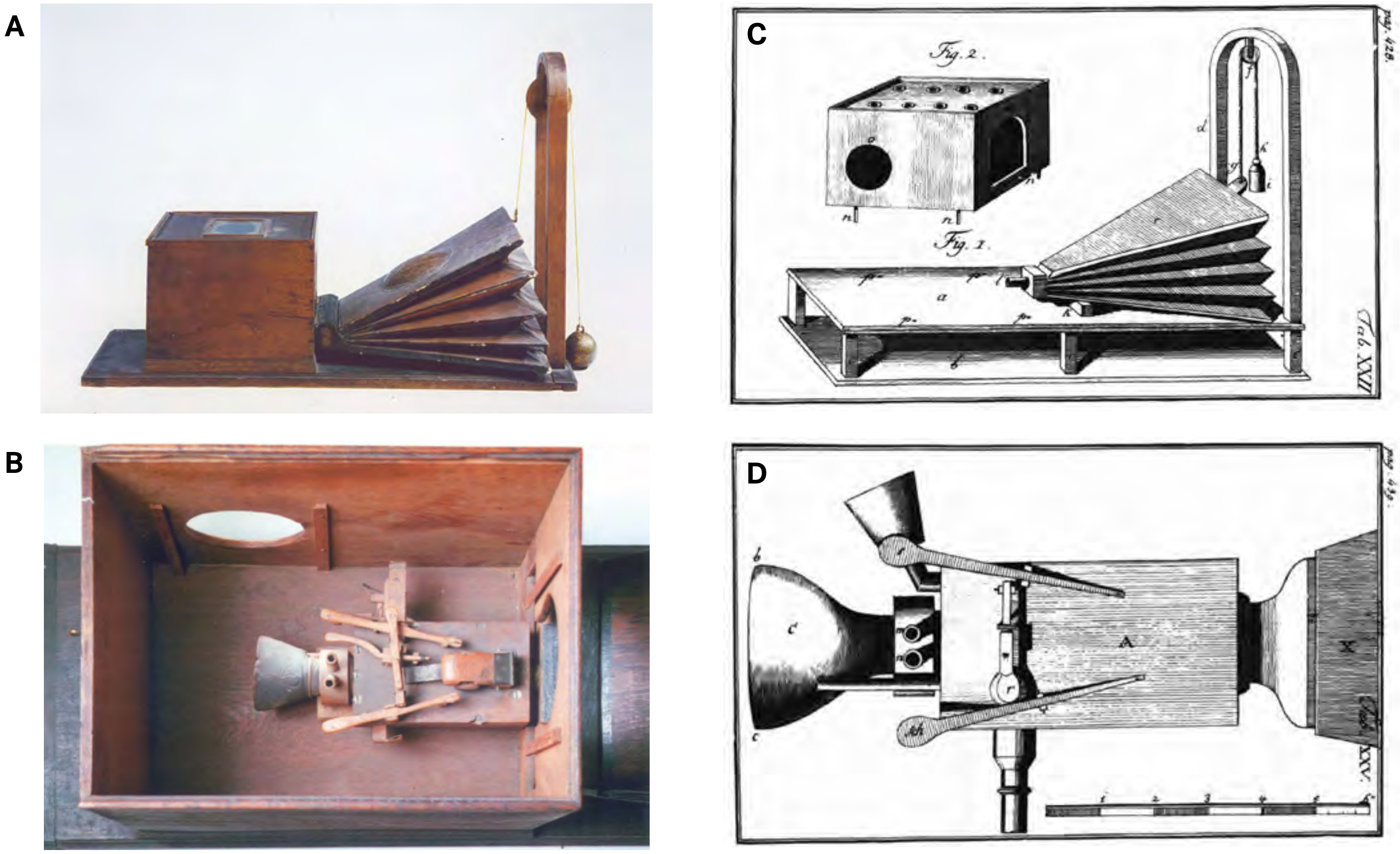

Figure 3. *Kempelen's speaking machine.* ***A*** *and* ***B****: photographs of the mechanism exhibited in the Deutsches Museum in Munich, Germany, thought to be a reconstruction of the original.* ***C*** *and* ***D****: corresponding illustrations from Kempelen (1791).* ***D****: details shown (see text for discussion) include the bellows (X), the box containing the vibrating reed (A), and the mouth tube (C); the other pipes (m and n) and levers (r and sch) are extra modifications needed for nasals, fricatives, and trills. Photographs reproduced from the Deutsches Museum, Munich, Germany, with permission. Copyright Deutsches Museum, München, Archiv, BN37402 and BN37404.*

The same elements persisted from previous attempts. A pair of bellows and a tube mimicked the lungs and trachea and a set of valves directed airflow into a collection of boxes. The entry of each box was covered with a leather diaphragm over an elliptical hole representing the glottis, while a parchment reed covering the hole vibrated like the vocal folds; by moving a metal tongue over the reed, the tone could be adjusted. The different actuators shaping the inside of each box simulated movements of the vocal tract with levers and shutters pulled by cords. Vowels and diphthongs were produced by connecting particular boxes in sequence. Stops were produced by rapidly opening and closing shutters over the ends of boxes. Fricatives were synthesized by silencing the reed and blowing air into the boxes. Trills were produced by a special vibrating reed. Syllables were produced by sequences of movements built into the actuators for each box. Unlike previous mechanisms, the boxes seem to have modeled dynamic articulations approximating specific consonant-vowel combinations.

Most importantly, following Engramelle and Vaucanson, a pinned cylinder was turned to activate the different articulations in sequence, and the position of the pins could be altered to program whole sentences. Examples of utterances given in newspaper reports from the period include single vowels, *a, e,* and *o*; diphthongs, *oa*; syllables, *pe, la, le, fe, fai, ra,* and *ro*; and the following extended series of sentences mimicking a conversation between the two heads that was presented before Louis XVI at Versailles in September 1783 (see **Figure 4** for translation). The 1st Head begins, "*Le Roi donne la paix à l'Europe*"; the 2nd Head replies, "*La paix couronne le Roi de gloire*"; the 1st Head responds to the 2nd head, "*Et la paix fait le bonheur des peuples*"; and then addresses the King, "*O Roi adorable, père de vos peuples, leur bonheur fait voir à l'Europe la gloire de votre trône.*" Public reaction was divided. Many thought the display was sensational as proof that speech could be synthesized mechanically, whereas others complained that they could barely understand what was being said.

__Figure 4.__ The "talking heads" of the Abbé Mical, exhibited in Paris in 1783. The dialogue spoken by the two heads is written on the curtain hiding the mechanism (see text for actual French): "1st Head: 'The King gives peace to Europe'; 2nd Head: 'Peace crowns the King with glory'; 1st Head: 'And peace makes the people happy'; and 1st Head: 'O adorable King, father of your people, their happiness shows Europe the glory of your throne.'" At the bottom of the display is the caption: "Talking Heads: A problem solved in mechanics that up to this day had been considered unsolvable, or at least very difficult. The Academy of Sciences has said in its report that these talking heads can throw the greatest light upon the mechanism of the vocal organ and on the mystery of speech. It added that this work was worthy of its approval by its novelty, by its importance, and by its execution." Illustration reproduced from the Bibliothèque Nationale, Paris, France, with permission. Copyright Bibliothèque Nationale, Paris, Gallica, ark:/12148/btv1b8410437r.

This mechanism is remarkable in the history of speech synthesis for several original contributions. The Abbé Mical's "talking heads" constituted the first automatic programmable speech synthesizer. They were the first synthesizer based on concatenation of phonetic units and also the first synthesizer based on replicating the serial ordering of articulations seen in the human vocal tract, using a form of demisyllable synthesis. Finally, as the examples above show, they synthesized the first dialogue between two machines. Against all of these advances is the undeniable deficiency that they seem to have relied on coordinating and switching between multiple separate mechanisms to produce the illusion of speech instead of controlling a single unified model of the vocal tract, which partly accounts for the poor and unnatural sound quality.

Faber's "Euphonia"

In the early nineteenth century, an Austrian mathematician and astronomer, Joseph Faber, came across Kempelen's book and built a replica of the mechanical speaking machine for himself. Quickly realizing the problems involved in playing it by hand, he determined to improve on the original design by turning it into a keyboard instrument to automate the means of control. Like Kempelen's machine, he used bellows and a vibrating reed as lungs and larynx to provide an airflow and sound source. However, he replaced the simple half-open mouth tube that Kempelen shaped by contortions of the hand with a fully configurable model of the whole vocal tract. By mounting six adjustable metal blocks back-to-back in a square box behind a pivoting tongue resting on a rotating jaw that terminated in a pair of moveable rubber lips, he was able to create tube shapes with front and back cavities that could be easily and directly related back to actual vocal tract configurations. As in a real vocal tract, the tongue, jaw, and lips moved to create simple opening and closing movements in the front cavity of the model, incorporating natural articulatory constraints, whereas the blocks behind resemble a six-section area function that could be used to create a more detailed shaping of the back cavity. Following Kempelen, Faber also added a more realistic nasal cavity, inserted a rotating vane to interrupt the airflow for trills, and used a moveable lever to alter the effective length of the reed, raising and lowering the pitch or cutting off the reed vibration completely.

The real ingenuity of Faber's talking machine, however, lay in the control mechanism. The jaw, tongue, lips, six blocks, nasal opening, vane, and reed were all controlled by a set of vertical rods such that the continuously adjustable heights of the rods entirely determined the configuration of the vocal tract model at any point in time. Faber connected the rods to a keyboard with 14 keys and 3 pedals, using a grid of cross-patched levers to transform each single key or pedal depression into a predetermined setting for multiple rods. He

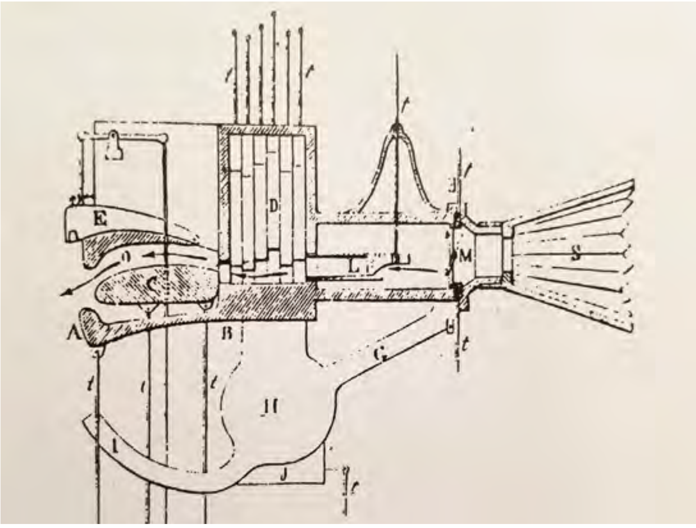

Figure 5. The mechanism of Faber's "Euphonia," illustrated by du Moncel (1882), showing the bellows (S), the vibrating reed (L), the trill mechanism (M), the moving blocks (D), the jaw (A and B), the tongue (C), the palate (E), the nasal cavity (G, H, and I), and the levers (t) connected to the keyboard; ***arrows*** *indicate the direction of airflow. Reproduced from du Moncel (1882).*

set up the keyboard mapping so that the keys would produce the following basic sounds: *a, o, u, i, e, l, r, v, f, s, ch, b, d,* and *g,* which we now recognize phonetically as subsets of vowels, liquids, fricatives, and plosives. One of the pedals controlled nasality and another controlled voicing and pitch, with the last pedal manipulating the bellows. By pressing different keys and pedals either together or in sequence while pushing air out of the bellows, any utterance that could be transcribed in terms of these basic articulations could be played on the keyboard and intonation could be added by continuously varying the pitch pedal. Spring loading in the key and rod mechanisms contributed inertia and damping, resulting in a smooth interpolation between adjacent sounds, approximating coarticulation. When demonstrating his invention, Faber would ask for sentences from the audience in any language, which he would then play back on the machine after transcribing them phonetically in his head, reportedly with a German accent. In London in 1846, he even managed to get it to sing "God Save the Queen."

A full description of the machine and its operation was published by du Moncel (1882), and the only known diagram of the mechanism is reproduced from that account in **Figure 5**. An illustration of the entire machine is shown in **Figure 6**, taken from a contemporary newspaper report in Paris in 1877, exactly one hundred years after Mical.

Faber called his talking automaton the "Euphonia" and first presented it in 1841, giving public performances almost continuously for many years until his death in 1864. Afterward, his invention was further improved and exhibited as the "Amazing Talking Machine" by his niece, Marie Trunka, and nephew-in-law, Samuel Husserl, until 1887. Fascinating accounts of the travels and travails of Faber's mechanical speaking machine can be found in Altick (1978) and Lindsay (1997a).

Faber's speaking machine is notable for many significant advances in the synthesis of human speech. For the first time, all sound production occurs by modulating the passage of airflow through a single tube shape, just like in a real vocal tract, whereas previous models had to coordinate multiple separate mechanisms to create different classes of sound, breaking the analogy between model and physics. Also for the first time, synthesis is controlled by direct manipulation of the vocal tract area function, under physiological constraints inspired by the articulators. Completing the gamut of musical analogies, this was the first keyboard instrument to successfully play speech, and this is scientifically significant because the keyboard mechanism encapsulated the need for coordination of multiple

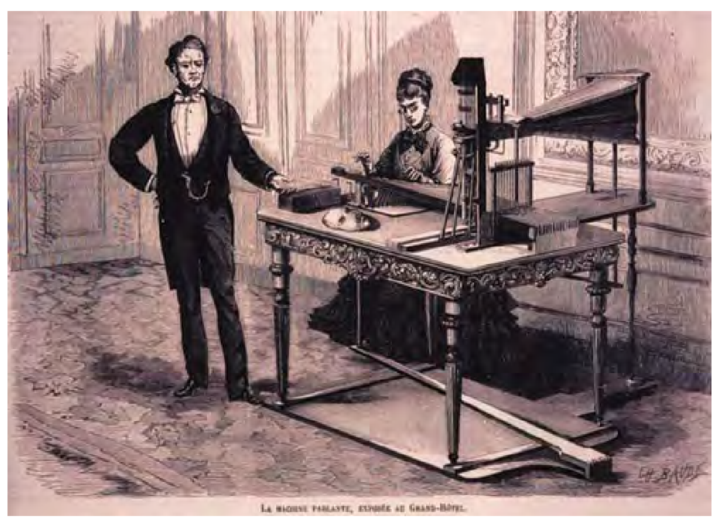

Figure 6. Faber's "Euphonia," exhibited at the Grand Hôtel in Paris in 1877 by his niece and nephew-in-law. This is one of the few illustrations of the whole speaking machine, showing the bellows driven by a foot pedal, the box containing the mechanism shown in ***Figure 5****, and the system of rods and levers linking the different articulators to the keyboard. Reproduced from L'Illustration (January 1877).*

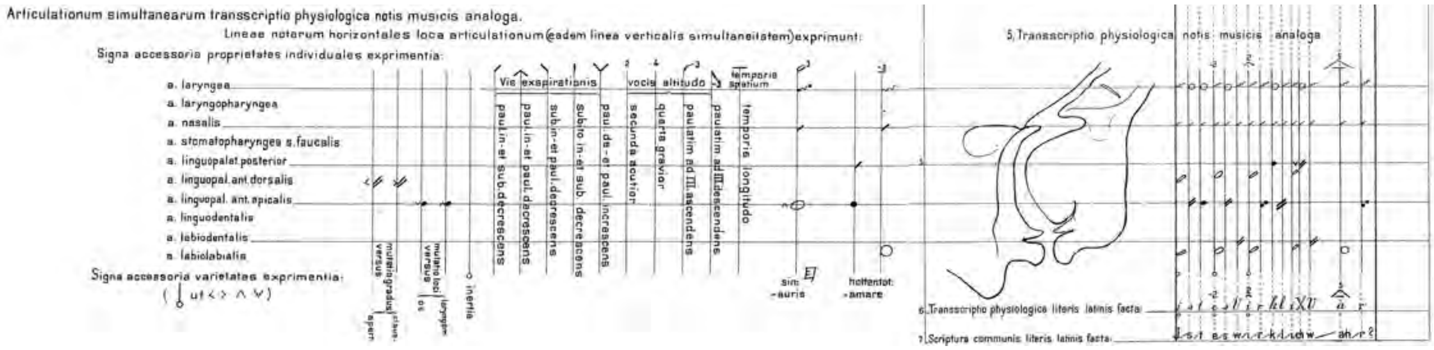

Figure 7. *Techmer's "articulatory score," inspired by early speaking machines. The caption reads "A physiological transcription of simultaneous articulations by analogy with musical notes. The* ***horizontal lines*** *of notes express the place of articulation, whereas the* ***vertical lines*** *express the simultaneity of articulations, with additional signs denoting individual properties of the articulations and their variants." Definitions of different signs are shown on the main chart. Two examples transcribing the Chinese word for "ear" (with a tone) and the Khoisan word for "to love" (with a click) are given to the left of the schematic vocal tract, while a full articulatory score for the German phrase "Ist es wirklich wahr?" is given on the right. Reproduced from Techmer (1880).*

vocal tract articulations, simultaneously and sequentially, to produce each single coherent unit of speech. This was also the first system for unrestricted real-time speech synthesis, allowing the performer to play any desired sequence of speech sounds based on concatenation of discrete phonetic units defined by the keys. It was the first system to systematically incorporate the synthesis of intonation and performed the first song ever sung by a machine. All of these achievements are quite remarkable for their time and represent the zenith of what was accomplished with mechanical synthesis until very recently.

Techmer's "Articulatory Scores"

Faber's "Euphonia" was exhibited across the whole of Europe, Russia, and America for more than 40 years, with hundreds of newspaper accounts of public demonstrations that often also refer back to Mical, Kempelen, and Kratzenstein. Although these speaking machines are now almost forgotten, they were well-known to the major scientists of the day, not only as public spectacles for entertainment but also as genuine objects of scientific inquiry into the nature of human speech (Lindsay, 1997b).

One of those scientists, Friedrich Techmer, developed an entire theory of articulatory phonetics based on his fascination with talking automata. In his "Habilitationschrift" from the University of Leipzig, published in 1880, he reviewed the last century of progress in speech physiology and phonetics and attempted to synthesize many of the principles embodied in the speaking machines, with which he was intimately familiar, into a practical method for phonetic transcription. Techmer (1880) proposed a symbolic alphabet of vocal tract constriction types as the fundamental units of speech. Revisiting the analogy between music and speech, he proposed that utterances could be represented in terms of such constrictions, organized according to an "articulatory score" by analogy with a traditional score in music. Different lines of the score represent independently controllable articulators; single notes represent the activation of specific articulators at particular points in time, whereas chords represent the simultaneous coordination of multiple articulator combinations to achieve particular constrictions. Critically, for the first time, the temporal as well as the spatial coordination of articulatory movements is explicitly represented, and timing becomes an intrinsic part of the representation of speech. The example he gave to illustrate his system, an analysis of the German phrase, "*Ist es wirklich wahr?*" is partly reproduced in **Figure 7**.

Techmer's system can be viewed as the natural extension to speech of Engramelle's earlier proposal for transcribing individual musical performances. It could potentially have been employed to combine Mical's programmable cylinder mechanism with Faber's vocal tract keyboard to yield a fully automated, programmable, mechanical speech synthesizer, realistically simulating the articulations and acoustics of a physical vocal tract to reproduce natural speech.

Unfortunately, popular and scientific interest in mechanical speech synthesis largely vanished with the appearance of

Edison's phonograph in 1877, and attention shifted to acoustic reproduction of the speech signal rather than simulation of the physical system that produced it, using the next new technology.

Modern Recapitulations? Links to the Prehistory of Speech Synthesis

When reviewing the history of mechanical speaking machines, it is remarkable how many of the problems and solutions that preoccupied whole generations of early speech scientists continue to reappear today, with striking parallels in modern theories of speech production and perception.

How is sound produced in the vocal tract? The source-filter model of speech production (Fant, 1960) was never explicitly articulated before the twentieth century, yet in all of the speaking machines there was clear recognition early on of the need for an aerodynamic flow from the lungs, a vibratory or turbulent source from the larynx, and the shaping of sound by a tube. Debates about the generation of sound by the motion of the vocal folds and glottal airflow that began with Dodart and Ferrein continue to be central to current research on aeroacoustics and fluid-structure interaction in speech (McGowan, 1992). Kempelen, Mical, and Faber all experimented extensively with different glottal geometries, making meticulous empirical observations about the influence of the glottal shape and vocal fold tension on airflow, vibration, turbulent noise, and the quality of the resulting sound. They realized the importance of damping the reed with leather and leaving a gap to bias the airflow to avoid irregular vibration and harshness. Experiments on excised larynges and mechanical analogs of the vocal folds continue this vein of inquiry to the present day (e.g., Birk et al., 2017), albeit with the added novelty of computer simulations. A further constant thread has been the realization that the mechanisms of human speech have parallels in vocal production across other species. Casserius (1600) includes comparative anatomies of the larynx in a variety of creatures (cf. Negus, 1929), whereas Vicq d'Azyr (1779) and Kempelen (1791) both consider in detail analogies between sounds and sound production in humans and other animals (cf. Fletcher, 1992).

Which vocal tract shape produces what sound? Understanding the complex many-to-one relationship between vocal tract geometry and acoustics is a perennial theme. Puzzling to all of these investigators was the difficulty in deriving appropriate tube shapes corresponding to particular speech sounds, perhaps because they lacked the ability to see inside the vocal tract but also because of the laws of physics. The low-frequency eigenmodes of the vocal tract are only sensitive to long-wavelength perturbations of vocal tract geometry, so any tube that replicates the macroscopic shape of the quasi-1-D area function regardless of microscopic 3-D details will approximate the same resonances (e.g., Ungeheuer, 1962), which is the origin of the inverse mapping problem. Following the modern tendency toward increasingly overdetailed 3-D vocal tract models, Faber chose to bring his machine closer and closer to an actual vocal tract to be able to exploit physical constraints, whereas Kratzenstein, Kempelen, and Mical perhaps intuitively understood that extreme spatial accuracy or exact reproduction is not always needed, as long as a functionally equivalent tube shape is somehow achieved by hand or box. Kratzenstein's tubes, which sound like vowels but look nothing like vocal tracts, are the classic example.

How is the vocal tract controlled, and what are the underlying goals and units of speech production? For all of the speaking machines, progress toward intelligible synthesis was only made when the temporal dynamics of speech began to be accurately captured, either mechanically, as in Mical's programmable cylinder, or by harnessing human action systems to bootstrap the sequencing of vocal tract movements, as in Kempelen and Faber's wind and keyboard instruments. Mical's attempts at concatenative synthesis using fixed demisyllabic units were less successful than the flexible manual coarticulation that Kempelen's speaking machine allowed. The solution afforded by Faber's keyboard, which succeeded in yoking multiple articulators together in sequence as composite actions to realize the discrete sounds played by each key, is directly analogous to the modern concept of "coordinative structures" in task dynamics by which multiple end effectors are flexibly co-opted to realize a sequence of goals (Turvey, 1990). In the same light, Techmer's "articulatory score," which relates those goals to an alphabet of vocal tract constrictions that function as embodied phonological symbols, has striking parallels with the influential theory of gestural phonology proposed by Browman and Goldstein (1992). Articulatory control and timing have always been central theoretical and practical issues in speech, then as now.

All of these examples demonstrate that mechanical speaking machines were not simply idle amusements but rather can be considered as early attempts at fully embodied theories of speech production, successfully tackling problems that continue to preoccupy research in speech communication into the present and proposing solutions that continue to be echoed in current research. Now that embodiment has returned full cycle as a theme, it can be hoped that the historical undercurrent of productive research on mechanical speaking machines will be more fully appreciated and once again merge with the mainstream.

Acknowledgments

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BioSketch

Gordon Ramsay is an assistant professor in the Department of Pediatrics, Emory University School of Medicine, Atlanta, GA, and also director of the Spoken Communication Laboratory at the Marcus Autism Center. He received his PhD in electronics and electrical engineering from the University of Southampton, UK, and was a Marie Curie Research Fellow at the Institut de la Communication Parlée, Grenoble, France, for two years. His research focuses on mathematical models of speech production and perception and early vocal development in infancy.

Satisfying Hunger, Thirst, and Acoustic Comfort in Restaurants, Diners, and Bars... Is This an Oxymoron?

Kenneth P. Roy

Address:
LeShanShui Consulting LLC
136 Magnolia Drive
Holtwood, Pennsylvania 17532
USA

Email:
kenneth.p.roy@gmail.com

Keely Siebein

Address:
Siebein Associates, Inc.
625 NW 60th Street
Suite C
Gainesville, Florida 32607
USA

Email:
ksiebein@siebeinacoustic.com

We all go to these places, but how can we ensure that the acoustic environment will be conducive to our needs?

It's Probably More Than Just Food and Drink!

All of us go to a restaurant or diner for food and drink, but unless you are going alone, you will probably wish to have a conversation with your companion(s) while enjoying a meal. Or, if you are on the way to a bar and grill, then you may also be interested in watching "the game" on the oversized TV(s) or even listening to "live music."

Once you enter the eating establishment, the issue of acoustic comfort comes into play; it is part of the interior environmental quality (IEQ) associated with an architectural space. We, as a matter of course, talk about building IEQ in offices, in health care, and in schools and especially so if designing to meet green or well building ratings. But we have not, to date, seriously focused on this aspect of architectural performance for hospitality spaces such as restaurants, but we certainly need to do so.

People have noticed that noise in restaurants seems to be ever increasing, and more recently, this issue has gotten the attention of both researchers and restaurant customers. A Special Topics Session on this subject was presented at the December 2017 Acoustical Society of America (ASA) Meeting in New Orleans. At that meeting, a paper was given by Faber and Wang (2017) that provided analyses of crowdsourced sound levels in both restaurants and bars in New York City. In total, sound level surveys were collected from 2,376 restaurants and bars using the smart-phone app SoundPrint (soundprint.co). Noise levels were categorized as "low," "moderate," and "high," with high levels being over 76 dB(A). By comparison, normal voice levels are generally taken to be about 60 dB(A) when conversing with someone at about an arm's length, so the measured noise levels in eating establishments are easily 2-4 times as loud as a normal speaking voice.

We discuss SoundPrint more fully in **SoundPrint and Crowdsourcing Sound Levels at Restaurants**, and the Faber and Wang (2017) paper has an extensive list of references for anyone who is interested in more information on this topic.

Architects Design to Meet a Mission

When an architect sets out to design/build a new building, the focus has to be on meeting the mission for that building's use. For an office building, the mission is simply to have a place to do "work." For a school building, the mission is for a place to "learn," whereas for a hospital, it is to have a place to "heal." So, following this approach, what is the mission for a restaurant, diner, or bar and grill?

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The mission for food service (hospitality) probably needs to include meeting the customers' expectations for both the food and drink and for the social aspects of a shared experience. Hospitality covers a wide range of establishments, so accordingly we can anticipate that the expectations will be rather broad, which is why this particular segment of the building market is more difficult to define and as yet not adequately addressed in terms of acoustic comfort.

Service and Expectations!

In the case of an upscale restaurant, one's expectations are for great food and a quiet acoustic environment that allows for casual conversation. After all, the diner is often there with friends and family or is trying to conduct business. However, when one heads off to a "fast food" restaurant or diner, the expectation is for good food and not too stressful communication because one is there primarily to eat and to take a break from life. But when one is at a bar, the expectation is to communicate in a loud voice at close range and maybe even communicating by "text" as opposed to "voice" because the primary expectation is usually the entertainment. But even within these examples, "a bar... is not a bar... is not a bar," means, for example, that a hotel bar at the Marriott carries different expectations than the bar at Jimmy Buffett's Margaritaville.

You have probably heard the saying that "restaurants managers want their property to sound loud and busy because it's good for business." Really? Activity noise is, of course, expected with high occupancy, but does it need to be unmanageably noisy? In fact, many people walk out of restaurants and bars on occasion because the establishments were either so loud that it was uncomfortable due to the noise level (it hurts!) or too loud because the diner wanted to have a conversation with friends across the table.

So then, what is the mission that a food service facility needs to meet, especially with reference to acoustic comfort? We know that there are noise problems because there is dissatisfaction and complaints relative to acoustic comfort, and these are being communicated by the restaurant rating services such as provided by *The Washington Post* (wapo.st/2HbjG11) or Yelp, and these now include comments on the noise environment, at least as a subjective rating such as "quiet or noisy."

And we can expect even more comments about the noise environment because simple smart-phone apps such a SoundPrint are now available and allow anyone to make a noise reading on-site and in real time (some apps are reasonably accurate) in decibel noise level. Surely, the owners do not consider losing customers due to unmet expectations on noise to be a good thing for business; now do they?

Customer Wants and Needs

And what is it that we want: good food, good drink, a pleasant environment, and the appropriate level of acoustic comfort to meet the needs for a specific choice of establishment. Here is a short list of some possibilities:

- A restful environment after a day of hard concentration (low-noise annoyance, quiet music);
- The need to have casual conversation for business or personal matters (moderate noise level, good speech intelligibility, and adequate speech privacy); or
- A wish to enjoy social interactions with sports or music entertainment (significant sound level OK, limited direct conversations OK).

Acoustic factors such as noise level, reverberation, speech intelligibility, speech privacy, and sound quality are all part of the acoustic environment and relate to architectural factors including the size, shape, and surface treatments in each building space.

Architecture and Acoustics

As we have learned in the design and performance of offices, schools, and health care, architecture has a strong impact on the acoustics of any building space, and this holds for the hospitality industry as well. The architectural design (size, shape, and surfaces) of each building space determines the clarity of speech at any point within a room, and the level of background noise in conjunction with the speech clarity will determine the intelligibility of speech (think schools; see ANSI/ASA S12.60, 2010; Brill et al., 2018).

So, what do we know specifically about the relationship between architecture and acoustics in restaurants? Many times, restaurants suffer from excessive loudness and reverberation, harsh reflections, and echoes. But architectural acoustics (the science of sound as it pertains to buildings; Sabine, 1922) is a bit of an enigma because most restaurant patrons and owners don't know that there can be a way to solve their noise problems because they are not even aware that this is a field of study and that engineering solutions are available.

A starting point used to analyze the acoustic environment of restaurants is to calculate the average midfrequency absorption coefficient of the space. The midfrequency content of human

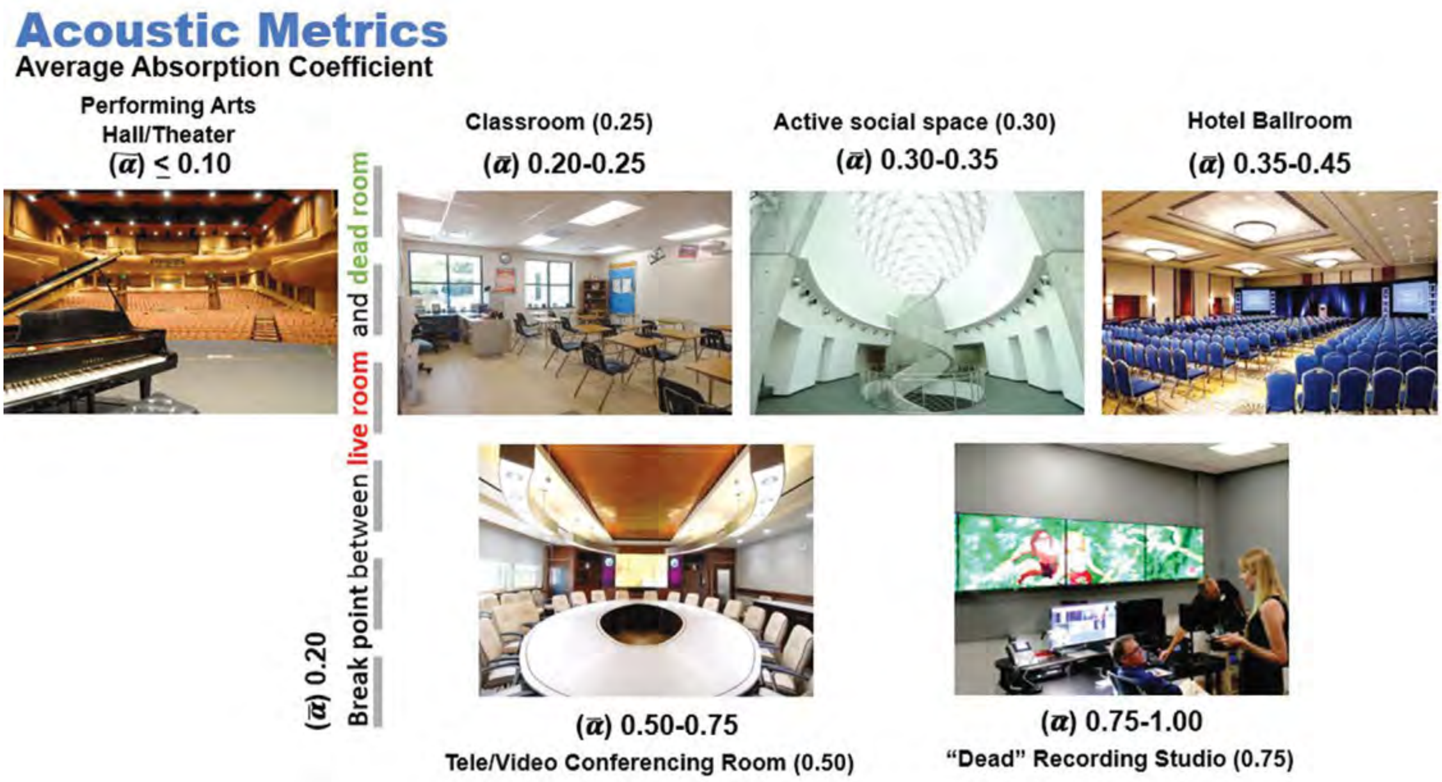

Figure 1. *Examples of various rooms and a typical average coefficient* ($\bar{\alpha}$) *associated with each of them.*

speech is what is important in determining both speech intelligibility and speech privacy, both of which will be important in restaurant acoustic comfort. Each surface in the room is either acoustically reflective or absorptive. Every material absorbs or reflects sounds to some extent across the frequency range in which people can hear.

Equation 1 is used to calculate the total sound absorption in the room. This is done by summing the surface areas of the various materials in the room multiplied by their respective absorption coefficients. The total sound absorption in the room is then divided by the total surface area in the room using **Equation 2** to get the average absorption coefficient ($\bar{\alpha}$) for that room.

The total sound absorption in a room is

$$A = S_1\alpha_1 + S_2\alpha_2 + .. + S_n\alpha_n = \Sigma S_i\alpha_i \tag{1}$$

where A is the absorption of the room (in m^2 sabins), S_n is the area of the actual surface (in m^2), and α_n is the absorption coefficient of the actual surface.

The $\bar{\alpha}$ for the room is

$$\bar{\alpha} = A/S \tag{2}$$

The $\bar{\alpha}$ in a room is a number that falls between 0 and 1. Zero means a room that is completely sound reflective, and 1 is a room that is completely sound absorbent. Most practical rooms will fall somewhere in the middle of this range, not being either too reflective or too absorptive. **Figure 1** gives examples of typical rooms and their corresponding $\bar{\alpha}$ values to show where various room types may fall within this range. For example, a concert hall (see Hochgraf, 2019 for a related article) or a music recital hall may have very little sound-absorbing material (but instead having very carefully angled reflective surfaces that direct sound to where it needs to go), therefore having an $\bar{\alpha}$ of 0.10 or thereabouts. Whereas a hotel conference room or ballroom, with carpeted flooring, acoustic ceiling tile, and acoustic wall panels, may have an $\bar{\alpha}$ of 0.35. And a specialty recording studio designed to be acoustically "dead," with almost every single surface as sound absorbent as possible, may reach $\bar{\alpha}$ values of 0.75 or so.

Analysis of over 20 dining spaces that suffered from sufficient acoustic issues to drive the owners to call in an acoustician had a variety of materials in the rooms, with some establishments having almost no sound-absorbing surfaces (meaning hard floors, walls and ceilings), whereas others had some absorbing materials, as shown in **Figure 2**.

Acoustic Design in Restaurants

The rooms that had absorbing materials but still needed interventions often had the absorbing material on the floor in the form of carpet. Some rooms had heavy carpet and drapes along the windows, yet still resulted in unsatisfactory acoustic environments. Where the absorbing material is installed matters! Certainly, adding absorbing material anywhere will cut down on the amount of reflected energy in the room (to some extent), but putting it in areas where sounds are more likely to actually interact with the material will result in a more favorable acoustic environment. As more absorbing material is added to the space, the $\bar{\alpha}$ gets higher.

It is also very important to think beyond the simple equations that we use to calculate "bulk" performance variables such as the average absorption coefficient and consider the above discussion. Once while teaching a design workshop in Mexico City, an architect asked if it was possible to solve the noise issue in one of the most famous restaurants in the city in a simple way. The architect wanted to know if putting acoustical treatment under all the tables and chairs would solve a "big" noise problem. The entire workshop group talked through this proposed solution and came to the conclusion that the likely outcome would be a 1 dB level reduction because no more than one-half of the floor area could be covered, and even if this was done, the likelihood of getting sound up under the tables and chairs was not so good.

The untreated rooms that required acoustic treatment had an $\bar{\alpha}$ of 0.12, with a range of 0.05 to 0.23, as seen in **Figure 3, *red,*** as the "untreated" option. Adding absorbing materials to 50% of the walls or ceiling resulted in an $\bar{\alpha}$ of 0.20 (which is typically considered the "break point" between an acoustically live room and a room that begins to absorb sound). This step might be considered a "first pass" in attempting to control excessive reverberation.

However, if a more subdued environment is desired, adding sound-absorbing material to more than 50% of the wall or ceiling surfaces will result in the next tier of treatment, which has an $\bar{\alpha}$ of 0.27. Treating 80% or more of the ceiling surface,

Figure 2. *All of these restaurants suffered from acoustic defects and all having a varying amount of absorbing material.* ***Top:*** *Heavy carpet, drapery, and upholstered seating.* ***Center:*** *Mainly reflective materials.* ***Bottom:*** *Acoustic ceiling tile (in grid).*

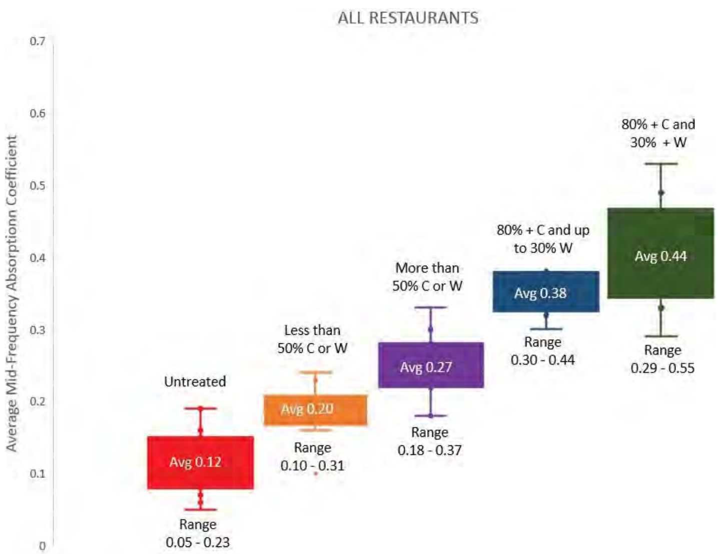

Figure 3. *Average absorption coefficients associated with various amounts of absorbing materials in restaurants. C, ceiling; W, wall;* ***color blocks****, average absorption coefficient of the actual surface ($\bar{\alpha}$); vertical bars, ranges of measured α values. Averages for $\bar{\alpha}$ are 0.12, 0.20, 0.27, 0.38, and 0.44, respectively.*

in conjunction with up to 30% of the wall surfaces, will result in an $\bar{\alpha}$ of 0.38. And treating 80% or more of the ceiling surface and over 30% of the walls will result in an $\bar{\alpha}$ of 0.44. In most restaurants, it is difficult to treat more surfaces than this due to the number and locations of windows, lighting fixtures, mechanical ducts, etc. Accordingly, the $\bar{\alpha}$ of a restaurant typically tops out around 0.44.

The higher the average absorption coefficient, the more sound will be absorbed by the room surfaces. So, if a restaurant is to offer a quiet, subdued environment, where people can talk quietly, it is important to use larger amounts of sound-absorbing material on the available ceiling and wall areas. If a venue is to have a more "energetic" feel, less sound-absorbing material should be used but that material should be used in strategically placed areas that have the potential to get louder than others.

Using no absorbing material in a restaurant, however, often results in acoustic environments that are uncomfortable and become excessively loud, even in places that want a more "energetic feel." This is typically why noise is considered one of the chief complaints of patrons of restaurants. Many restaurants have no acoustic material; they have hard floors, with painted gypsum board walls and ceilings. Some restaurants have acoustic ceiling tiles, but older establishments may have "refreshed" the space with a new coat of paint, so the ceiling tiles are often old and painted. Unless the tiles were spray painted with nonbridging paint, the paint seals up the surface of the tiles and essentially reflects sound back into the room, making the tiles that would previously absorb sound actually reflect it.

Technical Analysis of Intelligibility in Restaurants

The speech transmission index (STI) is "an objective measure used to predict the intelligibility of speech transmitted from talker to listener" (British Standards Institution 2011, BS EN 60268-16) or how well speech is heard and understood from one person to another. The STI was calculated in 13 untreated restaurants that suffered from poor acoustic environments (Siebein and Siebein, 2017). The STI values for the untreated restaurants ranged from 0.49 to 0.75 when unoccupied. To give context, according to BS EN 60268-16, an STI of 0.50 is considered the target value for voice alarm systems (a life safety system designed to provide spoken emergency alerts in a building but may also include background music or other nonemergency signals); a STI of 0.58 is considered a "high-quality public address (PA) system"; an STI of 0.70 is considered "high speech intelligibility"; and an STI of 0.76 or greater is considered "excellent intelligibility but is rarely achievable in most environments." This may be why in these 13 restaurants, one could clearly hear conversations from other diners at other tables when the restaurant was minimally occupied.

The STI for patrons sitting at the same table should be maintained as high as possible in all situations to optimize the ease of communication among those diners. Assuming no other patrons are in the area and the background noise is quiet, the STI value here will be higher, meaning that speech will be more likely to be understood. It is desirable to maintain high STI values for this situation under all conditions. The STI from locations across the room should be minimized under all conditions to limit the buildup of noise that would reduce the STI across the table. Generally, the more sound absorption present in the room, the higher the STI value.

However, the background noise level also has a significant relationship to the STI. In a dining or social space, average background noise levels of 77 dB(A) (Scott, 2018) are often found. The "background noise" is the voices of all the other diners speaking at their tables reflecting across the room

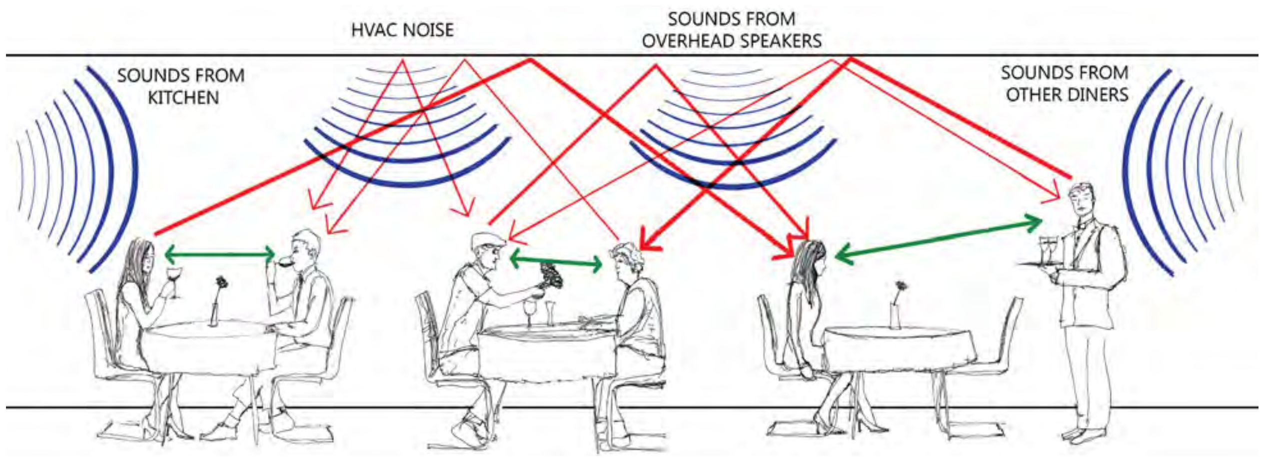

Figure 4. *Diagram showing communication paths between multiple people seated in a restaurant. Assuming that the seating area is full and the background noise is high, the speech transmission index (STI) value here will be lower, meaning that speech will not be understood very well.* ***Green lines****, direct speech;* ***thick and thin red lines****, reflected speech;* ***blue curves****, other noises such as the air diffusers.*

to other seating locations as well as the sounds of dining including the clanking of dishes, preparation of food, bussing tables, and cleaning.

An analysis was also performed of the same 13 restaurants where an "occupied" environment was simulated. When the same rooms were simulated to be occupied with more patrons, the STI levels decreased to a range of 0.21 to 0.31. These STI values are considered "bad or poor" according to BS EN 60268-16 and perhaps provide some confirmation of users' experience that they are unable to understand conversations clearly at their own table, especially when the restaurants are more fully occupied. **Figure 4** shows conceptually what happens when many sound sources are present in a restaurant, making it more difficult to carry on conversations.

SoundPrint and Crowdsourcing Sound Levels at Restaurants

The SoundPrint app has the potential to make restaurant owners and operators aware of whether the sound levels at their venue are acceptable to patrons or not, with the idea of hopefully inspiring them to change their acoustic environment when needed. The app combines basic sound level meter technology with crowdsourcing functions that essentially allows restaurantgoers to measure sound levels in an establishment and report them to the SoundPrint database, where they can be stored and viewed by other members. The restaurants that receive data are ranked into four categories: quiet [70 dB(A) or lower], moderate [71-75 dB(A)], loud [76-80 dB(A)], and very loud [81+ dB(A)]. The founder of SoundPrint, Greg Scott, initially created the app as a way to find a quiet spot to take a date in New York City. The idea springboarded, and users all over the United States have begun measuring and submitting their sound levels to the database. According to Scott, the SoundPrint app has, to date, received data of over 60,000 sound samples in 30,000 venues around the world, the majority within the United States. The database will be expanded to countries abroad soon.

This kind of app gives restaurantgoers the power to report venues that are too loud, make management aware that noise issues exist, and hopefully open a dialog for the owners/operators to engage in and determine how they can tone down the space to make it more acceptable to patrons. The app is being used not only in restaurants but in bars and coffee shops and recently in retail stores, movie theaters, libraries, and arenas! In a sense, it is a way of educating the public about building acoustics and the importance of good acoustic design in buildings.

What Can or Should Be Done About Acoustic Comfort in Restaurants?

The concept of "proper acoustics" in places of public accommodations including restaurants, diners, and bars has been an ongoing issue for quite some time. ASTM International (formerly the American Society for Testing and Materials) considered writing a standard 20 years ago for the measurement/performance of such spaces, but it died an uncertain death during development because no consensus could be found on specific acoustic requirements that would be acceptable to all the interested parties (owners, workers, and users). Then, in 2017, the ASA was requested to look at the possibility of writing such a standard, and, to that end, a special session on "Restaurant Acoustics" was sponsored by the ASA Panel on Public Policy[1] at the Boston meeting. Since then, additional special sessions have been offered and more test data have been collected, but what to do next?

The normal practice for the development of acoustic standards generally follows a defined path that starts with design practice and ends with building codes and regulations. To date, design knowledge for the acoustics of these spaces is generally available to architects, engineers, designers, and consultants, often based on research into the design practice and performance as previously discussed. Design guidelines for restaurants tend to be internally held by the owners. For instance, chain "fast food" restaurants such as McDonalds and Burger King usually have model design standards for their buildings. However, despite all the talk about "noisy is good for turnaround," the fast food industry has certain model building specifications that include acoustic ceiling tiles, usually in the form of 2-foot × 2-foot suspended ceilings. Although their first consideration is likely to be installation costs, accessibility, and esthetics, acoustics is being provided in the suspended ceilings despite the contention that noisy is good. Really?

Can We Quantify or Qualify Acoustic Comfort?

One can choose to address acoustic comfort in restaurants in either of two ways. The most obvious approach is to address the need for acoustic comfort in hospitality using the same methods and metrics currently used in other building segments, which would be a quantitative mode using measurement and performance standards. A second but more qualitative mode would be to develop a classification standard.

We certainly know how to go about accomplishing the first option, and the tools for doing so are shown in **Figure 5**.

ASTM International is well-known for its portfolio of acoustic measurement standards, and these are referenced in the ANSI/ASA S12.60 standard for acoustics in classrooms, for example, where both measurement and performance standards are applied. This is not difficult to specify for schools

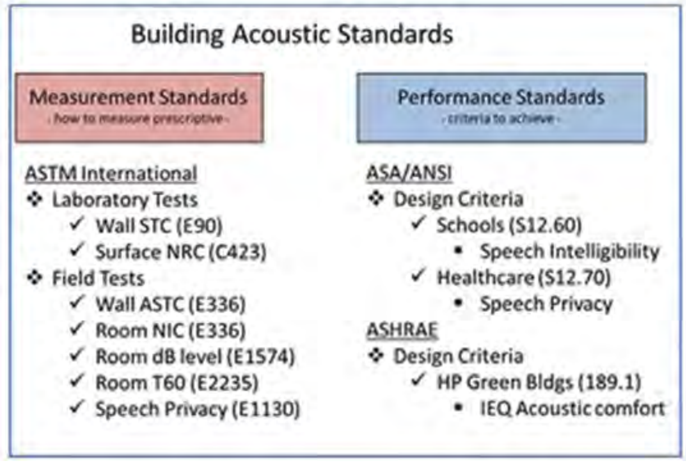

Figure 5. *Measurement and performance standards for quantitative approach. ASA/ANSI, Acoustical Society of America/American National Standards Institute; IEQ, indoor environmental quality. STC, sound transmission class rating; ASTC, field-measured apparent STC; NRC, noise reduction coefficient rating; NIC, noise isolation class rating; HP, high performance; T60, reverberation time; ASHRAE, American Society of Heating, Refrigeration, and Air-Conditioning Engineers; terms in parentheses, actual test standard designation by ASTM International, ASA, or ASHRAE.*

because all classrooms need a good listening environment for students to learn from the teachers (Brill et al., 2018; Leibold et al., 2019), and so the focus is on speech intelligibility. Additionally, many classrooms are architecturally very similar in size and shape, making the acoustic needs relatively easy to define.

Restaurants, diners, and bars, on the other hand, have a list of requirements including speech intelligibility, speech privacy, annoyance, and entertainment, and within these, there is a range of conditions for each acoustic factor depending on the type of establishment, time of day, or day of the week. So, treating a restaurant in the same way as a school does not make a whole lot of sense without addressing a very complex set of requirements. Although it may be possible to develop a range of performance requirements for acoustic comfort in the hospitality building segment, this may take a significant level of research and "buy-in" from all the interested parties (owners, customers, and employees). This is why a previous attempt by ASTM International to take this approach was not successful. Accordingly, we may wish to take a more simplistic approach just to get started, and then see where this may lead.

[1] *See Sound Perspectives essay on this panel by Walsh in this issue of* Acoustics Today.

How to Qualify Acoustic Comfort

A simple way to qualify acoustic comfort would be to develop a classification standard such as that which is currently being developed at ASTM International for the classification of electronic sound masking systems for use in architectural spaces. This rating approach for electronic sound masking is intended to give the designers and users a method to choose wisely in providing the degree of performance needed when a consistent level of speech privacy is necessary, for instance, in offices and health care facilities. So, what kind of subjective classification might work in the hospitality market? One approach is to model the system of classifications in a similar way as was done on ski slopes (see **Figure 6, *left***).

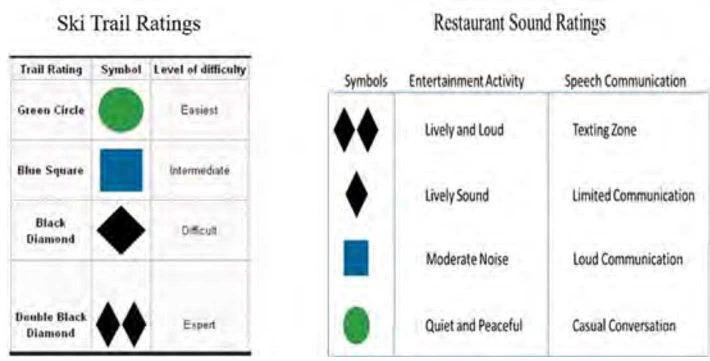

Figure 6. Left: *classification system used in downhill skiing.* ***Right:*** *proposed classification system for use in restaurants.*

When standing at the top of a ski slope, we see visual indicators that grow increasingly ominous as the degree of difficulty increases, starting with a green circle (bunny slope) and ending with a restrictive-looking black double diamond (dare devil, i.e., cliff). This is a rating scheme that could also be implemented in the hospitality building segment by adapting the descriptive columns to reflect the pertinent factors related to "acoustic comfort." We know from the previous discussion that some customers will be expecting a quiet space for casual conversations, whereas others will be looking for a lively and loud space for music entertainment. We are trying to address customer satisfaction that is based on their expectations, So how to proceed?

Why not give the customer a "heads-up" on what to expect in different areas of a restaurant or bar? We could ask the owner to label the various areas within the hospitality space according to customer expectations. This might look like what is shown in **Figure 6, *right***. It should be noted that the entire purpose of this system of classifications is to satisfy the expectations of the customers who have chosen to go to this establishment relative to the acoustic environment that they will find when there. If the customer is satisfied, then the owners will be delighted. In any case, the issue of noise as relates to the employees will be covered under the US Occupational Safety and Health Administration (OSHA) occupational noise regulations.

And How Might This Work?

The business owner may wish to post a sign (as seen in **Figure 6, *right***) at the entry of the establishment to alert the customers that acoustic comfort has been rated by room or space within the building and that each space will have a visual notification at the entry to the space. A placard with the appropriate symbol can be affixed to the wall or ceiling on entry to that specific space such as the formal dining area, informal snacking area, or bar.

The rating system applied to a specific establishment has to be determined by the establishment owner, and this could be accomplished in a number of ways. The owner may wish to actually hand out customer satisfaction surveys on-site, use electronic customer surveys on their website, or review on-line satisfaction surveys from the local newspaper or restaurant rating services such as SoundPrint, TripAdvisor, and Yelp. In any case, it is to the advantage of the facility owner to help the customers choose wisely to meet their acoustic comfort needs. Happy customers mean return business.

What Does the Future Bring?

If we wish to move this classification system to a more analytical form as time goes on, then we need to look next to our "smart phone" because we now have many available apps that can be used to measure in real time and on-site the sound environment in any space. This will take additional longer term research into how to make the measurements. Currently, the SoundPrint app, for example, has a sound level meter feature, but the details and accuracy are not specifically discussed, other than that a minimum 15-second measurement period is recommended. Those of us who have conducted SoundScape measurements (sound-level time history survey at either an outdoor or indoor site) would likely believe that the measurement period needs to be related to the type of noise being measured, and 15 seconds is not sufficient as a general recommendation.

How to conduct these measurements would be a nice academic exercise. The classification categories could be based on an integrated sound level such as the A-weighted equivalent continuous sound level (L_{eqA}) over 15 minutes, with a value not exceeding something like 95 dB(A) for the highest noise spaces, and down to an L_{eqA} over 30 minutes, with a value not exceeding perhaps 50 dB(A) for the more casual dining spaces. Again, it would be dependent on the owner or other interested parties, maybe the National Restaurant Association, to conduct this type of research to identify the actual decibel-level ranges and how best to measure them.

Good luck and happy eating!

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BioSketches

Kenneth P. Roy is the director/owner of LeShanShui Consulting LLC, Holtwood, PA, that provides international consulting in topics relating to architecture, acoustics, and human performance in buildings. Since 1990, he has been an invited lecturer on topics relating to "Architecture and Acoustics" at 26 universities in 8 countries and presented over 200 seminars and design workshops on topics relating to "Architectural Acoustic Design" in 24 countries. Before starting his own consulting practice, he worked for the firms of Armstrong World Industries, Owens-Corning Fiberglas, and Paul Veneklasen Associates Consultants in Acoustics.

Keely Siebein is a senior consultant with Siebein Associates, Inc., Gainesville, FL, and has completed research on natural, historic, and urban soundscapes, restaurant and classroom acoustics, and performance space acoustics as well as worked on over 250 projects around the world. She recently served as editor for an upcoming publication entitled *Bertram Y. Kinzey, Jr.: Contributions and Influences on Current Research, Teaching and Design of the Architecture of Sound.* Keely chaired the Ad Hoc Committee on Aquatic Facility Acoustical Design for the Council for the Model Aquatic Health Code (CMAHC) from 2016 to 2017.

The Peculiar Acoustics of Rocks

James A. TenCate

Address:
Geophysics Group
Earth and Environmental
Sciences Division
Mail Stop D446
Los Alamos National Laboratory
Los Alamos, New Mexico 87545
USA

Email:
tencate@lanl.gov

Marcel Remillieux

Address:
Geophysics Group
Earth and Environmental
Sciences Division
Mail Stop D446
Los Alamos National Laboratory
Los Alamos, New Mexico 87545
USA

Email:
mcr1@lanl.gov

Surprisingly, understanding how sound behaves in rocks is not very well-known.

Introduction

For centuries, humans have used rocks as building materials. From the Parthenon of ancient Greece (Pentelic marble; bit.ly/2THk7XL) to the more recent Strasbourg cathedral (Vosges sandstone; bit.ly/2TtjZLY) to the Texas State capital building (Texas pink granite; bit.ly/2Ts6wE8), rock endures.

Although the mechanical and acoustical properties of rocks should be very well-known, it turns out that quite the opposite is true. Rocks, in fact, exhibit some very peculiar behaviors. In addition to often being nonlinear, they exhibit hysteresis when pushed and pulled and have mechanical properties that slowly vary in time. All of these behaviors may also vary in their response, depending on the stimuli. Thus, although in some ways rocks can be treated as simple solids, in other ways they behave more like fluids. The real answer, however, is somewhere in between.

Because of the complexity of the behavior of rocks, our quest is for measurements and for the simplest models that can capture all the important features of the pecu-liar behavior of a rock. Ultimately, such models can be used to predict and better understand what goes on beneath our feet.

Motivation

Why is wave propagation and, in general, the acoustics of rocks of interest? One answer is for building restoration, a research area of continued study. Exadaktylos et al. (2001) and many others, for example, describe the (nonlinear) mechanical and acoustical testing on the Pentelic marble of the Parthenon.

However, there are other more compelling (financial) motivations. Knowing the sound speed profiles and how waves propagate in the ground underneath can inform seismic prospecting, such as where and how deep to drill for oil and gas, or for carbon sequestration. For example, in 1935, Conrad Schlumberger was issued a US patent (No. 2,191,119; bit.ly/2T3raFU) for the use of a sonic logging tool for oil and gas research. Imagine trying to determine the depth of a highly reflective layer (which may have an oil reservoir trapped underneath) without knowing the sound speed profile of the subsurface rocks. A considerable amount of research and development by various oil companies over the years followed from that first patent.

Rock acoustics is also an invaluable tool in understanding our heavenly neighbors. For example, in the 1970s, there was additional interest in the acoustics of rocks as a result of the return of the Apollo moon rocks. Acoustics was used to study these rocks to help discern the history and geology of the Moon. More recently, the Mars Rovers (Spirit, Opportunity, Curiosity, and now InSight) all had or have instruments onboard to try and understand the rocks on Mars. The purpose of these instruments is to see if Martian rocks may have formed in a wetter environment.InSight has actually placed a seismometer on the surface of Mars to listen for marsquakes to

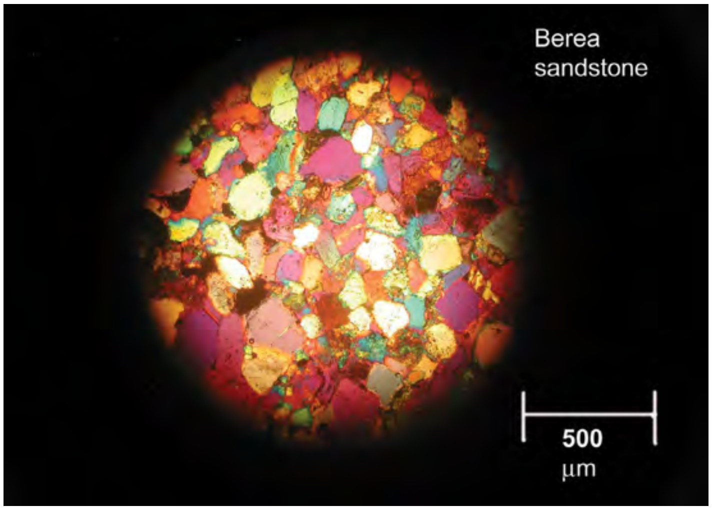

Figure 1. *Thin section of a Berea sandstone sample under cross-polarizing filters. Different colors highlight different grain orientations.* ***Black areas*** *are voids, and some of the pore space between grains contains clays and silt in this sample. See text for further details.*

aid and interpret the underlying structure beneath the surface (go.nasa.gov/2Fe9KRP; Smrekar et al., 2019).

Finally, the question of where to store high-level radioactive waste may find an answer in rocks too, such as in the Waste Isolation Pilot Plant (WIPP; wipp.energy.gov), a deep geological repository in New Mexico. For the WIPP, understanding rock properties (e.g., fluid and gas migration in the salt, how the rock was formed, mechanical behavior) in this case, and really in *all* cases above, is key.

Properties of Rocks

To better understand the mechanical and acoustical properties of rocks, it is instructive first to know something about how they are formed. Most of the rocks of financial interest are sedimentary. Indeed, sedimentary rocks are a focus of commercial oil and gas companies, The Office of Basic Energy Sciences, US Department of Energy, supports such research as well.

The primary building blocks of sandstones are weathered quartz grains that are cemented together under millions of years of pressure and fluid flow. These cementation processes are called *lithification* and/or *diagenesis*, and books are written about these processes and especially about those sandstones that are relevant to oil and gas exploration (Burley and Worden, 2009). For example, Berea sandstone (rocks are usually named for the places where they are first commonly found; Berea is a town in Ohio) is often used for research as a representative oil- and gas-bearing rock. It was formed about 400 million years ago from river sands deposited in what is now the US Midwest from an ancient river delta up in what is now Canada. It is perhaps worth noting that some buildings are constructed of Berea sandstone (e.g., the Johnson County Courthouse in Iowa; Rossman, 1975). What is especially notable about this sandstone is that the constituent grains are cemented together in such a way that they also contain extensive pore space. These pore spaces contain remaining fluids, occasionally some fine clays and silts, and in an oil and gas reservoir the remains of plants and animals in the form of oil.

Figure 1 shows a thin section of Berea sandstone, with the light through it observed through cross polarizers to best show off the crystalline orientation of the grains. The dark material in between the grains is the amorphous quartz and clays holding the rock together. From a mechanical and acoustical point of view, this imperfect grain-to-grain bonding, with distributions of stress concentrations via various grains and the ability for grains to rotate in and out of pore spaces under stress, make for an interesting solid.

How does a stress change or acoustic pulse get transmitted through such a collection of grains? Unlike a homogeneous solid, forces are not distributed smoothly through a rock. Each individual grain is cemented to its neighbors in various random ways. The particular collection of grains that participate, and not all do, in transferring a force or acoustic wave through a sandstone is called a *force chain*. Many hundreds of these force chains might participate in wave propagation or maybe just a few. You can imagine that building a (finite-element) model of such a rock is no easy task. Add trapped fluids to that matrix, and you have a recipe for fascinating and challenging material behavior.

Ideal Solid Versus the Behavior of a Rock

So how does such an interesting solid behave? The mechanical quasi-static behavior will be examined first. Imagine first a spring that obeys Hooke's law, $F = -kx$, where F is the required force to extend or compress a spring, k is the spring constant, and x is the distance to be moved. (Of course, such a spring cannot be compressed *too* much lest the coils of the spring will come in contact with each other.) Put the spring in a stress-strain (load-frame) machine, compress and release

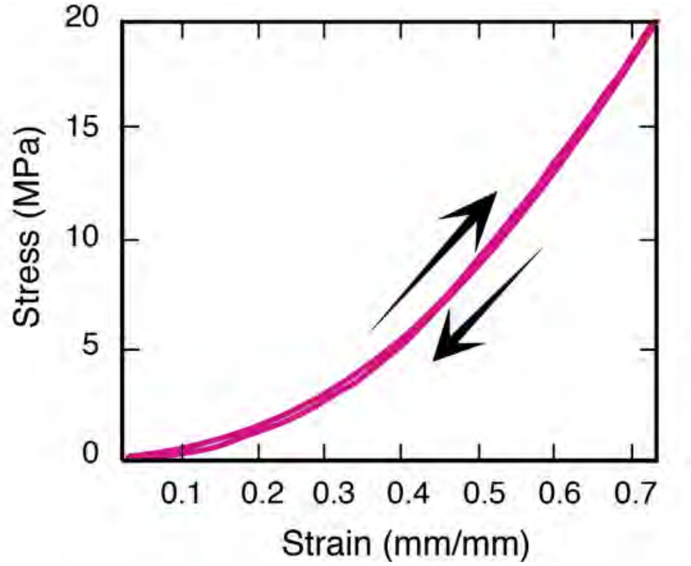

Figure 2. Very slow stress-strain measurement on a sample of Berea sandstone (over four days). Stress is applied linearly and then released at the same rate. The error bars in the strain measurements (not shown for clarity) are ±0.02. Upward and downward curves are the same within the error bars. (Plot axes are swapped because of tradition; strain always goes on the y*-axis.)*

it, and plot the resulting stress-strain data. The experiment results in a straight-line force-displacement curve.

Many solids also have straight-line stress-strain curves for small forces. In the solid, there is an additional Poisson effect, it bulges as it is squeezed, that can usually be ignored in a rock. Now put a small core sample of Berea sandstone in that stress-strain (load-frame) machine, compress and release it, and plot the resulting stress-strain data. As seen in **Figure 2**, Berea sandstone does not behave like a linear spring or solid. Instead, the rock gets stiffer as it is compressed.

This is not surprising considering the structure of the rock. Much like squeezing a linear spring so hard that the coils touch, the applied force is squeezing grains into the pore spaces, and eventually, they all come in contact with one another. This behavior is not new or surprising. In fact, it has been known since the early twentieth century when Adams and Coker (1906) published a series of quasi-static nonlinear stress-strain curves for a wide variety of rocks and showed that many were nonlinear. You might note that these measurements are all in large strains and are quasi-static (i.e., at extremely low frequencies). How is this relevant to acoustics where the effective strains and frequencies are quite different? As we discuss in ***Wave Propagation***, nonlinearity can be seen in measured waveforms too. So, is it sufficient to just add nonlinearity to a rock to describe its behavior? No.

There are two additional and important complications to the stress-strain behavior inherent in a rock. The stress-strain curve in **Figure 2** was taken at a very slow rate (data were acquired over a period of several days). The nonlinearity is clearly present, and the compression phase essentially matches the release phase (within errors). However, the *rate* at which the stress-strain data are acquired matters. Imagine repeating the stress-strain measurement in **Figure 2**, this time linearly, increasing and then decreasing the stress at different rates and measuring the resultant strain. The results of taking data slowly (e.g., days) and then quite quickly (e.g., minutes) on a pair of different sedimentary rocks is surprising.

Figure 3 shows four sets of stress-strain measurements on two sedimentary rocks, two done over the period of a several days and two done at normal laboratory timescales of less than an hour (see Claytor et al., 2009). The fast measurements (**Figure 3, *right***) both start to take on distinctive banana shapes. These are, in fact, *hysteresis* loops similar to what is seen in ferromagnets. But the fact that *different* hysteresis loops are measured depending on the rate at which the experiment is

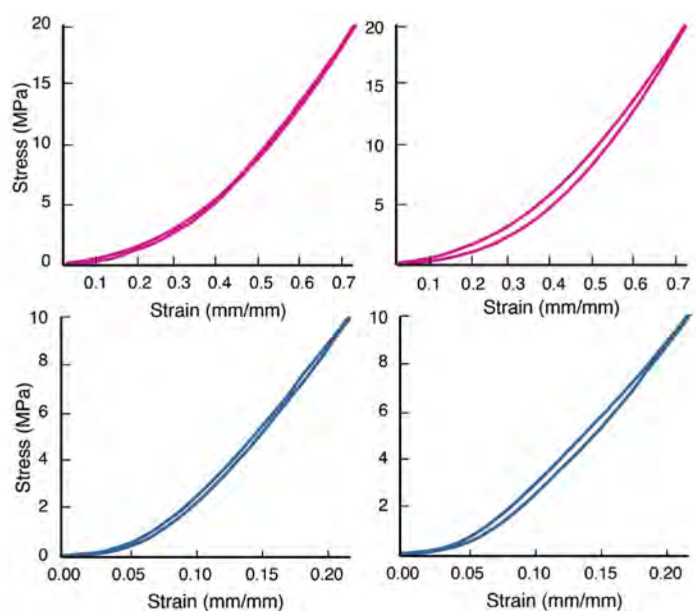

*Figure 3. Stress-strain plots of two sedimentary rock samples: Fontainebleau sandstone (**top, red**) and Berea sandstone (**bottom, blue**). **Left plots** were made at a very slow rate (days); **right plots** were made at a reasonably fast rate (30 minutes). Hysteresis, manifested as banana-shaped loops, is apparent in the fast measurements (**right**). Measurement rate matters. See text for further discussion.*

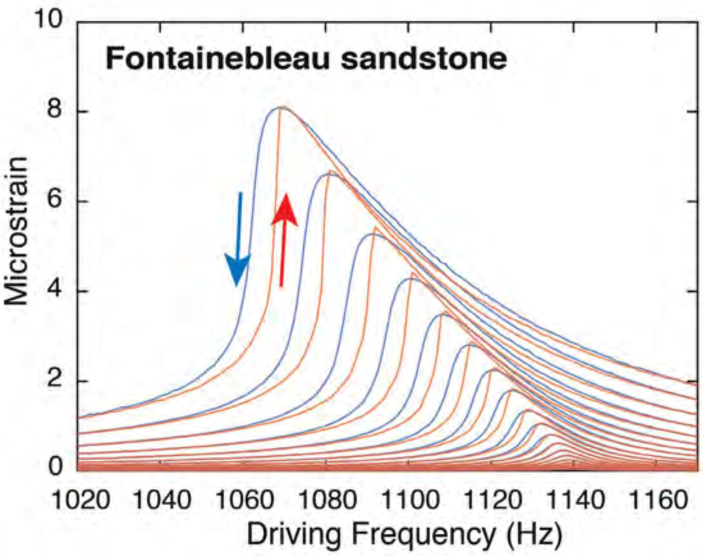

Figure 4. *A series of resonance curves at increasing amplitudes for the lowest resonance frequency of a long thin bar of Fontainebleau sandstone. The driving frequency is swept upward (**red**) and downward (**blue**), and the response of the sample is measured with a laser vibrometer and converted to strain. Note the softening nonlinearity (resonance frequency drops) with increasing excitation amplitude and the different up-and-down curves that result from slow dynamics.*

done complicates the behavior of a rock much more. A rock is not only nonlinear; there is hysteresis *and* there is some kind of time-dependent behavior present as well.

The measurements described above are quasi-static and at fairly large stresses and strains. What about at lower strains and higher frequencies? Does hysteresis still persist, can it be measured, and does it really matter for acoustics? Lest you think this hysteretic behavior isn't present in wave propagation, it is. At much lower strains and at higher frequencies, those typical for seismic waves, you see "cuspy" triangular waveforms, also indicating the presence of hysteresis (McKavanagh and Stacey, 1974). Some of these waveforms are seen at even higher frequencies and are shown in ***Wave Propagation***. Hysteresis is present at many frequencies and amplitudes of interest to the acoustician.

Perhaps it should not be surprising that the hysteresis described above and seen in **Figure 3** was also found to be time dependent. There is a term for this behavior, *elastic aftereffect* (e.g., see Becker, 1925), and it has an analogy with magnetic materials where the effect takes place over years instead of days. Elastic aftereffect is present in rocks, and it fortunately (or unfortunately) manifests itself on timescales relevant to most acoustic measurements. To clarify discussions about rocks, the rate-dependent effects were dubbed "slow dynamics" in the geophysics literature quite a while ago and the name stuck (TenCate and Shankland, 1996).

For the acoustician then, questions remain. Are nonlinear, hysteretic, and slow-dynamic effects large in rocks? Can they be seen in wave propagation down a long thin bar or maybe in the acoustic waves sent across a block of sandstone? What about nonlinear wave interactions in rocks; do they occur too? These kinds of questions have been the focus of roughly 25 years of research of a group of researchers and colleagues at the Los Alamos National Laboratory and many others elsewhere. The acoustical experiments to date fall into two distinct types.

Two Kinds of Experiments

Resonance

The first type of experiment, resonance measurements on long thin bars, is occasionally used to characterize the mechanical properties of rock cores. Long thin cores have geometries that make it easy to find and precisely locate resonance frequencies. These are useful to characterize the elastic moduli and intrinsic attenuation of the core.

However, with increasing excitation amplitudes, something surprising happens. A series of resonance curves taken around the lowest resonance frequency, 1-D wave motion that in a solid resembles a snake swallowing, takes on peculiar shapes with increasing drive amplitude. **Figure 4** shows a family of up-and-down sweeps of frequency versus amplitude for yet another sedimentary rock, this one from Fontainebleau, south of Paris, France. The resonance frequency drops, and the upward and downward curves are not the same. These curves resemble those of softening nonlinear spring-mass systems, such as those whose motion is described by a Duffing equation. The springs in a Duffing equation do not obey (linear) Hooke's law and have a cubic nonlinear spring constant. Upward and downward sweeps in frequency (versus amplitude) produce different resonance curves. Even the jump in the upward sweeps resembles a Duffing oscillator spring-mass system. In fact, a great number of early studies went into trying to fit the resonance curves of rocks with the Duffing models. However, although a nonlinear spring-mass description works quite well down at very low strains, where nonlinearity dominates, above a certain drive level, slow dynamics matters more.

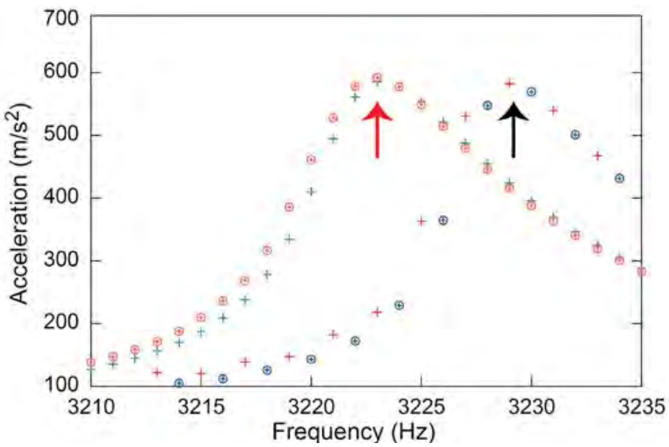

*Figure 5. Up-and-down resonance curve data points taken quickly (2 minutes; **orange circles**, upward data points; **green plus symbols**, downward data points) and taken very slowly (2 days; **blue circles**, upward data points; **red plus symbols**, downward data points), both at the same excitation amplitude. In contrast with the smooth curves shown in **Figure 6**, resonance curve data were taken sparsely, point by point. Error in measurement is ±20 m/s^2. **Red arrow**, resonance frequency for the slow experiment at 3,239 Hz; **black arrow**, resonance frequency for the fast experiment at 3,223 Hz, a significant difference.*

Examples of the above behavior abound. Depending on how fast or slow the resonance sweep is done, the slope, jumps, and shapes of all the resonance curves can vary dramatically (TenCate and Shankland, 1996). In particular, by doing the sweep measurements very slowly or very quickly, it was possible to get two very different resonance curves from the same rock sample (see **Figure 5**). Rate is the only variable here. In fact, later work shows that the resonance behaviors at frequencies and amplitudes of most interest to the acoustician are almost entirely dominated by slow-dynamic rate effects (Pasqualini et al., 2007; Remillieux et al., 2017). Classical nonlinearity of the sort that an acoustician would expect (e.g., which cause sonic booms), although large, takes a back seat to slow dynamics in many cases.

Wave Propagation

Wave propagation experiments fall into the second type of measurement carried out by Los Alamos researchers and colleagues. Are nonlinear, hysteresis, and rate effects visible in these kinds of experiments too? Yes indeed, they are all present. Numerous papers show nonlinearity in the form of harmonics and at strains roughly 1,000 times less than the typical quasi-static stress strain measurements (e.g., Meegan et al., 1993; TenCate et al., 1996; Remillieux et al., 2017). Recall that McKavanaugh and Stacey (1974) show that cuspy hysteresis is present in wave propagation measurements as well as in rate effects.

Remillieux et al. (2017) showed such behavior at higher frequencies and lower strains. **Figure 6** shows the results of sending a tone burst down a long thin Berea sandstone bar. The waveforms are recorded 0.5 meter from the source and at several different increasing source amplitudes. **Figure 6, *inset***, shows just how distorted the waveform has become. The triangulation is severe, and even the zero crossings have moved. Further in-depth discussion and more results can be found in the aforementioned paper.

What sort of physics is causing the peculiar behavior of rocks? Recall that a sandstone typically consists of a random collection of quartz grains cemented together in unusual ways, with odd contact surfaces and porosity for the grains to move and rotate around under stress. In addition, a rock may also have fluids trapped within that matrix during its formation. These fluids may also play a role, especially at crack tips and contact points. Bittner and Popovics (2019) made a remarkable observation under an environmental scanning electron microscope (a scanning electron microscope that can visualize wet objects) that shows fluids in a cement pore disappearing under acoustic excitation and reappearing after the acoustic excitation is turned off. A video of the experiment shows an initially wet pore (youtu.be/H_ahCbbYt3Q). However, when an acoustic field is turned on, all the water disappears. Once the acoustic field is turned off, water is seen seeping back into the pore.

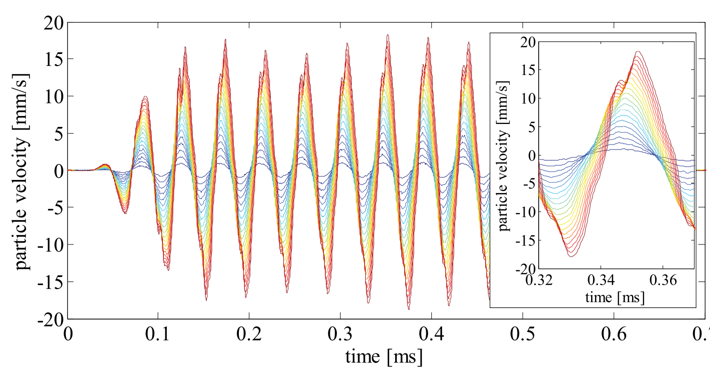

*Figure 6. Distorted waveforms measured 0.5 meter from the source, a tone burst, sent down a long thin Berea sandstone bar at increasing drive amplitudes (**blue to red**). **Inset:** zoom of one cycle and shows how distorted these waveforms become. The spectrum of these waveforms is dominated by odd harmonics. The waveforms also show how the pulse is progressively delayed with increasing amplitudes at the zero crossings. There is more than nonlinearity present in these waveforms.*

It has also been suggested by Page et al. (2004) and many others that there may be disturbances within the quartz crystals themselves. Perhaps nonlinearity is a result of the movement of crystalline lattice structures (i.e., *dislocations*) under an acoustic excitation. However, such physics at the crystalline level do not appear to play a role. A set of experiments where quasi-static stress-strain curves were obtained simultaneously with neutron-scattering measurements (Darling et al., 2004) shows that the average crystalline behavior in a sandstone is linear (i.e., each grain behaves as a perfect little spring), even though the macroscopic stress-strain curves are quite nonlinear! It seems reasonable to conclude that *it is the geometric structure of the entire cemented-grain matrix that is largely responsible for the nonlinearity* and not the crystals themselves. In addition, having fluids present at the contact surfaces seems to be necessary as well. Researchers are actively seeking other experiments to learn more about the processes at the grain scale and larger levels responsible for the behavior seen in rocks.

Conclusions

In summary, there are three general classes of behavior that have been observed in rocks: (1) classical nonlinearity; (2) hysteresis; and (3) slow dynamics. There are also three important features in rocks that we think are the key contributors to the observed behavior: (1) grain-to-grain contact dynamics; (2) geometrical arrangement of grains (e.g., how they are cemented and oriented and how much pore space there is between them); and (3) fluids that provide lubrication between grains, fluid-grain surface tension effects, and maybe even high-pressure chemistry at contact points.

Many key questions about the acoustic behavior of rocks still remain to be answered. What is the connection between the proposed physics described in this article and the observed behavior? To further understanding, there is a great need for more very small scale experiments, like the one done by Bittner and Popovics (2019). There is also a need for very detailed finite-element models with all the above physics embedded, as now being done at Los Alamos National Laboratory, and perhaps also working with larger than life-scale representative models. The quest is for the simplest models that capture all the important features of the peculiar behavior of a rock. Ultimately, such models can be used to predict and better understand what goes on in the earth deep beneath us.

Acknowledgments

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BioSketches

James TenCate started his acoustics career as a musician who quickly developed a keen interest in acoustics. After college (physics), he looked for graduate schools that specialized in acoustics and ended up at the University of Texas at Austin working under David Blackstock. During that time, he developed an appreciation and understanding of nonlinear acoustics in air and then in water. At the time, Los Alamos National Laboratory, Los Alamos, NM, was building a team to study nonlinearity in rocks. TenCate joined the Geophysics Group as a postdoc and spent the rest of his acoustics career at Los Alamos. TenCate is a Fellow of the Acoustical Society of America.

Marcel Remillieux has been a member of the Geophysics Group at Los Alamos National Laboratory, Los Alamos, NM, since 2013, first as postdoc and now as research scientist. He specializes in using nonlinear acoustics for nondestructive testing, from the integrity of structures in the nuclear energy industry to geophysical exploration for the oil and gas industry. His background is in acoustics, with MS and PhD degrees obtained from Virginia Tech, Blacksburg, VA, in Prof. Fuller's group. In his spare time, he and his wife Stephanie run Fleur de Lys, a busy and cozy French bakery/café in the heart of the atomic city.

From Biology to Bytes: Predicting the Path of Ultrasound Waves Through the Human Body

Bradley E. Treeby

Address:
Department of Medical Physics and Biomedical Engineering
University College London
Gower Street
London WC1E 6BT
United Kingdom

Email:
b.treeby@ucl.ac.uk

Jiri Jaros

Address:
Centre of Excellence IT4Innovations
Faculty of Information Technology
Brno University of Technology
Bozetechova 2
612 66 Brno
Czech Republic

Email:
jarosjir@fit.vutbr.cz

Eleanor Martin

Email:
elly.martin@ucl.ac.uk

Ben T. Cox

Email:
b.cox@ucl.ac.uk

Address:
Department of Medical Physics and Biomedical Engineering
University College London
Gower Street
London WC1E 6BT
United Kingdom

Computer simulations are increasingly used to guide ultrasound therapies, but what makes a good model and when can we trust them?

Introduction

The use of ultrasound as a diagnostic imaging tool is well-known, particularly during pregnancy where ultrasound is used to create pictures of developing babies. In recent years, a growing number of *therapeutic* applications of ultrasound have also been demonstrated. The goal of therapeutic ultrasound is to modify the function or structure of biological tissue in some way rather than produce an anatomical image. This is possible because the mechanical vibrations caused by ultrasound waves can affect tissue in different ways, for example, by causing the tissue to heat up or by generating internal forces that can agitate the cells or tissue scaffolding. These ultrasound bioeffects offer enormous potential to develop new ways to treat major diseases. In the last few years, clinical trials of different ultrasound therapies have demonstrated the ability of ultrasound to destroy cells through rapid heating for the treatment of cancer and neurological disorders, target the delivery of anticancer drugs, stimulate or modulate the excitability of neurons, and temporarily open the blood-brain barrier to allow drugs to be delivered more effectively (Konofagou, 2017). These treatments are all completely noninvasive and have the potential to significantly improve patient outcomes.

The fundamental challenge shared by all applications of therapeutic ultrasound is that the ultrasound energy must be delivered accurately, safely, and noninvasively to the target region within the body identified by the doctor. This is difficult because bones and other tissue interfaces can severely distort the shape of the ultrasound beam (see **Figure 1**, ***bottom***, for an example). This distortion can have a significant impact on the safety and effectiveness of therapeutic ultrasound and is one of the major hurdles for the wider clinical acceptance of this exciting technology. In principle, it is possible to predict and correct for these distortions using models of how ultrasound waves travel through the body. However, the underlying physics is complex and typically must consider nonlinear wave propagation through absorbing media with spatially varying material properties. Simple formulas do not exist for this scenario, so models used for studying therapeutic ultrasound are instead based on the numerical solution of the wave equation (or the corresponding constitutive equations). This article is primarily concerned with the development of such models.

Circle of Model Development

One way to consider the development of numerical ultrasound models, and indeed any scientific software that models a physical phenomenon, is described by the circle of *model development* (see **Figure 2**). This has five distinct components:

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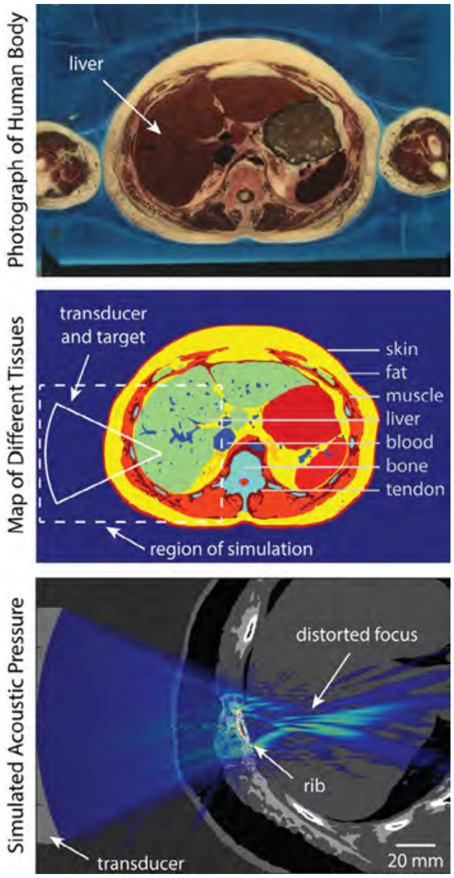

Figure 1. *Predicted distortion of the acoustic field from a therapeutic ultrasound transducer for a liver target when the beam path is occluded by the ribs (**bottom**). The spatially varying acoustic properties for the simulation (**middle**) are derived from cryosection images from the Visible Human Project run by the US National Library of Medicine (**top**). The predicted ultrasound field is calculated using the open-source k-Wave Toolbox (Jaros et al., 2016).*

(1) deriving equations that describe the underlying physics;
(2) choosing a suitable algorithm (numerical method) to solve these equations;
(3) implementing the numerical scheme as computer code;
(4) defining inputs to the model, for example, the spatial discretization and material properties; and
(5) validating the model (numerically and experimentally).

The process is often iterative (**Figure 2**, ***dashed line***) and is repeated until the model predictions agree with the experimental observations (the level of agreement required depends on the context). For ultrasound therapy, it is critical that each component in the circle of model development is carefully considered before models are used to assist in calculations and predictions because any deficiencies could have serious ramifications for patient safety.

The circle of model development can be used as a general framework to guide developers. Equally, it can be employed by end users to ask, *Is this model appropriate for my application?* For example, considering each of the five components, questions arise.

(1) Do the model equations capture enough of the physics to simulate the phenomenon of interest?
(2) Is the chosen numerical method stable, efficient, and accurate? What are the convergence properties?
(3) Is the computer code fast, fault tolerant, portable, scalable, well-documented, and easy-to-use? Is it regulatory compliant?
(4) What are the model inputs? Are they material properties, physical constants, or tuning parameters, and are they easy to measure or specify? What is the sensitivity of the model to errors in the inputs? What settings do I need to use to ensure accurate results?
(5) Has the model been validated against analytical solutions, experimental measurements, or clinical data? Do I have confidence in using the model to make clinical predictions?

In this article, each component of the circle of model development is discussed in more detail as a general framework for the development of software for modeling therapeutic ultrasound in the human body. Like many endeavors in modern science, adequately addressing all five components requires a team of people with a wide breadth of expertise. This includes physical acoustics, numerical methods, computer science, software engineering, ultrasound metrology, and medical imaging. In many cases, input from regulatory experts, clinicians, and other end users will also be needed.

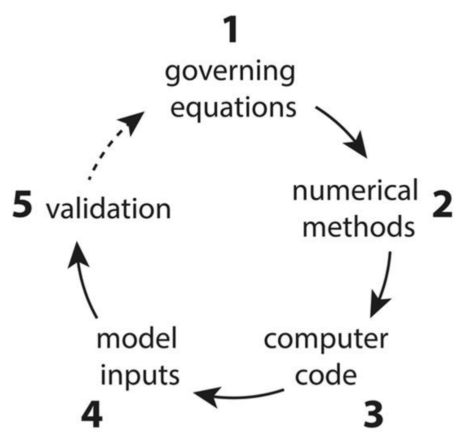

Figure 2. *The circle of model development showing the five key components that should be considered when developing scientific software. See text for explanation.*

Governing Equations

The mathematical expressions that describe the physics of ultrasound wave propagation in tissue are known as *governing equations*. These are typically based on the conservation of momentum (which accounts for the tissue having inertia), the conservation of mass (which accounts for the tissue being compressible), and an equation of state or pressure-density relationship (which encapsulates the thermodynamics of wave propagation). In many branches of acoustics, these equations can be simplified by assuming linear wave propagation in a lossless and homogeneous medium, which leads the widely known *wave equation*. In biomedical ultrasound, this equation is appropriate for studying the spatial distribution of acoustic pressure from therapeutic ultrasound transducers in water at low output levels. However, for modeling therapeutic ultrasound in the human body, the simplifying assumptions mentioned above generally no longer hold.

First, the pressure amplitudes used in biomedical ultrasound are often sufficiently high to give rise to nonlinear effects (this is true for both therapeutic and diagnostic applications of ultrasound). At high acoustic pressures, the stiffness of the tissue depends on how much it is being compressed (material nonlinearity) and the cyclical motion of the medium, due to the acoustic wave, affects the wave speed (convective nonlinearity). Together, these cause the sound speed in the medium to depend dynamically on the local values of the acoustic pressure and particle velocity. For example, during the compressional phase of the wave where the particle velocity is positive (i.e., the medium is being displaced in the same direction as the wave is traveling), the effective sound speed increases and vice versa. This causes a cumulative distortion in the time-domain waveform, which corresponds to the generation of higher frequency harmonics in the frequency domain. From a modeling standpoint, this type of nonlinearity can be captured by retaining second-order terms in the governing equations (Hamilton and Blackstock, 2008).

Second, biological tissue can strongly attenuate ultrasound waves, particularly waves at megahertz frequencies. The exact mechanisms for the absorption in tissue are complex and occur at both the cellular level (e.g., viscous relative motion and thermal conduction between the cells and their surroundings) and the molecular level (e.g., molecular and chemical relaxation). These processes cause the gradual degradation of acoustic energy into random thermal motion and, consequently, the attenuation of the wave amplitude. In addition to absorption, acoustic energy is also lost due to scattering. This is generally negligible in soft tissue at low megahertz frequencies but can become significant as the wavelength decreases or in highly scattering media such as bone. Overall, the acoustic attenuation in soft biological tissue (which includes both absorption and scattering) has been experimentally observed to follow a frequency power law of the form $\alpha_0 f^y$, where f is the frequency and the power law exponent y is between 1 and 2. This type of behavior can be captured in the governing equations by including a distribution of relaxation processes or by using fractional derivative loss operators (Holm and Nasholm, 2014). A commonly used rule of thumb is that ultrasound in soft biological tissue is attenuated at a rate of 1 dB/MHz/cm.

Third, in biological tissues, medium properties such as the sound speed, mass density, and acoustic absorption coefficient are heterogeneous across multiple scales. At the microscopic level (much smaller than an acoustic wavelength), there are variations in the acoustic properties between individual cells and between cells and other tissue constituents such as blood plasma and the extracellular matrix (the structural scaffolding that holds many cells in place). These differences give rise to diffusive scattering, which is responsible for the speckle pattern characteristic of diagnostic ultrasound images. However, from an ultrasound therapy perspective, this scattering is generally weak and can be accounted for as part of a phenomenological attenuation term in the governing equations.

At a macroscopic level, different structures within an organ, such as blood vessels or regions of fatty and fibrous tissue, can also give rise to scattering. There are also differences at the organ level, again due to variations in the underlying tissue constituents and their structure. For example, tissues with a higher proportion of lipids (e.g., fat) typically have a lower sound speed compared with water at body temperature, whereas tissues with a higher proportion of proteins (e.g., liver) have a higher sound speed. These macroscopic variations in the acoustic properties of tissue can have a significant impact on the propagation of focused ultrasound fields, including changing the shape, position, and amplitude of the focal region (see **Figure 1**, ***bottom***). In some cases, the aberrations are so strong that the focus is completely destroyed. Spatially varying material properties can be included in the governing equations by starting with the conservation equations and retaining the spatial gradients of the material parameters during the linearization process.

The combination of the mass and momentum conservation equations (retaining heterogeneous and nonlinear terms) and an equation of state (accounting for absorption through a fractional loss operator or sum of relaxation terms) can account for the complex wave behavior seen in biological tissue. This includes scattering, refraction, nonlinear wave steepening, and acoustic absorption following a frequency power law. However, in some cases, additional factors must also be considered, for example, the temperature dependence of the tissue material properties, the motion of organs due to breathing or the cardiac cycle, and/or acoustic cavitation (Maxwell et al., 2012; Gray et al., 2019). Systematically incorporating such extensions into the governing equations in a tissue-realistic manner is not straightforward. For modeling scenarios that involve bones, the generation, propagation, and absorption of shear waves must also be considered. In this case, the mass conservation equation and the equation of state are replaced with a model of viscoelasticity (a generalization of Hooke's law).

Numerical Methods

The techniques used to discretize the governing equations so that they can be solved by a computer are known as *numerical methods*. There are many different types of numerical methods used in acoustics. These include the finite-element method, boundary-element method, finite-difference method, Green's function methods, and spectral methods (Verweij et al., 2014). The most appropriate choice depends on the problem specifics, for example, the distribution of material properties (e.g., homogeneous, piecewise constant, or continuously varying), whether the problem is linear or nonlinear, whether the source is single frequency or broadband, and the scale of the domain of interest. For therapeutic ultrasound (which usually involves nonlinear wave propagation in heterogeneous and absorbing biological tissue), the most common approach is to use computationally efficient collocation methods, such as the finite-difference time domain (FDTD) or pseudospectral time domain (PSTD) methods (Gu and Jing, 2015). These methods can be used to directly solve the governing equations as a system of coupled equations, or the equations can be combined and solved as a generalized wave equation. The former has some advantages for numerically imposing radiation conditions at the edge of the computational domain (such as a perfectly matched layer) and for inputs and outputs that depend on the acoustic particle velocity (including modeling dipole sources and calculating the vector acoustic intensity).

A significant challenge when modeling biomedical ultrasound is the large distances traveled by the ultrasound waves relative to the acoustic wavelength at the highest frequency of interest. Consider the case of transcranial focused ultrasound surgery, where ultrasound waves are used to destroy a small region of tissue deep in the brain. The domain of interest encompassing the ultrasound transducer and the head is on the order of 30 cm in each direction. For a center frequency of 650 kHz, this distance is on the order of 130 wavelengths at the fundamental frequency and 650 wavelengths at the fifth harmonic. Applying the engineering rule of thumb of 20 points per wavelength (PPW) sometimes used for finite-element and finite-difference methods, this corresponds to a computational grid size of $13{,}000 \times 13{,}000 \times 13{,}000$ grid points (more than 2 trillion degrees of freedom). Simply storing one matrix of this size in single-precision floating-point format would consume 8 terabytes (TB) of memory, and typically several such matrices are needed. To put this into context, the current generation MacBook Air comes equipped with 8 gigabytes (GB) of memory, so 1,000 of them would be required to store one matrix at a cost of more than one million US dollars! Of course, supercomputing is not done using consumer laptops, but the point remains: problems of this nature can become extremely large scale.

So why is the engineering rule of thumb to use 20 PPW when the Nyquist theorem tells us we should only need two? The primary reason is *numerical dispersion*. This is a numerical error in which approximations made in the numerical method cause the modeled ultrasound waves to travel at different speeds depending on their frequency (the dependence of sound speed on frequency is known as dispersion). This dependence means that broadband waves will become increasingly distorted compared with the true solution as they propagate across the computational grid (equivalently, single frequency waves will travel at the wrong speed). This is a particular challenge for the large domain sizes encountered in therapeutic ultrasound (often hundreds of wavelengths), because errors due to numerical dispersion accumulate the further the waves travel.

For finite-difference methods, provided that the numerical scheme mathematically reduces to the governing equations in the limit that the spatial and temporal steps reduce to zero (a condition known as consistency) and that the method is stable (there are standard mathematical and numerical tools for analyzing stability), the *Lax equivalence theorem* tells us that the scheme will be convergent. This means that the numerical solution will approach the exact solution of the governing equations as the size of the spatial and temporal steps is reduced. In general, this provides a very practical way to test the accuracy of almost any numerical model. Reduce the size of the grid spacing (Δx) and the time step (Δt) or otherwise increase the mesh density, and check to see if the answer remains the same. If not, keep reducing Δx and Δt until the answer no longer changes. This procedure is called a *convergence test* and should always be carried out for every modeling scenario. In general, the output from a numerical model should not be trusted unless convergence has been demonstrated!

Finite-difference methods have been widely used for modeling in acoustics; however, these methods often require very large computational grids to avoid numerical dispersion. To reduce dispersion errors, higher order finite-difference schemes can be implemented that use more neighboring grid points to estimate the spatial and temporal gradients. *Spectral methods* take this idea to the limit and use all of the grid points simultaneously by fitting a finite sum of basis functions to the data. In acoustics, a common choice is to use trigonometric functions, where the fitting is performed by taking a fast Fourier transform (FFT). This is the idea behind the PSTD and *k*-space methods that calculate spatial gradients in the spatial-frequency domain. Although computationally more expensive than the FDTD method for a fixed grid size, these methods can significantly reduce dispersion errors and thus the number of points per wavelength required for accurate solutions (Tabei et al., 2002).

A remaining challenge for collocation methods computed on regular Cartesian grids is the introduction of medium staircasing. This arises because the material properties must be represented at discrete points in the model (think of the intersection of lines on a sheet of graph paper), and in many cases, the material boundaries are not aligned with the grid. This leads to stair-like edges between regions with different material properties that generate spurious acoustic reflections. For the PSTD method, this can be the dominant source of error (Robertson et al., 2017a). Although these errors will reduce with increasing grid density, in some cases, it can be challenging to perform a convergence test because the properties are only known at a fixed resolution (e.g., from a medical image), often of the same order as the acoustic wavelength.

Computer Code

Once a numerical method has been developed, this must be turned into *computer code* that can be used to perform simulations. Typically, the high-level goals are to (1) implement the numerical algorithm correctly, (2) maximize performance (e.g., reduce run time), and (3) minimize the computational resources needed (e.g., memory). Unsurprisingly, the development of efficient high-performance computer code is closely connected to a deep understanding of the underlying computer hardware. This is particularly relevant for models of therapeutic ultrasound where the grid sizes are often extremely large and complex calculations such as the FFT are performed (Jaros et al., 2016).

Computational hardware has undergone rapid changes since the first appearance of microprocessors in the late 1960s. Huge increases in performance have been enabled by continual improvements in semiconductor lithography leading to a doubling in the number of transistors on a computer chip approximately every 18 months. During the twentieth century, performance increases were also obtained through increases in transistor switching frequency. These days, however, performance increases are instead driven by increases in parallelization across all levels of processing along with the development of specialized compute units such as graphics processing units (GPUs). This means a modern supercomputing cluster can be highly heterogeneous, consisting of multiple interconnected computers, each potentially containing multiple central processing units (CPUs) and GPUs, where each CPU and GPU has multiple cores, each of which can execute multiple instructions simultaneously on multiple data points! Similarly, there is hierarchy of local and remote memory with different storage capacities and access speeds. Although these details may not be familiar to many acousticians, they are nonetheless important. Effectively programming for such heterogeneous architectures is highly nontrivial and can have a large impact on the performance and tractability of running therapeutic ultrasound simulations (Jaros et al., 2016).

For heterogeneous computer environments, there are two fundamental requirements to consider: data locality and workload balance. Data locality is critical because there is huge difference in the transfer speed (20 times slower) and latency (100 times slower) when accessing data stored on another interconnected computer compared with data stored in local memory (e.g., cache). For the large computational problems encountered in ultrasound, this means the data must be carefully decomposed into different levels of memory so that communication is minimized or overlapped with other useful calculations. Workload balance is critical because different parts of a heterogeneous system can have significantly different compute power. For example, a GPU can be an order of magnitude faster than a single processor at basic arithmetic but extremely slow at control processes. Naturally, the performance of the code taken as a whole is limited by its slowest component.

There are several other factors that can influence the performance of a computer code. The first is the choice of programming language. Although the general trend in software engineering is towards high-level languages (such as MATLAB, Python, C#, or Java), high-performance computing often still relies on low-level languages (such as C/C++ and Fortran) that allow direct access to the hardware characteristics of the target system. Unfortunately, this also complicates the design, implementation, testing, and portability of the codes. Computing in lower (or mixed) precision can increase the speed of arithmetic operations and reduce memory transfers. However, care must be taken to avoid numerical overflow and round-off errors. For large domain sizes, extracting outputs from the model (for example, saving the time-varying pressure field) can also have a significant impact on performance due to the time taken to write data to disk.

During the design of computer code, many implementation details must also be considered. First, the complexity of scientific software often makes the use of test-driven development crucial. In this paradigm, every component of the software has a corresponding test suite validating its results against a ground truth. Additional tests can also be used to investigate changes in code performance. Second, care must be taken to ensure the code (and the development cycle) is adequately documented. Even smaller software projects can be impossible for other developers to understand without proper documentation. Third, the software development environment must be considered. Generally, modern software projects are managed through software version control systems. These incorporate many useful features, including allowing multiple developers to work simultaneously and providing tools for issue tracking, automated testing, and code release. For software used in a medical context, regulatory standards may also mandate additional documentation, testing, and reporting requirements. Finally, the support of users outside the development team must also be carefully considered, for example, through the publication of a user manual or other articles, the development of worked examples, and a user forum or mailing list.

Model Inputs

Once a computer code has been developed, using it to predict how ultrasound waves travel through the human body requires specification of the *model inputs*. From a physical perspective, this includes the properties of the transducer used to transmit (and in some cases receive) the ultrasound waves and a map of the acoustic material properties and how they vary through the body. From a numerical perspective, this includes the size and distribution of the spatial grid and the number and size of the time steps (or an error threshold if using an adaptive integration scheme). These parameters are normally chosen based on a convergence test as discussed in **Numerical Methods**. Finally, from a computational perspective, this includes which computational hardware is used and how the computational effort is distributed among the available resources. This choice is usually made based on heuristics obtained from previous model runs.

Considering the physical inputs starting with the ultrasound transducer, the most straightforward way to include this in a numerical model is as an ideal radiator that vibrates uniformly across the transducer surface (Martin et al., 2016). However, in many cases, physical transducers do not act as uniform radiators due to the propagation of surface waves. To improve accuracy, the size and shape of the ideal source can be adjusted until a reasonable match is obtained with an experimental measurement. Alternatively, a full characterization of the spatially (and sometimes temporally) varying pattern of source vibration can be performed using holography or direct measurement with a laser Doppler vibrometer. Holography involves measuring the acoustic pressure over a surface that encloses the source or, in practice, over a surface that captures most of the emitted energy (Sapozhnikov et al., 2015). The measured pressure is then numerically projected back to the source surface (or a nearby plane) to obtain a spatially varying pressure or velocity distribution for input into the model. Holography measurements are normally conducted with the transducer driven at a low level to ensure linear wave propagation, with source conditions at higher drive levels extrapolated based on additional measurements made using a radiation force balance.

Regarding the acoustic material properties, for patient-specific simulations, these are typically obtained from standard medical images such as X-ray computed tomography (CT) or magnetic resonance (MR) imaging. When using CT images, it is possible to convert the grayscale values in the image to the mass density of the tissue based on a stoichiometric calibration of the CT scanner. The sound speed and absorption coefficient can then be inferred from the mass density, albeit with relatively large uncertainties (Mast, 2000). When using MR images, the different organs within the body must first be segmented, and then values for the tissue properties are assigned (these values are usually taken from previous measurements reported in the literature made using ex vivo tissue samples). Perhaps unsurprisingly, uncertainties in the geometry and properties of the body (particularly the sound speed) form a significant source of error in model-based predictions made for ultrasound therapy (Robertson et al., 2017b).

Model Validation

Checking whether a computer program gives the correct answer under different circumstances is known as *model validation*. Errors can come from any of the four preceding steps in the circle of model development, including invalid assumptions made when developing the governing equations, the wrong choice of grid parameters in the numerical model, mistakes in the computer code or rounding and overflow errors, and inaccuracies in the acoustic material properties or source conditions. The validation of numerical models is an important part of the software design life cycle, particularly in the context of therapeutic ultrasound where software may be used to derive treatment parameters or influence clinical decisions.

Model accuracy is generally tested in several stages, including

(1) performing a convergence test;
(2) comparing with analytical solutions, for example, the scattering of a plane wave by a sphere;
(3) quantitatively comparing the predicted acoustic field against well-controlled laboratory experiments;
(4) quantitatively comparing with experiments conducted using ex vivo tissue or animal models; and
(5) comparing against the outcome of clinical treatments in patients, for example, comparing the volume of ablated tissue after a treatment using high-intensity focused ultrasound.

For therapeutic ultrasound, there are a limited number of relevant analytical solutions, and it is often difficult to quantify model accuracy (or the origins of any discrepancies) using clinical data. Consequently, the bulk of model validation is performed using experimental measurements.

When performing experimental validation, there are two main challenges. The first is precisely replicating the experimental setup in the computer simulation, for example, the characteristics of the ultrasound transducer, the acoustic properties of the medium, the geometry and position of any scattering objects, and the spatial locations at which the pressure is measured. Errors in any of these will lead to discrepancies between the model and measurement. One approach is to use simple geometries and standardized materials with well-known properties. For example, phantoms with precisely known geometries can be created using 3-D printing as seen in **Figure 3** (Robertson et al., 2017b). Unfortunately, performing quantitative validation measurements using more realistic biological specimens such as ex vivo skull samples remains a difficult task.

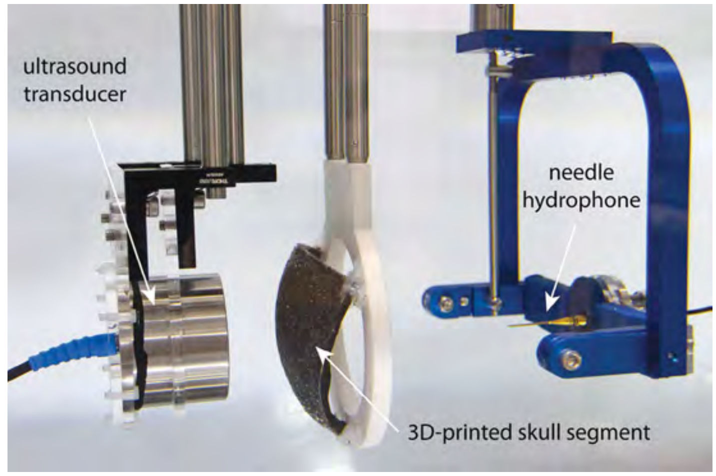

Figure 3. *Measurement of the acoustic field behind a 3-D-printed skull segment (**center**) using a focused ultrasound transducer (**left**) and a needle hydrophone (**right**) in a water tank.*

The second challenge is obtaining accurate, absolute measurements of acoustic pressure. It cannot be assumed that a measurement is the ground truth because there are many factors that give rise to measurement uncertainties. Variations can occur in the transducer output due to fluctuations in the supplied voltage, the electrical impedance, or changes in the water temperature. Errors can also arise from the alignment and positioning of the source and receiver, misalignment of scanning-system axes, and interference from acoustic reflections. Perhaps most importantly, the properties of the hydrophone used can have a significant influence on the measurement. For example, the finite size of the hydrophone detector element can give rise to spatial averaging effects, particularly for the tightly focused fields used in ultrasound therapy. Moreover, for some hydrophones, the frequency-dependent sensitivity is nonuniform in both magnitude and phase, which can result in significant pressure errors if not properly deconvolved from the measurement data (Wear et al., 2014). Unfortunately, uncertainties in the sensitivity are typically 6-15% depending on frequency, and the angle dependence is not normally known, which ultimately limits the precision of any pressure measurement. These uncertainties should be carefully considered when using experimental data for model validation.

Outlook and Summary

Recent advances in numerical methods and high-performance computing mean that large-scale full-wave simulations of ultrasound propagation in the human body are now within reach. These models have a myriad of uses in ultrasound therapy, including patient selection (determining whether a patient is a good candidate for a particular procedure based on their individual anatomy), treatment verification (determining the cause of adverse events or treatment failures), and model-based treatment planning (determining the best transducer position and sonication parameters to deliver the ultrasound energy). Models are also being increasingly used to characterize clinical equipment and as part of regulatory submissions (the US Food and Drug Administration has recently published guidance on the reporting of computational modeling studies that form part of medical device submissions). One major challenge is obtaining sufficiently accurate maps of material properties. Ultimately, models must balance increasing model complexity (e.g., including shear waves) with the effect of parameter uncertainty on the simulated results. The circle of model development discussed here can be used as a guide for those developing models as well as to aid users in the selection and evaluation of models.

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BioSketches

Bradley E. Treeby is an Engineering and Physical Sciences Research Council (EPSRC) Early Career Fellow, Department of Medical Physics and Biomedical Engineering, University College London, and coauthor of the open-source k-Wave Toolbox. He received the 2017 R. Bruce Lindsay Award from the Acoustical Society of America for "contributions to the modeling of biomedical ultrasound fields."

Jiri Jaros is an associate professor in the Faculty of Information Technology, Brno University of Technology, Czech Republic, leader of the Supercomputing Technologies Research Group, and coauthor of the k-Wave Toolbox. For more than a decade, he has been working in the area of high-performance computing, scientific code development, parallel and distributed algorithms, and numerical simulations.

Eleanor Martin is a research associate in the Department of Medical Physics and Biomedical Engineering, University College London, and an expert in ultrasound metrology. Her current research interests include model validation and the design and characterization of multielement arrays for therapeutic ultrasound.

Ben T. Cox is a reader in the Department of Medical Physics and Biomedical Engineering, University College London, Undergraduate Programme Director of Medical Physics, and coauthor of the k-Wave Toolbox. He teaches ultrasound and biomedical optics, and his research interests are in ultrasound and photoacoustic imaging.

Sound Perspectives

Ask an Acoustician: Sam H. Ridgway

Sam H. Ridgway

Address:
National Marine
Mammal Foundation
2240 Shelter Island Drive
Suite 200
San Diego, California 92106
USA

Department of Pathology
School of Medicine
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093
USA

Email:
sam.ridgway@nmmpfoundation.org

Micheal L. Dent

Address:
Department of Psychology
University at Buffalo
State University of New York (SUNY)
B76 Park Hall
Buffalo, New York 14260
USA

Email:
mdent@buffalo.edu

Meet Sam H. Ridgway

In this issue, "Ask an Acoustician" features Sam H. Ridgway. Sam is president of the National Marine Mammal Foundation, San Diego, CA, and is known as the father of marine mammal medicine. He is a Fellow of the Acoustical Society of America (ASA) for his pioneering work on marine mammal hearing. Sam is also the recipient of numerous prestigious awards, including the Lifetime and Clinical Medicine Award from the International Association for Aquatic Animal Medicine and the Kenneth S. Norris Lifetime Achievement Award from the Society for Marine Mammalogy.

A Conversation with Sam Ridgway, in His Words

Tell us about your work.

I currently provide corporate memory, mentor professionals, and serve as a knowledge resource for the Navy Marine Mammal Program. My current work can be described in three words: dolphin, brain, and ear. We have just started a project, "Sounds as Indicators of Health and Welfare," where we will surreptitiously record dolphin sounds to identify their call repertoire. The dolphins will go about their regular tasks and behaviors without interference. We think that dolphin sound production may give us an early warning of their illnesses and injuries. To see if this is true, we must identify their individual sounds and the context and frequency of their use. Over the three years of the project, these data will be correlated with veterinary observations in our current care program. At the end of the project, we hope to be able to use sound to appreciate dolphin welfare, detect illness early, and keep them healthy.

I also look at brain structure to compare different cetacean species. I want to know how the auditory system scales in different-size brains (Ridgway et al., 2018). I also want to know how sound production is implemented by the two hemispheres of the brain. Dolphins pulse on the right side and "whistle" on the left side of the nasal system, and so it is possible that both sides of the brain are involved in interesting ways (Ridgway et al., 2015; Wright et al., 2017).

Describe your career path.

Growing up on a Texas farm, surrounded by livestock, I admired the work of veterinarians and chose that field at the age of 12. I did not deviate from my goal, and Texas A&M University, College Station, awarded me a Doctor of Veterinary Medicine 11 years later, in May 1960. Commissioned as a military veterinarian, I was ordered to a base in Ventura County, CA. Some of my responsibilities were

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at nearby Point Mugu. There, the Navy was starting a study on marine mammal hydrodynamics, diving, and sonar, and I became Animal Health Officer. Excited by this challenge, I have been with the Navy Marine Mammal Program since, except for a fellowship to earn a PhD in neurobiology at the University of Cambridge, UK.

What is a typical day for you?
Before breakfast, I sit and grab my laptop and check two email accounts. After breakfast, I try and answer emails that are mostly from my coworkers. Later, I go in to the office for meetings with our different teams. I look out on our dolphin and sea lion areas and enjoy seeing boats coming to and fro taking animals out to sea for their daily ocean work. In between, I try and get some work on reports and papers. These days, I am at the office only 4 or 5 hours and then go back home.

Twenty to 50 years ago, my day was quite different. I would make rounds, checking all the animals, and perhaps go to sea for a test or experiment. I describe this in *The Dolphin Doctor* (Ridgway, 1987).

How do you feel when experiments projects do not work out the way you expected them to?
Some of my earliest experiments did not work out the way I expected. It was very exciting to me! I had to learn more and find out why.

Do you feel like you have solved the work-life balance problem? Was it always this way?
I was once given an award by some college classmates at a reunion: "Made It with Limited Capabilities." I quote from one of my mentors: "Sam possessed an inexhaustible energy along with a wide-ranging curiosity, an inventive mind, and a dogged persistence. He worked all day at the facility, usually came in on weekends to check the animals and administer needed medication, and spent his evenings writing technical papers. Within three years he had acquired an international reputation in the field of marine mammal medicine, and a couple of years later he was also becoming known as a physiologist" (Wood, 1973).

Fortunately, my wife Jeanette was an English teacher (later a college professor at the University of California, Los Angeles) who also had after hours work to do. Not long after our marriage in 1960, we learned we could not have children. Thus, life and work were intertwined in such a way as to allow for play in many gaps.

What makes you a good acoustician?
I stay in my own lane. When I have a problem, I ask my many friends in acoustics for help. A good acoustician must be involved in the field and must communicate with colleagues.

How do you handle rejection?
I immediately look for a work-around. I do not give up. If I get lemons, I try and make lemonade.

What are you proudest of in your career?
Some colleagues call me the father of marine mammal medicine. When, as a military veterinary officer and recent graduate, I was handed the task of keeping Navy marine mammals healthy, I had no knowledge of the subject and few resources to guide me. There were no other veterinarians working full time in the field. My efforts were supported by many mentors who knew the science but not the medicine. From such beginnings, we erected marine mammal medicine. Well over 100 individuals around the world practice it today.

We learned how to safely handle and treat dolphins in a safe and humane manner. For example, development of safe anesthesia allowed studies of the ear and brain that could not be done otherwise. Thus, medical knowledge served science. In 1965, I published a safe and humane method of dolphin anesthesia (Ridgway, 1965; McCormick and Ridgway, 2018). On the recommendation of W. E. (Bill) Schevill of Woods Hole, MA, E. G. Wever of Princeton, NJ (see acousticstoday.org/7408-2), and his graduate student James McCormick sought me out to work with them on dolphin hearing mechanisms. McCormick spent two summers with me at Point Mugu perfecting methods. Then I got to work several productive periods at the Princeton Auditory Research Laboratories. In the late 1960s, Jim Simmons, Jim Saunders, and Richard Fay were also there. It was an exciting time. On occasion, McCormick and I would work around the clock to complete an experiment. The experiments revealed not only the physiology of dolphin hearing but also the structure of the dolphin cochlea (McCormick et al., 1970; Wever et al., 1971).

The Princeton experiments baptized me in acoustics. In the 1970s, Don Carder, Bob Seeley, and I developed some methods for electrophysiological tests of dolphin hearing. We made many proposals to test this method on beached whales and dolphins. Along with C. Scott Johnson, we frequently needled our Navy sponsors about supporting more work on whale and dolphin hearing. In more recent years, our primitive methods have been made effective and modern by Dorian Houser and James Finneran (e.g., Finneran et al., 2018). Finally, in the early 1990s (encouraged by Dennis McFadden and others), we got the first funding to look at temporary threshold shift (TTS) in dolphins and belugas.

This is the story. In 1995, I was in Washington, DC, and Kim DePaul of the Navy Environmental Office took me over to one of the Program Executive Officers who had a pending Environmental Impact Statement. Fortunately, I had my new 14-pound laptop (COMPAQ SLT/286). I set it up on a conference table and completed the proposal right there (to paraphrase President Theodore Roosevelt: "If you have them by the nuts, their hearts and minds will follow"). Tim McBride was a Navy environmental manager who helped move the project along. This funded proposal led to a long series of TTS tests to set safety criteria for marine mammal sound exposure for many species by many investigators. For me, the field leaped forward when the ASA gave James Finneran a Hunt Postdoctoral Fellowship, and he joined our group 19 years ago.

What is the biggest mistake you've ever made?
In acoustics, my biggest mistake was to miss the high-frequency narrowband pulses emitted by Dall porpoises. I had some of these interesting animals from 1964 to 1966 but published a low-frequency sonogram that apparently recorded only the envelope. Now we know that all porpoises (family Phocoenidae), including Dall porpoises, produce very short (50-ms) narrowband pulses centered at frequencies over 100 kHz. But I learned from the Dall porpoise mistake. When Don Carder and I went to Baltimore, MD, to test the hearing of a pygmy sperm whale, we were prepared. We were surprised to find that this little whale could echolocate almost continuously with high-frequency narrowband clicks similar to the porpoises. It had hearing sensitivity to match its clicks (Ridgway and Carder, 2001; Madsen et al., 2005).

What advice do you have for budding acousticians?
Learn math and how to calibrate instrumentation needed in the field.

Have you ever experienced imposter syndrome? How did you deal with that if so?
Yes! I experience imposter syndrome every time I am at an ASA meeting and the presenter starts showing complex equations. (Bill Schevill called this "sheet music.") I do not understand these. A good acoustician should understand. I calm myself by thinking "maybe I can help with anatomy."

What do you want to accomplish within the next 10 years or before retirement?
I agreed to do a book called the *Brains of Dolphins*. I also agreed on two book chapters. I hope to revise my old book *Mammals of the Sea: Biology and Medicine* (Ridgway, 1972). Also, I would like to do a sequel to *Dolphin Doctor*. And like all biologist and bioacoustics folks, there are observations still to publish. So that should take up 10 years!

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Sound Perspectives

Taking the Leap and Getting Involved as a Student in the Acoustical Society of America

Kali Burke

Address:
Department of Psychology
University at Buffalo
State University of New York (SUNY)
Buffalo, New York 14260
USA

Email:
kaliburk@buffalo.edu

William J. Doebler

Address:
Graduate Program in Acoustics
The Pennsylvania State University
University Park, Pennsylvania 16802
USA

Email:
wfd5057@psu.edu

Are you an undergraduate or graduate student with an interest in any aspect of acoustics? Are you a graduate student who has attended a meeting of the Acoustical Society of America (ASA)? Perhaps you are an investigator interested in learning about the opportunities within the ASA available to your students? In this essay, we will outline numerous ways to get involved in the ASA as a student.

The whole process of navigating scientific societies such as the ASA can sometimes seem daunting and overwhelming for students, especially first-time conference attendees. You may have spent months or years preparing your research for a poster or presentation, and you are feeling nervous. The nervousness can affect the amount of time you spend planning your schedule to optimize your conference experience from both academic and networking perspectives. Travel funding can be difficult to obtain as a student researcher, adding to your stress levels.

What you will quickly discover, however, is that the ASA welcomes, supports, and values student members and does all that it can to make student participation at the meetings a really meaningful and valuable experience. Just to start, student members of the ASA can apply for travel subsidies and grants to alleviate some of the financial burden. These subsidies are designed to allow students to extend their conference attendance from the one day they present their research to several days or even the entire week. More time at the conference means more time learning from and interacting with experts in your field of acoustics. As a student member of the ASA, you are also eligible for its many scholarships and fellowships. Furthermore, if you will be presenting your research at the conference, you can opt to be considered for the Best Student Paper competitions, which include cash prizes. More information about all of these opportunities are available on the ASA student web page (ASAStudents.org).

At the fall and spring meetings of the ASA, there are several student activities geared toward meeting new people and learning more about the Society. The first afternoon at each conference is packed with activities for students. First, there is an orientation presentation, which highlights the events and opportunities available specifically for students at the conference. Immediately following the presentation, all students are invited to attend the Student Meet and Greet for hors d'oeuvres, to mingle with other students in acoustics, and to pick up the exclusive ASA Student swag item such as headphones or a mug. The evening concludes with the Student Outing, another opportunity for peer-to-peer networking and camaraderie at a local gastropub.

The second and fourth evenings of the conference feature more food and networking opportunities at the ASA Social Hour where students can mingle with more senior members and develop networking opportunities. The third evening features the Students Reception, which is yet another networking event that brings students and potential employers together. This event also features food and drink in a relaxed

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atmosphere as well as a raffle to attend the Society Luncheon and Lecture. For more information about student activities at the meeting, see Flynn and Young (2018) in a previous issue of *Acoustics Today*.

Another amazing program that students can sign up for is Students Meet Members for Lunch. This program matches a student and an ASA member with similar interests so they can get to know each other over lunch. These events are described in more detail by Blackstock (2015) in a previous issue of *Acoustics Today*. Be sure to follow the ASA Student Council on Twitter and Facebook (@ASAStudents) for updates on these events and other news.

The Technical Committee (TC) meetings also provide excellent opportunities to learn about news from previous ASA meetings (e.g., award winners from the Best Student Paper competitions) as well as learning about other symposia or workshops that may be relevant to your TC. It is also useful to attend the TC meetings adjacent to your primary research interests to get to know other acousticians and form cross-TC collaborations.

There are other events, some of which require the purchase of a ticket, which provide excellent opportunities to meet experts in your field. The Women in Acoustics Roundtable Discussion and Luncheon are two opportunities for men and women interested in any area of acoustics to speak with successful women who have paved the path for other women (more by Ronsse and Neilsen [2017] in a previous issue of *Acoustics Today*). The Society Luncheon hosted by the College of Fellows is another opportunity to have lunch with a Fellow in your TC and ask them questions about any stage of your academic or industry-based career. The Fellows are generally more senior members of the ASA who have made significant contributions to their discipline and can share a lot of information about the field.

Another opportunity to keep an eye out for is one of the smaller satellite meetings, often sponsored by the ASA and usually associated with one or two TCs and focusing on one main area of acoustics. For example, the 4th Acoustic Communication by Animals Symposium was held in Omaha, NE, at the Henry Doorly Zoo in 2017. Another example is the Physical Acoustics Summer School hosted by the University of Mississippi, Oxford. Ask members at your TC meeting if there are any upcoming symposia that might be of interest (or attend the TC meeting at the next conference). Regional or student chapters of ASA (discussed by Good and Mauck [2018] in a previous issue of *Acoustics Today*) are another great way to connect with local acousticians in your area. A listing of these chapters is available at ASAChapters.org.

Other ways to engage with the Society as a member are by reading issues of *Acoustics Today* and *Physics Today*, both of which are included as part of your ASA membership. Articles in these magazines are typically written by established investigators who describe their research in an approachable manner. You can also subscribe to the Acoustics list-serv to get updates on the most recent articles published in *The Journal of the Acoustical Society of America*.

If you are in an earlier stage of your career, perhaps an undergraduate or a student in a master's program looking for doctoral programs in acoustics, you can check out the ExploreSound site (exploresound.org) as a way to search for programs that might fit your graduate study interests. ExploreSound is not just a site for early-career students, however; it is also a site that can help senior doctoral students find postdoctoral opportunities. This site is also useful for anyone looking for collaborations.

The networking opportunities available to students through the ASA can help you to develop better research questions, learn about the most recent research in your field, find a postdoctoral position or future job opportunity, and hopefully help lead to a fruitful career in acoustics. For more information about networking, see the essay by Neilsen, Ronsee, and Zhao in this issue of *Acoustics Today*.

In summary, there are a number of ways for students to get involved in the ASA. Please consider becoming a student member. Graduate students receive a discounted rate for membership fees; they can get print copies of the program mailed before the conference, if requested (to help with planning out your weekly schedule in advance), and automatically get access to the online resources of the Society. Membership is also the best way to get updated on things like job postings, future symposia, and other ways to engage with the Society.

Take the first steps to getting involved in the ASA and reach out to your Student Council representative. Members of the Student Council are friendly graduate students who are informed about all of the upcoming events within the Society. Should you become a member, you can also apply to become a Student Council representative for your TC. Putting forth the effort and getting involved as a student in the ASA will develop strategies for a successful career in your field.

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Where do you read your *Acoustics Today?*

Take a photo of yourself reading a copy of ***Acoustics Today*** and share it on social media* (tagging #AcousticsToday, of course). We'll pick our favorite and include it in the next issue of ***AT***. Don't do social media but still want to provide a picture? Email it to ksetzer@acousticalsociety.org.

** By submitting, the subject agrees to image being used in* AT *and/or on the* AT *website. Please do not include children in the image unless you, as their parent or guardian, can give explicit written permission for use.*

Kelsey Hochgraf of Acentech, Inc. poses with the winter 2018 issue of AT, which includes her article about concert hall acoustics. Photo taken by Amanda Alcamo.

It's never too young to start learning about acoustics! Marek Kovacik (Convergent Technologies Design Group) reads to his son, Isaac, from the spring issue of AT. Photo taken by Cory Kovacik.

Dan Russell (Pennsylvania State University) used some of his downtime during the recent ASA meeting in Louisville, KY to visit the Louisville Slugger Museum & Factory. He shows off his winter 2017 cover article about baseball bat acoustics while standing in front of the world's largest baseball bat. Photos taken by Dr. Kenneth A. Pestka II.

Sound Perspectives

It Is Our Responsibility to Teach Science Communication to Students

Laura N. Kloepper

Address:
Saint Mary's College
262 Science Hall
Notre Dame, Indiana 46556
USA

Email:
lkloepper@saintmarys.edu

Science and technology impact the lives of everyday citizens, but we currently face a lack of understanding of even basic scientific concepts by the general public. For example, only about one in five Americans is considered "scientifically literate" (Miller, 2010). Various factors affect knowledge and attitudes toward science, including age, race, educational level, and political ideology (PEW Research Center, 2015; American Academy of Arts and Sciences, 2018), but the perception of science directly influences public support of funding for scientific research (Allum et al., 2008; Muñoz et al., 2012). Unfortunately, we have a history of a bad public perception of science, especially in the media. Perhaps you remember the "shrimp on a treadmill" story from 2011, in which a National Science Foundation-funded study to investigate the response of marine organisms to climate change was twisted into headlines proclaiming scientists were "wasting" millions of taxpayers' dollars to force shrimp to exercise (National Public Radio, 2011). Or what about the current "anti-vax" movement, initiated by dramatic headlines and celebrity endorsements, which has led to multiple measles outbreaks across the United States (*The New York Times*, 2019)? As scientists, we may think this isn't our problem. After all, we are scientifically literate. We conduct research, attend conferences, and publish papers. It's not our fault that nonscientists can't understand the different between evidence-based research and headline-grabbing taglines. That's the job for the media, right?

Albert Einstein once said, "You do not really understand something unless you can explain it to your grandmother." Even though this statement was delivered before the rise of social media and 24/7 news cycles, his words are even more important today. I argue that it is indeed every scientist's responsibility to learn how to effectively communicate the key ideas of their research to the general public, including the societal relevance of their work. As scientists, we cannot rely on others to communicate our research. We must all be advocates for science and help promote the importance of research funding through effective science communication. Otherwise, we face the continued problem of science skepticism, which bleeds into our politicians and directly impacts our ability to secure future research funding. Whether our communication is through technical writing, conference presentations, discussions with the media, tweets, or even informal conversations with airline seatmates, scientists everywhere need to learn effective strategies to communicate science to a wide audience. Fortunately, we are beginning to understand the importance of science communication, and there are numerous workshops and seminars that scientists can attend to hone their communication skills (e.g., aldacenter.org/workshops; aaas.org/programs/communicating-science; comscicon.com; sciencetalk.org). But with the increasing demand of time on scientists, are extracurricular workshops enough?

If we want to truly effect change, we need to view science communication as a fundamental skill that we teach our students. A recent survey of the acoustics graduate programs listed in the Acoustical Society of America Acoustics Program Directory determined that although writing is informally part of the graduate education process, only 9% of programs have required science writing courses (either technical, i.e., scientific papers,

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or nontechnical, i.e., writing for the public) for graduate students, and 36% have optional science writing programs. No programs have required courses on science communication, and only 32% of programs have optional science communication courses.

Including a required scientific writing and communication course into the curriculum of a program, especially in the first year of graduate school, would better equip students to present at conferences, network with future employers, write a thesis, and communicate science at outreach events. For several years, I have been teaching a semester-long course emphasizing both technical and nontechnical science communication (Kloepper, 2017). Through this course, students learn to design and deliver effective scientific presentations, speak to potential program officers or collaborators in the form of an elevator pitch, write organized research papers with clarity and flow, and speak informally to the public about science. More importantly, students immerse themselves in science communication outside the classroom, evaluating science communication activities from a wide range of events including academic lectures, public outreach events, TED talks, and press conferences. Student evaluation of the course has always been high, with many students stating this as a transformative course for their education and career development.

I designed this course as a writing-intensive course with the goal of improving every student's writing, and students submit weekly writing assignments. My class compositions have ranged from nonnative English speakers to accomplished writers, but every student has consistently shown improvement in writing style by the end of the course. Students complete online grammar quizzes and watch videos from the Comma Queen at *The New Yorker* (2019) to understand common writing pitfalls. Peer review is also a strong component of the course; students learn to critically and constructively evaluate the writing of their peers, which leads to a better awareness of one's own writing.

In addition to an emphasis on writing, the course also helps students develop more confidence with public speaking. Early in the course, students learn how to develop and present an elevator pitch about their research, which they deliver to the class and a panel of faculty evaluators. Students also learn the fundamentals of a PowerPoint slide design and give a research presentation to their peers. Once students have mastered the technical communication of their work, we move on to nontechnical communication. The first step is teaching students how to identify and communicate the societal relevance of their work or, as I call it, the "why should my tax dollars fund your research" approach. Once students have identified how to communicate the societal relevance, they learn how to tailor their nontechnical communication to diverse audiences. Effective oral communication is honed through regular simulations in which students draw a target audience from a cup and then deliver their message to their peers, who act as the target audience. Through these simulations, students learn to be comfortable discussing science to audiences of different ages, education levels, and political ideology. More importantly, students learn to engage others in a conversation about science rather than a one-way lecture.

I encourage all readers who are part of academic departments to consider including a science writing and communication course into required graduate and undergraduate coursework for your students. It is our responsibility to equip students with the skills necessary to be effective communicators of science; their future research funding depends on it. Changing the public's attitude and understanding about science won't happen overnight. It won't happen with one headline. Change happens slowly, one conversation at a time. Let us help inspire students to control the narrative, regain the public's trust in and excitement about science, and lead that change.

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Tracianne B. Neilsen

Address:
Department of Physics and Astronomy
Brigham Young University
Provo, Utah 84097
USA

Email:
tbn@byu.edu

Lauren M. Ronsse

Address:
Durham School of Architectural
Engineering and Construction
University of Nebraska-Lincoln
1110 South 67th Street
Omaha, Nebraska 68182
USA

Email:
lronsse@unl.edu

T. Christina Zhao

Address:
Institute for Learning &
Brain Sciences (I-LABS)
University of Washington
Seattle, Washington 98195
USA

Email:
zhaotc@uw.edu

Networking Up

Introduction

"No one told me that a career in STEM would require me to be an entrepreneur!" summarizes a discovery commonly made by scientists, engineers, and other professionals. Whether in consulting, industry, or academia, success at all stages of your career is expedited as you develop entrepreneurial skills. One of these important, lifelong skills is networking. Although some might feel uncomfortable networking or think that their work should speak for itself, a slight shift in perspective can make networking more palatable and provide opportunities that you can get in no other way.

Indeed, consider yourself in the center of a web, connected to others in your field and at your place of employment. You have opportunities to assist those less experienced on the web through mentoring students or early-career colleagues (Bent, 2016; Gee and Popper, 2017). Peer networking is reaching out to those on roughly the same level of the web or stage in their career. These connections can provide camaraderie, support, and opportunities for fruitful collaborations starting as early as graduate school. However, if you desire to advance your ideas, you need to "network up" by connecting with experts and other influential people. At all levels, expanding your networking web requires making personal connections, from which lifelong mentoring opportunities and friendships can emerge.

Examples of networking are provided by the women honored at the Women in Acoustics Named Luncheons in 2018: Winifred Strange and Patricia (Pat) Kuhl. Here we highlight their careers and provide concrete ideas for networking up, with input from other Acoustical Society of America (ASA) members. We hope that these suggestions will increase motivation and help reduce fears as students and young professionals strive to network up.

Honored Women

Spring 2018 Honoree Winifred Strange

Winifred Strange is a pioneer in cross-language speech perception research and the influence of linguistic experience and perceptual training on nonnative speech perception. She completed her PhD in Psychology at the University of Minnesota, Minneapolis, in 1972 and then served as a faculty member at the University of Minnesota, the University of South Florida, Tampa, and the City University of New York Graduate Center. Winifred was elected a Fellow of the ASA in 1992 and served as a member of the Executive Council from 2001 to 2004. In 2008, she received a Silver Medal in Speech Communication for her contributions to understanding speech perception.

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Winifred supported and mentored more than 50 students and junior colleagues through 20+ federally funded grants. Her contagious enthusiasm for her field attracted students and colleagues from many disciplines. Winifred expanded the field of speech perception research through her inspiring mentorship and her active participation in national and international collaborative research. She has also been an excellent example in showing how having a nonacademic passion, in her case, dance, allows us to maintain a healthy work-life balance and, in return, energizes our science careers.

Fall 2018 Honoree
Patricia Kuhl

Patricia (Pat) Kuhl has devoted her research career to understanding speech perception and early learning of speech and language. Pat completed a PhD in Speech Science at the University of Minnesota, Minneapolis, and postdoctoral training at the Central Institute for the Deaf, St. Louis, (MO), before joining the University of Washington, Seattle, as a faculty member.

Pat has served on numerous ASA committees and was the president of the Society from 1999 to 2000. As ASA president, she focused on issues close to her heart: women's and students' involvement. She initiated the ASA Student Council, which has improved the student experience tremendously (Flynn and Young, 2018), and the percentage of female members in the Society has risen significantly (Ronsse and Neilsen, 2017).

Pat has an extensive network that includes experts from around the world. Pat is a Fellow of the ASA, the American Psychological Society, and the American Association for the Advancement of Science and a member of the National Academy of Sciences. She has received many awards, including the ASA Silver Medal in 1997 and Gold Medal in 2008 for contributions to understanding how children acquire spoken language and for leadership in the Society. She belongs to the Seattle Hall of Fame: 125 Most Influential People in a 50-year History. Pat spoke at three White House conferences: First Lady Hilary Clinton's White House Conference on Early Childhood Development and Learning in 1997, First Lady Laura Bush's Learning to Read Conference in 2001, and President Obama's Summit on Early Learning in 2014.

Discussion

Both Winifred and Pat are successful, in part, because of their ability to connect with people at all levels and share their enthusiasm for their research.

One of Winifred's former students, Kanae Nishi, recalls how Winifred provided her mentees with opportunities to interact in a casual setting with those in different career stages. "Her lab meetings were open to anyone interested. She is a big supporter of the multidisciplinary research environment and collaborations."

A senior mentor once told Pat, who was extremely nervous about making a research presentation, that she should concentrate on the fact that "science is always about the ideas, not about you." She has been living by that rule ever since. When there were difficult talks to give in front of hundreds of people or a research finding that was unpopular among colleagues, she focused on making the science clear, producing more and stronger experimental results, and seeking advice and comments from senior colleagues about her research. Through that process, she gradually established herself and grew her network.

For some, networking up may come naturally; for others, questions abound as to how to approach the experts. For specific advice, we consulted a few ASA members at different stages of their careers and who are based in different work environments. Their responses and advice that are found in a few of the many available references (e.g., Burnett and Evans, 2016; Misner, 2017; Golde, 2016) are summarized here.

General Ideas for Networking Up

Networking on all levels is a give-and-take process. As a student or early-career professional, you benefit greatly by forming connections with senior people. Natural concerns may arise that you are inconveniencing or bothering them, or you may have fears that you will be rejected by or upset them. If plagued by such concerns or fears, expand your focus to include the other person. Consider how this interaction can benefit the person with whom you are connecting. As your focus expands, nervousness lessens, and the interaction becomes more shared, balanced, and meaningful.

Try to engage in a balanced conversation by asking questions about their career and experiences while also discussing your background, ideas, and interests. Avoid over-the-top praise. Instead, prepare genuine compliments about their contributions (e.g., technical, professional, service to the community) and how they have influenced you or, better yet, others (Misner, 2017).

Although connecting with a wide variety of people is useful, efforts for networking up with those in your professional area benefit from preparation. When approaching an expert with whom you hope to connect, prepare by familiarizing yourself with the technical language and/or jargon of the field and a general understanding of their work and its value.

Many senior professionals appreciate the opportunity to help others, especially students. However, when approaching a senior person, remember that they are likely to have many obligations and only limited available time. When asking for help, try to leave a way for them to politely decline without embarrassment or suggest an alternate timeline. If they agree to meet with you, review a proposal, or give a presentation, find ways to efficiently use the limited time they have to offer. Never ask a senior mentor for a last-minute favor; make your request with a long lead time.

Networking at Conferences

Meetings, workshops, and conferences provide remarkable opportunities for learning and expanding your network. Make sure your speech, dress, and body language are respectful and professional at all times. (This holds for all professional interactions, especially job interviews.) Avoid complaining or sharing critical comments about colleagues; you don't want to be remembered for being negative.

At the conference, attend presentations and ask good questions. If you follow up with the speaker after their presentation, begin by briefly introducing yourself. Sometimes it's useful to lift your name tag up to eye level during the introduction so that they can see your name and affiliation, especially if spelling or pronunciation is tricky. If they know (or know of) your mentor or collaborators, mention your connections. Prepare business cards before the conference and tuck some in your name badge so they are easily accessible. If there is limited time for discussion, offer your business card and ask if it is OK to follow up with an email. Because conferences can be hectic, especially for people in leadership roles, follow-up communications should include a reminder of who you are, where you met, and about what you talked. One idea for following up is sending a "thank you" message, especially if the person spent significant time talking with you, referred you to another colleague, or gave you a new idea (Golde, 2016).

If you initiate a conversation that is awkward or ends poorly, try to take it in stride. After calming down, remind yourself that the other person might have a lot going on "behind the scenes" that may have influenced their reaction. Review the conversation to learn if there was something you could have said or done differently, then move forward (Golde, 2016).

Socials and coffee breaks are also great opportunities to overcome your natural fears about approaching people who you don't know or to whom you haven't yet been introduced. If you see someone standing alone, that's a great time to approach them and start a conversation.

Conferences are also a good time to look for opportunities to volunteer. Volunteering expands your network because you interact informally with others, including senior people. Shared experiences, such as those formed while working together on committees, create connections that make it easier to talk with people about other topics and expand your networking web in multiple directions. For students, the ASA Student Council has ways to get involved. Nonstudent volunteers are needed for numerous tasks (e.g., judging student talks, organizing special sessions). Volunteers are often requested at the open meetings of the technical committees.

Initiating a Discussion via Email

Because senior mentors receive a lot of unsolicited email messages, sending one to someone you've never met rarely works. If you are following up on a face-to-face meeting, such as at a conference, you have a better chance of receiving a response. If not, a good approach is to ask a trusted advisor or some other senior person you might have networked with informally to send an email introducing you to the senior mentor. Depending on the response, you can then follow up with your own email to the senior mentor with more specifics.

When composing an email to a new contact, use a professional tone and be sure to do your homework. Your initial email should be short and professional and include a clear subject line, a brief introduction including any professional connections, and where you've met before (if applicable). Develop an understanding of their contributions, experiences, or interests and ask specific answerable questions. A request for a phone call or video conference is often a good way to continue the connection.

Remember that senior people have a lot of email to wade through, so you will usually need to be patient. Wait at least

10 days before sending a second email and generally do not send a third unless they respond.

Connecting with Important People at Work

In addition to networking with those in your scientific field, it is necessary to build a network at your place of employment. These connections allow you to have people you can turn to as questions arise and have allies who can advocate for you. Take advantage of the natural opportunities that arise to mingle with people. Participate in social functions and events. Engage in balanced conversations, then follow up.

Another way to build your network is to look for opportunities to join committees or participate in other administrative tasks where you can interact with senior people outside your immediate work colleagues. Let the director of your program or your department chair know that you are interested in serving in this way. Often these leaders are asked to nominate people for these positions, so they usually appreciate knowing you will accept if asked. At the same time, be careful that you do not accept so many administrative tasks that it affects your work.

Conclusion

Networking up is the practice of seeking additional mentoring and opportunities throughout your career. Although finding your networking style will take practice, the first step is accepting that networking up is a good way to promote your ideas. If you focus on the ideas, as Pat Kuhl explained, it becomes easier not to take things personally and to push beyond your comfort zone. Ultimately, we are networking to achieve things, not networking for networking's sake. Networking up may require you to embrace discomfort as you try different approaches to enlarge your networking web. As you seek help from your networking-up connections, at some point you will be senior to others (e.g., a senior graduate student), and when someone seeks advice from you, be sure and give them the same courtesies and consideration given to you by your network.

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Sound Perspectives

Administrative Committee Report: Panel on Public Policy

Edward J. Walsh

Address:
Center for Applied and Translational Sensory Sciences
Department of Speech- Language-Hearing Sciences
University of Minnesota, Twin Cities
Minneapolis, Minnesota 55455
USA

Email:
ewalsh@umn.edu

The primary mission of the Panel on Public Policy is to represent the interests of the general public on matters of public policy related to acoustics and the advancement of science (bit.ly/2TUu7wE).

In June 2001, at the Chicago meeting of the Acoustical Society of America (ASA), the President and Executive Council authorized the formation of an ad hoc Panel on Public Policy. The inaugural meeting of the Panel convened at the Pittsburgh meeting in June 2002 and was integrated into the ASA infrastructure as an Administrative Committee in 2007. Now, nearly 20 years later, the Panel continues its work to identify and address public policy concerns related to acoustics and the advancement of science. This is the essential purpose of the Panel and its mission aligns with but also extends the Society's commitment "to generate, disseminate, and promote the knowledge and practical applications of acoustics" (acousticalsociety.org).

During its first 17 years of operation, the Panel focused on a number of questions with relatively wide-ranging societal, cultural, and global implications. However, within this larger framework, a significant fraction of time and effort has been devoted to societal concerns centering on the influence of noise on a variety of human as well as on nonhuman animal activities. From concerns related to the acoustic environment of the classroom to the soundscape of our national parks, cities, and oceans, Panel members work to determine whether it is in the interest of the Society and its members, and to society more generally, to prepare and advance policy positions on questions of science and human rights that arise in the workplace, in the halls of justice, and the corridors of government. The Panel has considered numerous policy-related questions over its lifetime, including:

(1) What should the ASA have to say on reverberation times and noise levels in classrooms?
(2) What guidance can the ASA offer policy makers on the complex question of anthropogenic ocean noise and its impact on marine mammals and other forms of sea life?
(3) Should the Society weigh in on the question of universal rights of persons with disability?

These, and many other like-minded questions, occupy the attention of the Panel on Public Policy at each ASA meeting.

Now, as the Panel emerges from its nearly two decades of operation, a new course has been set and new challenges await its members. In addition to the implementation of a restructuring plan designed to further enhance inclusivity (see **Reorganization and Inclusivity**), two initiatives with the capacity to alter the tenor as well as the structure of future meetings were considered at the ASA meeting in Victoria 2018. One outcome of those deliberations was a consensus to place greater emphasis on questions relating to the rights of acousticians, scientists, and engineers around the

https://doi.org/10.1121/AT.2019.15.2.57

world to carry out their work in a free and open environment. A second initiative to concentrate more attention on environmental concerns related to acoustics was also advanced. Although both of these areas have been of interest from the earliest days of operation of the Panel, the decision renews the commitment of the Panel to these public policy concerns by integrating two new subcommittees, the ASA and Human Rights Subcommittee and the Sound and the Environment Subcommittee, as part of its infrastructure.

The Acoustical Society of America and Human Rights Subcommittee

Although the ASA has a long record of commitment to a human rights agenda, that commitment was recently reinvigorated by accepting an invitation to become a Member Organization of the American Association for the Advancement of Science (AAAS) Science and Human Rights Coalition (SHRC; bit.ly/2KUOXoS). The mission of the SHRC is centered on the tenets of Article 15 of the International Covenant on Economic, Social and Cultural Rights (bit.ly/2MOWMwA), an international covenant that is an outgrowth of the 1948 Universal Declaration of Human Rights (bit.ly/1O8f0nS). There are four principal elements that form the core of Article 15, and they serve as an operational framework for the work of the ASA in the human rights arena.

(1) Recognize the right of everyone to enjoy the benefits of scientific progress and its applications.
(2) Conserve, develop, and diffuse science and culture.
(3) Respect the freedom indispensable for scientific research.
(4) Recognize the benefits of international contacts and cooperation in the scientific and cultural fields.

Arguably, the work of the ASA in this area has been blunted by the lack of an operational procedure within the Society to monitor, prepare reports, and pass action recommendations to the Executive Council regarding human rights questions and issues that relate to the mission of the ASA. Although that work has been, and continues to be, authoritatively informed through our association with the SHRC, the vision and mission of the ASA in this arena will be served more directly by ramping up our own internal attention to human rights questions that are immediately relevant to the Society as the work of the Panel moves forward.

Sound and the Environment Subcommittee

The charge of the Sound and Environment Subcommittee is to identify concerns related to the impact of climate change on the affairs of the acoustic community. How will the impact of extreme weather and the attendant disruption of otherwise stable planetwide natural systems affect the work of ASA members studying underwater acoustics; colleagues tracking the influence of anthropogenic noise on the health and welfare of terrestrial and aquatic species; or efforts to monitor atmospheric and oceanic conditions? Attention to these and the myriad other climate change concerns will occupy the work of Panel members serving on this subcommittee as the work of the Panel presses on.

Reorganization and Inclusivity

Structural rules established early on in the life of the Panel called for the involvement of a diversity of the many technical areas comprising the ASA membership. This structural requirement was formulated to ensure that "no Technical Committee or other ASA constituency hold a majority vote of the whole (bit.ly/2TUu7wE)." Although efforts to satisfy this directive have been to a large extent successful in that all 13 technical committees (TCs) have been represented on the Panel at one time or another, a proposed rule change will ensure that this goal is achieved on an ongoing basis. To ensure representation from each TC, a liaison from each committee will have a seat on the Panel and will be tasked with the responsibility of representing the interests of the Panel at each TC meeting by reporting on the proceedings of each meeting and soliciting input related to public policy questions and concerns from its members. By opening a direct channel of communication, our goal is to achieve the Society's mandate and air a full and robust consideration of ASA-relevant public policy interests.

Public Policy, the Acoustical Society of America, and the Future

There is much more to say with regard to where the Panel on Public Policy is heading than it is about its accomplishments, which are substantial in their own right. Although the publication of ASA Policy Statements (bit.ly/2TR62qL), brief declarations stating the position of the ASA on questions of public policy, have been the mainstay of the work of the Panel thus far, as the Panel moves forward, members of the Panel as well as of the ASA membership at large will be encouraged to consider the implementation of other, more extensive, policy-promoting instruments. In addition to issuing policy statements, the founders of the Panel, former Executive Director Charles Schmid, then-President William Hartman, and the first chair of the ad hoc Panel, Edward Walsh, envisioned the limited publication of more detailed reports and comprehensive white papers that address policy matters of vital interest to the organization. Although policy-related documents of this ilk are unexercised thus far, that situation can and should change. The ASA is recognized as the world's premier acoustics society and, as such, a solid argument can be made that the responsibility to provide data-driven, objectively prepared, and authoritatively written scientific reports on questions of relevance to the acoustics community falls squarely in the lap of the Society. There is no doubt that the cost of conducting business at this level is high, in terms of both human energy and financial resources, but the cost of inaction on this front may very well be even higher.

The Politics of Science and Public Policy

Although not an innately political organization, the ASA leadership understands the essential role that scientists, engineers, and scientific organizations play in the formulation of public policy relating to the scientific and technologically complex acoustics questions of the day. One broad question that emerges from this understanding is both apparent and foundational: "Do all public policy questions centering on 'acoustics' demand input from acousticians?" A lucid, if quarrelsome, reply to that question one may argue is yes. If an issue rises to a level of societal interest such that policy considerations are initiated, then balanced, rigorously objective, scientifically validated guidance from experts in the area is important, if not essential.

A second and equally critical question emerging from a discussion regarding the future of public policy and the ASA is to what extent our Society should invest in this arena. The answer to that question, one might argue, depends on the nature of the specific question under consideration, primarily its complexity. Technologically sophisticated and complex questions will, of necessity, demand the consumption of greater resources than simpler ones. Furthermore, efforts to prioritize policy concerns within the organization are expected to play a larger role in Panel planning as inclusivity goals are achieved and the magnitude of the need for policy-driven engagement increases. Panel members welcome that challenge and urge members of the Society, especially students and more junior members, to join us in this endeavor. Consider contributing to the process by sharing policy concerns with TC Panel liaisons and by attending the open meetings of the Panel. A more inclusive Society is, without question, a vital, more progressive, and forward-thinking Society. Lend your voice to this call for action and help take the ASA to new heights in the policy-making realm.

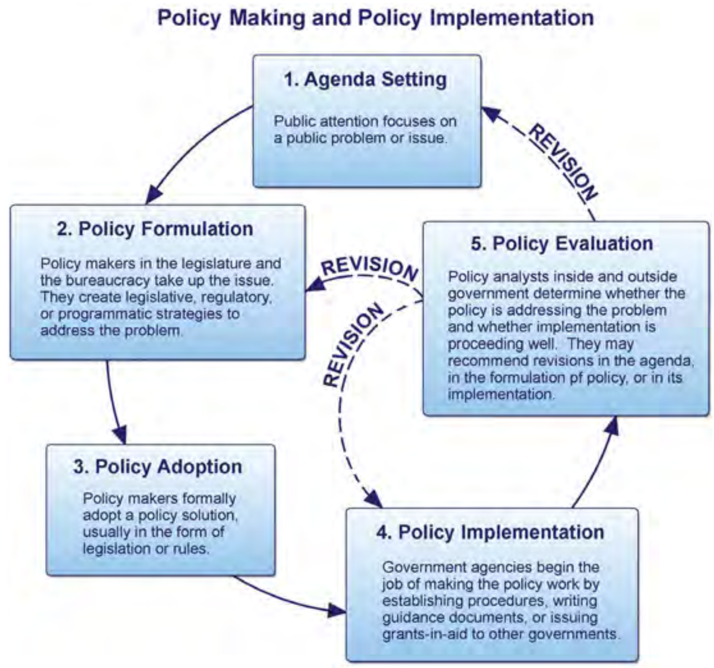

Figure 1. *Policy making is a cyclical process. It begins in the agenda-setting stage with recognition and definition of a significant public problem and an organized call to government action. In response, the legislative and bureaucratic machinery of government may formulate, adopt, and implement a strategy for addressing the problem. Analysis of policy effectiveness, in turn, often reveals shortcomings in formulation or implementation or new problems to add to the policy agenda. Adapted from "A Diagram of the Policy Making Process," with permission (bit.ly/2FfL2Sk).*

The Cyclical Nature of the Policy-Making Process

Before concluding, it may be worth reviewing the process whereby public policy is enacted. It is cyclical in nature, as suggested in the form of the flow chart shown in the **Figure 1**.

From the critical agenda-setting stage to the implementation and evaluation stages of the process, one key question that scientific and engineering organizations like the ASA have to internalize and resolve is the extent to which participation in each stage in the process should be formalized. To what extent and how, for example, should the ASA strive to take the lead in setting an agenda related to relevant public policy questions within the acoustics community are essential considerations when contemplating a coherent plan of engagement. It is at the early agenda-setting stage in the process that the influence of engagement can be most significant and most lasting. Solid scientific and engineering guidance based on rigorously applied rules of objectivity and reason, promulgated in a free and open atmosphere of exchange, can lay the foundation for meaningful deliberation at the next phase, the policy formulation or legislative phase that sets the stage for implementation.

How, then, does an organization like the ASA achieve this level of engagement? In the spring of 2015, four ASA Task Force Committees were established to advance the goals emerging from a Strategic Leadership for the Future Summit (bit.ly/2O879wN) that convened one year earlier and that was organized to address the question, "How will ASA need to change the way it does business... to maintain its position as the premier scientific society in acoustics?" (bit.ly/2JgSDnV). One evident change was to extend its mission by augmenting and enriching its commitment to public policy questions of interest to the Society.

Epilogue

A subset of the questions on the desk of the Panel on Public Policy today has been reviewed, and it is the consideration of these issues that will shape the future of the participation of the ASA in the public policy arena. As the Panel strives to refine and expand its mission and to develop innovative mechanisms to advance its goals, cultivating inclusivity remains a top priority. Although its mission remains essentially unchanged, it may well be time to consider a minor revision but one with powerful implications regarding the mission statement of the Panel, "to identify and address public policy concerns related to acoustics and the advancement of science," by extending its humanistic scope to include the phrase "and the welfare of humankind."

NEWS from the Acoustical Society Foundation Fund

I appreciate the opportunity to inform the membership and friends of the Acoustical Society of America (ASA) about the Acoustical Society Foundation Fund. The Fund derives from tax-deductible gifts and supports scholarships, grants, fellowships, and other special programs of the ASA. In future issues of *Acoustics Today*, I plan to feature each of these programs.

The William and Christine Hartmann Prize in Auditory Neuroscience was established in 2011 through a generous donation by Bill and Chris Hartmann to the ASA to recognize and honor research that links auditory physiology with auditory perception or behavior in humans or other animals. The Prize includes a cash award of $4,000 and a travel stipend to attend the ASA meeting where the award will be presented. Cindy Moss of Johns Hopkins University, Baltimore, MD, is a recent Prize winner and writes, "It's not every day that you're awarded a prize for work you love. I was thrilled and honored to be recognized with the Hartmann Prize for my research linking auditory neurophysiology and perception in echolocating bats. I'm now on sabbatical in Hong Kong, where I took very few personal items with me, but I did bring along my Hartmann Medal."

James H. Miller
Chair, Acoustical Society Foundation Board
miller@uri.edu

Mission of the Acoustical Society Foundation Board:
To support the mission of the ASA by developing financial resources for strategic initiatives and special purposes.

ASFF *For more information, contact James H. Miller at miller@uri.edu*

Obituary | Richard H. Lyon | *1929–2019*

Richard H. Lyon, former Acoustical Society of America (ASA) President and Gold Medal recipient and a key developer of statistical energy analysis, passed away peacefully on January 21, 2019, at the age of 89.

Born and raised in Evansville, IN, Dick graduated from Evansville College in 1952 as a physics major and did his doctoral thesis at the Massachusetts Institute of Technology (MIT), Cambridge, under Uno Ingard, on the turbulent excitation of strings, receiving his PhD in physics in 1955. Dick then joined the electrical engineering faculty at the University of Minnesota, Minneapolis, and in 1959 began a nine-month stay at the University of Manchester, UK, working with the statistician Maurice Bartlett on the statistical analysis of interacting vibrating systems. It was during this period that he combined his diverse background in physics, electrical engineering, and acoustics to formulate ideas that became the basis of his development of statistical energy analysis.

Returning from the United Kingdom, Dick joined Bolt, Beranek and Newman (BBN) where he continued his work on sound-structure interaction and also served as head of the Physical Sciences Division and corporate vice president. During his time at BBN, Dick made significant contributions to the field of structural acoustics, publishing more than 35 papers over 10 years.

In 1970, Dick joined the faculty of MIT as professor of mechanical engineering, where he headed the Division of Mechanics and Materials. Also in 1970, he joined Jerry Manning in forming Cambridge Collaborative, which specialized in the application of statistical energy analysis. His strong interest in and enthusiasm for acoustics inspired many of his students to pursue careers in the field and develop long-lasting ties with him. Dick retired from MIT in 1995 and devoted himself full time to his consulting firm, RH Lyon Corp, where he and others focused on vibration-based mechanism diagnostics, audio, quiet product design, and methods of designing for product sound quality.

The areas of Dick's research and contributions included statistical energy analysis of complex structures, acoustical scale modeling, signal processing for machinery diagnostics and remote sensing, statistical phase analysis, transducers, and sound quality; this diversity of study spoke to the great breadth of his interests and knowledge. During his career, Dick wrote 5 books, over 200 papers, and numerous technical reports. An avid sculler, he also took up learning the guitar in his later years. Of course, Dick being Dick, this led him to give an enthusiastic talk to the local ASA chapter titled "A Structural Acoustician Examines His Guitars."

Dick was a Fellow of the ASA and the Institute of Noise Control Engineering and a member of the National Academy of Engineering. Aside from the ASA Gold Medal, Dick also received its Silver Medal in Engineering Acoustics, the Rayleigh Medal from the Institute of Acoustics, and the Per Bruel Gold Medal for Noise Control and Acoustics from the American Society of Mechanical Engineers.

He is survived by his wife of 53 years, Jean Wheaton Lyon, children Geoffrey, Katherine, and Suzanne, and several grandchildren and great-grandchildren. Dick will be truly missed by all those who were fortunate enough to know and be inspired by him.

Selected Publications by Richard H. Lyon

Lyon, R. H. (1969). Statistical analysis of power injection and response in structures and rooms. *The Journal of the Acoustical Society of America* 45, 545-565. https://doi.org/10.1121/1.1911422

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Lyon, R. H. (2000). *Designing for Product Sound Quality*. Marcel Dekker, New York.

Lyon, R. H., and DeJong, R. G. (1995). *Statistical Energy Analysis*, 2nd ed. Butterworth-Heinemann, Boston.

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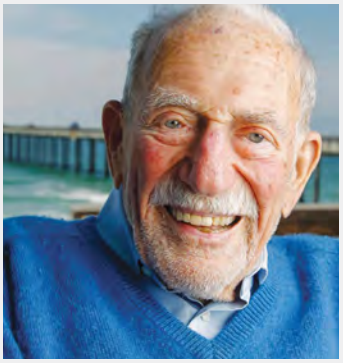
Written by:

David L. Bowen

Email: dBowen@acentech.com

Acentech Inc., Cambridge, MA

Obituary | Walter H. Munk | *1917–2019*



Walter H. Munk, an oceanographer and geophysicist who made seminal contributions to ocean acoustics, physical oceanography, and geophysics over a career spanning nearly 80 years, died at his home in La Jolla, CA, on February 8, 2019, at the age of 101.

Walter was born on October 19, 2017, in Vienna, Austria. He was sent to the United States at age 14 to finish high school. After an unhappy time at a financial firm in which his grandfather was a partner, he applied to the California Institute of Technology (Cal Tech), Pasadena, graduating in 1939 in applied physics. Walter first came to the Scripps Institution of Oceanography, University of California, San Diego, La Jolla, in 1939 for a summer job. He obtained a master's degree from Cal Tech in 1940 before returning to Scripps, where the director, Harald Sverdrup, accepted him as a PhD student.

Believing that war was imminent, Walter enlisted in the Army. He was discharged in December 1941, one week before Pearl Harbor, to join the University of California Division of War Research. During the war, Walter and Sverdrup developed a system to forecast wave conditions in preparation for the Allied landings in Africa. Their methods successfully predicted that the conditions for the D-Day landing in Normandy would be rough but manageable. Walter received his PhD in 1947. He spent his entire career at Scripps, founding and serving as director of the La Jolla Laboratories, Institute of Geophysics and Planetary Physics, from 1962 to 1982.

Walter made contributions to so many fields that there are some who think that there was more than one Walter Munk. In the early 1950s, he made fundamental contributions to our understanding of the wind-driven ocean circulation, coining the term "ocean gyres." He then became interested in the irregularities in the earth's rotation (wobble and spin), which form an elegant remote sensing tool from which one can infer information about the Earth's core, its air and water masses, and global winds. He made pioneering measurements of ocean swell (1958–1968) and deep-sea tides (1964–1974). He was one of the initiators of 1962 Project MOHOLE to drill into the Earth's mantle. In the early 1970s, Walter and Christopher Garrett devised the Garrett-Munk formulation of the ocean internal wave spectrum. In the mid-1970s, he was lured into the world of ocean acoustics through his participation in JASON (a scientific advisory group to the Department of Defense), which at the time was working on antisubmarine warfare. He was among the first to realize that internal waves cause sound-speed fluctuations, leading to fluctuations in acoustic signals. He, together with Carl Wunsch, invented ocean acoustic tomography to study the ocean mesoscale. He subsequently proposed that acoustic transmissions be used to study ocean warming on global scales and led the 1991 Heard Island Feasibility Test (HIFT) in which transmissions from near Heard Island in the southern Indian Ocean were recorded on receivers in both the Pacific and Atlantic. The HIFT was followed by the decade-long Acoustic Thermometry of Ocean Climate (ATOC) series of experiments in the North Pacific.

Walter received every conceivable honor, from the National Medal of Science to the Kyoto Prize to the Crafoord Prize. He was an Honorary Fellow of the Acoustical Society of America. The United States Navy and The Oceanography Society established the Walter Munk Award for Distinguished Research in Oceanography Related to Sound in the Sea in his honor.

Munk was preceded in death by wife Judith, who died in 2006, and daughter Lucian, who was born with a heart defect and died at the age of 7 in 1961. He is survived by daughters Edie of La Jolla and Kendall of State College, PA; three grandsons Walter, Lucien, and Maxwell; and current spouse Mary Coakley Munk.

A more complete account of Walter's life, including a list of selected publications, is available in Spindel, R. C., and Worcester, P. F. (2016). Walter H. Munk: Seventy-five years of exploring the seas. *Acoustics Today* 12, 36-42.

Written by:

Peter F. Worcester
Email: pworcester@ucsd.edu
Scripps Institution of Oceanography,
University of California, San Diego, La Jolla

Robert C. Spindel
Email: spindel@uw.edu
Applied Physics Laboratory,
University of Washington, Seattle

Obituary | Robert Daniel Sorkin | *1938–2018*

Robert Daniel Sorkin, 81, a scholar, educator, and avid sailor, passed away on Friday, December 28, 2018, in St. Augustine, FL. He was a Fellow of the Acoustical Society of America and past associate editor of Psychological Acoustics.

Bob was born in Manhattan and lived in the Bronx, NY, and Maplewood, NJ. After graduating from the Carnegie Institute of Technology, Pittsburgh, PA, he earned a PhD in psychology from The University of Michigan, Ann Arbor. Bob was a professor at Purdue University, West Lafayette, IN, and then moved to the University of Florida, Gainesville, to chair the Department of Psychology, with a dual appointment in industrial engineering. He also served in the Air Force Office of Scientific Research and the Air Force Research Laboratory as a senior scientist.

Bob published over 50 research articles and a book in areas of auditory perception, alarm detection, and decision theory. He was awarded four US patents.

Under the influence of his mentor W. P. "Spike" Tanner, Bob extended the theory of signal detectability to matching procedures in psychophysics. He applied this to characterize the listening process as a multichannel detection process. Multichannel listening evolved into an interest in warning systems. His early work examined the auditory detection of uncertain signals and monaural detection of signals with uncertain time distribution and frequency. By examining the detection of a monaural signal presented against the presence or absence of a contralateral sound, he determined the effect of the interaction of binaural listening channels.

Several papers published with his students examined optimized alarms based on detection with automated likelihood detectors monitored by human observers. This interest in how observers operate on available information led to an examination of group decision strategies. Although much of his early work was in psychoacoustics, Bob was really a "signal detector." His applications of signal detection theory led to the extension of his work to the development of auditory and tactile alarms such as would be applicable in factories and airplane cockpits.

If one is to install an alarm, someone else will surely turn it off. He postulated the reason for this is that the criterion set for the automatic alarm created a high false alarm rate. This led to the development of the concept of a likelihood alarm in which there is a situationally aware criterion set for the automated alarm.

Examining the relationship between observers and their decisions naturally led to the question of how decisions by individuals and groups evolve. In 2004, he published a paper in which he extended the theory of signal detectability to an analysis of group decision making.

In 2007, he retired as Emeritus Professor of Psychology and of Industrial and Systems Engineering and moved to St. Augustine. Bob is survived by his wife Nancy, with whom he shared 58 happy years, two children, five grandchildren, and his brother Barry. He was predeceased by his brother Bernard.

Selected Publications by Robert Daniel Sorkin

Kantowitz, B. H., and Sorkin, R. D. (1983). *Human Factors: Understanding People System Relationships*. John Wiley & Sons, New York.

Sorkin, R. D. (1962). Extension of the theory of signal detectability to matching procedures in psychoacoustics. *The Journal of the Acoustical Society of America* 34, 1745-1751.

Sorkin, R. D. (1965). Uncertain signal detection with simultaneous contralateral cues. *The Journal of the Acoustical Society of America* 38, 207-212.

Sorkin, R. D. (1989). Why are people turning off our alarms? *The Journal of the Acoustical Society of America* 84, 1107-1108.

Sorkin, R. D., Luan, S., and Itzkowitz, J. (2004). Group decision and deliberation: A distributed detection process. In D. J. Koehler and N. Harvey (Eds.), Handbook of Judgment and Decision Making. Blackwell, Oxford, UK, pp. 464-484.

Written by:

John Erdreich

Email: jerdreich@gmail.com

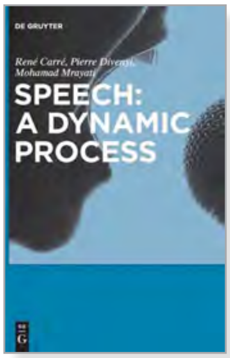
Ostergaard Acoustical Associates (Retired),

West Orange, NJ

Book Review

These reviews of books and other forms of information express the opinions of the individual reviewers and are not necessarily endorsed by the Editorial Board of this Journal. –Philip I. Marston, Book Review Editor

Speech: A Dynamic Process



Authors: René Carré, Pierre Divenyi, Mohamad Mrayati
Publisher: De Gruyter, Berlin, Germany, 2017, 214 pp.
Price: £79.56 (Hardcover); £63.96 (Kindle)
ISBN: 978-1-501-510601

The world's many tongues vary greatly in their sound patterns, lexicons, and grammar. Despite such variation, all languages share certain properties in common. One of especial interest is the intricate interleaving of consonants and vowels in the articulatory stream, instantiated as a low-frequency modulation in the speech waveform. Such fluctuations are the result of articulatory movement of the lips, tongue and jaw, and which serve as the acoustic foundation of a sophisticated information-bearing system.

Why speech is so configured is rarely addressed in the scientific literature.

Speech: A Dynamic Process examines the question from several vantage points through a clever combination of modeling, theory, and empirical studies.

The book begins with a consideration of two approaches to scientific inquiry — induction (with its focus on data collection, statistics, modeling and prediction) and deduction (emphasizing "universal" principles, "logic," formal modeling, and verification). These complementary perspectives are used to integrate the trifecta of speech production, acoustics, and perception within a unified theoretical framework.

This philosophical introduction is followed by an historical review of speech research, with a focus on the latter half of the 20th century that sets the scene for the vocal-tract modeling work discussed in later chapters.

The models range from the primitive — a simple tube — to the more elaborate, incorporating far greater degrees of freedom. A key issue considered is how a vocal tract model can be deformed in such a way that results in maximal acoustic variation with minimal vocal effort.

The authors propose a "Distinctive Region Model," (DRM) in which "privileged" acoustic trajectories (i.e., formant patterns) serve as "coding primitives." In their view, information is encoded in articulatory trajectories rather than as a sequence of quasi-static "targets." "Locus equations," which compute the slope and duration of formant transitions, are shown to reliably distinguish among vowels. Because these trajectories are shaped by the interaction of vocalic and consonantal context, the framework is essentially one in which the syllable forms a fundamental unit of speech production and perception.

Although the model is restricted to vowels and stop consonants, it appears to capture much of the speech signal's dynamic properties. One of the most intriguing properties of the DRM is its ability to produce a broad range of speech sounds with a relatively small number of control parameters, an insight of potential interest to speech clinicians and engineers.

A later chapter focuses on perceptual aspects, including empirical studies of processing dynamic speech sounds. This work is then linked back to the modeling and production studies discussed in the earlier chapters. A case is made for the human auditory system's specialization for speech, especially for processing communication signals in the presence of background noise and other forms of acoustic interference.

The final chapters are more philosophical in tone, presenting the case for a dynamic theory of speech based on melding the inductive and deductive approaches discussed earlier. The theory is also examined from the perspectives of linguistics, psychology, engineering, and evolutionary theory.

Speech: A Dynamic Process is a thought-provoking book that examines the speech signal in many interesting ways. However, the theoretical framework proposed has its limitations. The models discussed are, by necessity, simplifications of a very complex system that is still not well understood. The modeled data are drawn mostly from highly simplified speech, whose acoustic properties differ in many respects from the patterns observed in naturally spoken language. Another limitation is the framework's difficulty in explaining how extremely distorted speech remains intelligible under challenging listening conditions in which much of the waveform has been excised or heavily masked. How does the brain manage to track formant trajectories under such conditions? Also unaddressed are the roles of dynamic visual-speech cues and memory in decoding the speech signal.

Despite such limitations, the book is likely to interest researchers wishing to examine speech from an unusual vantage point that's both original and thought-provoking. The bibliography is excellent and comprehensive. The text is clearly written, and the figures informative and insightful.

Review by:

Steven Greenberg
Silicon Speech
17270 Greenridge Road
Hidden Valley Lake, CA 95467

(Published online December 10, 2018, The Journal of the Acoustical Society of America*, 144(6).)*

"In Tune"

by Alex Tolstoy

Watercolor

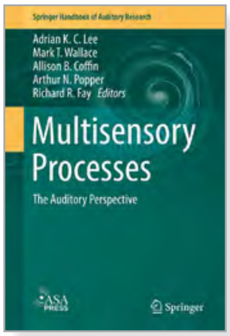
We are delighted that ASA member Dr. Alexandra Tolstoy will provide some of her original water colors (all with acoustics themes) for *Acoustics Today* from time to time. You can see more of Alex's paintings at atolstoyart.com.

Book Announcements | ASA Press

ASA Press is a meritorious imprint of the Acoustical Society of America in collaboration with the major international publisher Springer Science + Business Media. 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 Publications Office, ASAPublications@acousticalsociety.org, to discuss their ideas.

Multisensory Processes

The Auditory Perspective



Editors: Adrian K. C. Lee, Mark T. Wallace, Allison B. Coffin, Arthur N. Popper, and Richard R. Fay
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Topics: Otorhinolaryngology

- Presents a unique perspective on multisensory processing with an audiocentric focus
- Captures some of the most exciting contemporary research being done at the intersection of the auditory and multisensory fields
- Explores a rapidly changing and expanding field of research within the broader domains of psychology and neuroscience

Auditory behavior, perception, and cognition are all shaped by information from other sensory systems. This volume examines this multisensory view of auditory function at levels of analysis ranging from the single neuron to neuroimaging in human clinical populations.

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  David Alais and David Burr
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  Ken W. Grant and Joshua G. W. Bernstein
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- Cross-Modal Learning in the Auditory System
  Patrick Bruns and Brigitte Röder
- Multisensory Processing Differences in Individuals with Autism Spectrum Disorder
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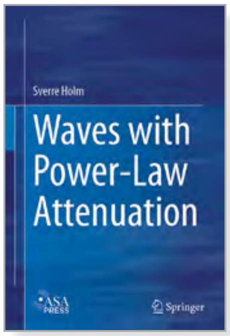
About the Editors | Adrian K.C. Lee is associate professor in the Department of Speech & Hearing Sciences and the Institute for Learning and Brain Sciences at the University of Washington, Seattle. Mark T. Wallace is the Louise B. McGavock Endowed Chair and Professor in the Departments of Hearing and Speech Sciences, Psychiatry, and Psychology and director of the Vanderbilt Brain Institute at Vanderbilt University, Nashville. Allison B. Coffin is associate professor in the Department of Integrative Physiology and Neuroscience at Washington State University, Vancouver, WA. Arthur N. Popper is professor emeritus and research professor in the Department of Biology at the University of Maryland, College Park. Richard R. Fay is Distinguished Research Professor of Psychology at Loyola University, Chicago.

Waves with Power-Law Attenuation



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Topics: Acoustics

- Couples fractional derivatives and power laws and gives their multiple relaxation process interpretation
- Investigates causes of power law attenuation and dispersion such as interaction with hierarchical models of polymer chains and non-Newtonian viscosity
- Shows how fractional and multiple relaxation models are inherent in the grain shearing and extended Biot descriptions of sediment acoustics
- Contains historical vignettes and side notes about the formulation of some of the concepts discussed

This book integrates concepts from physical acoustics with those from linear viscoelasticity and fractional linear viscoelasticity. Compressional waves and shear waves in applications such as medical ultrasound, elastography, and sediment acoustics often follow power law attenuation and dispersion laws that cannot be described with classical viscous and relaxation models. This is accompanied by temporal power laws rather than the temporal exponential responses of classical models.

The book starts by reformulating the classical models of acoustics in terms of standard models from linear elasticity. Then, non-classical loss models that follow power laws and which are expressed via convolution models and fractional derivatives are covered in depth. In addition, parallels are drawn to electromagnetic waves in complex dielectric media. The book also contains historical vignettes and important side notes about the validity of central questions. While addressed primarily to physicists and engineers working in the field of acoustics, this expert monograph will also be of interest to mathematicians, mathematical physicists, and geophysicists.

About the Author

Sverre Holm was born in Oslo, Norway, in 1954. He received M.S. and Ph.D. degrees in electrical engineering from the Norwegian Institute of Technology (NTNU), Trondheim in 1978 and 1982, respectively.

He has academic experience from NTNU and Yarmouk University in Jordan (1984–86). Since 1995 he has been a professor of signal processing and acoustic imaging at the University of Oslo. In 2002 he was elected a member of the Norwegian Academy of Technological Sciences.

His industry experience includes GE Vingmed Ultrasound (1990–94), working on digital ultrasound imaging, and Sonitor Technologies (2000–05), where he developed ultrasonic indoor positioning. He is currently involved with several startups in the Oslo area working in the areas of acoustics and ultrasonics.

Dr. Holm has authored or co-authored around 220 publications and holds 12 patents. He has spent sabbaticals at GE Global Research, NY (1998), Institut Langevin, ESPCI, Paris (2008–09), and King's College London (2014). His research interests include medical ultrasound imaging, elastography, modeling of waves in complex media, and ultrasonic positioning.

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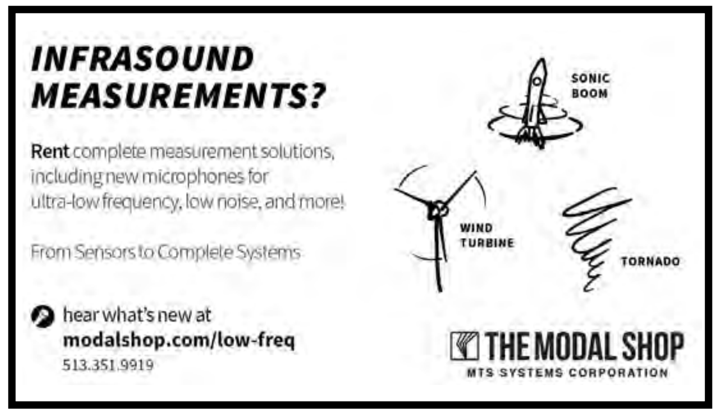

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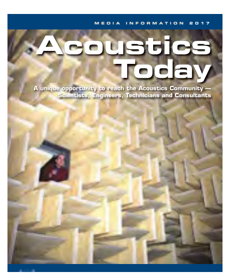

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