

Eric J. Heller

Why You Hear What You Hear

An Experiential
Journey
through Sound,
Music, and
Psychoacoustics

PRINCETON UNIVERSITY PRESS

Princeton and Oxford

Copyright © 2013 by Princeton University Press
Published by Princeton University Press, 41 William Street,
Princeton, New Jersey 08540
In the United Kingdom: Princeton University Press, 6 Oxford Street, Woodstock,
Oxfordshire OX20 1TW
press.princeton.edu

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Library of Congress Cataloging-in-Publication Data

Heller, Eric Johnson.

Why you hear what you hear : an experiential approach to sound, music, and psychoacoustics /

Eric J. Heller.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-691-14859-5 (hardback : alk. paper)

1. Hearing. 2. Sound—Transmission—Measurement. 3. Psychoacoustics.

I. Title.

QP461.H395 2012

612.8'5—dc23

2011053479

British Library Cataloging-in-Publication Data is available

This book has been composed in Minion Pro and Myriad Pro

Printed on acid-free paper. ∞

Typeset by S R Nova Pvt Ltd, Bangalore, India

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

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Preface

No book about vision and visual art is devoid of diagrams and reproductions, yet books about sound and music are traditionally mute. It has been possible to print images in books for centuries, but conveying sound has historically been much more difficult.

The situation started to change when the Laboratory of Psychophysics of Harvard University (active from 1940 to 1972) under Professor Stanley Smith Stevens produced and recorded 20 demonstrations on psychoacoustics, plus an explanatory booklet. Later Houtsma, Rossing, and Wagenaars created a set of improved demonstrations on a CD illustrating many important psychoacoustic phenomena. Available now on the Internet, their work has been recommended listening by many texts. This was a good beginning, but new technology has made it possible and relatively easy to do far more.

This book is integrated with many example sound files and interactive applets that generate and analyze sound. They are available on the book's website, whyyouhearwhatyouhear.com. If a picture is worth 1000 words, so too is a sound file. Sounds and effects created and analyzed on the fly with well-conceived applets are worth 10,000 words. Computer animation, Java, MAX patches, *Mathematica* applets, sound processing and analysis tools (such as *Audacity*) not to mention the World Wide Web, all flow into crisp display screens and high-fidelity headphones—at little or no expense. Any book on sound and acoustics that doesn't take advantage of these technological miracles is missing a huge opportunity. The many excellent books of the past, no matter how good they otherwise are, cannot provide the reader with the firsthand interactive knowledge and listening experience we integrate into this book. Yet we hope to have given new life to some parts of these older classics, by providing interactive examples illustrating some of their major lessons.

If nothing had evolved in the last 20 years, it would be quite presumptuous to offer a conceptually higher level book about acoustics to

the nonspecialist. But things *have* evolved: anyone with a laptop has a fully portable sound laboratory and recording studio that might have cost hundreds of thousands of dollars not so long ago. Now it is possible to achieve true understanding by showing and doing, at one's own desk or anywhere a personal computer is taken. We seize this new opportunity to actually *explain* sound to the nonspecialist, rather than to present *descriptions* or mnemonics received from on high. This approach certainly puts more demands on the reader, but the reward is an intuitive understanding previously reserved for the best sound engineers and acousticians.

In spite of its long history, acoustics is still wide open to discovery. The level of this book is only a step away from original research, and many times we point the way to something that needs further investigation. With the approach we take here and the new tools available, readers can experience the sense of discovery that scientists crave. New phenomena or interesting variants on known effects can be exposed using the tools and point of view provided here. You will certainly learn much about your own hearing, including whether it is “normal” and whether you have special abilities or tendencies, such as the ability to listen analytically rather than holistically to complex tones.

Musical instruments are understood through representative cases that focus on the way these instruments actually work. We trust the reader to extrapolate from trumpet to trombone, from violin to viola. This focus enriches the understanding of the important physical effects at play and explains rather than describes the instrument. Coupled resonators, Fourier analysis, autocorrelation, impulse response, impedance mismatch and reflection at open tube ends and toneholes, wall losses, phase of drives near resonance, and launching of sound by accelerating surfaces all help explain the effects of a mouthpiece, bell, violin body, the phase of the lip buzzing on a trumpet, the bending of notes on a sax, and so on.

We do not shy from controversy; indeed, we welcome it and even try to stir some up from time to time. Nothing could be a better learning experience for practitioners or students than to participate in spirited debate. It gives us practice in applying the principles and demonstrates to students that their own struggles are not so distant from those at the research frontier.

This book grew out of years of teaching *The Physics of Music and Sound*, first a core curriculum course and then a general education course after Harvard switched to that system. Originally designed and taught by Professor John Huth and myself, the course was never intended primarily as an excuse to teach physics to nonscience undergraduates; rather, our first love and our first intent was to really understand sound and the mechanisms that generate it and receive it.

It is always a challenge to arrange a linear path through a multidimensional subject. Rather than adopting a “the rewards will come later” approach, we seed many of the applications as early as possible as we

introduce the principles. This does mean that not all the relevant material about pianos—for example, piano soundboards—is actually in the chapter on pianos. There is a significant component of spiral learning: we are never finished with the topic of resonance, for example.

Most universities have general education requirements that help to ensure a liberal education. For humanities students, these requirements used to mean enrolling in Rocks and Stars or Physics for Poets classes, often with predictable results. These courses are now evolving into more interesting and relevant ones, as professors are discarding the “eat your spinach” approach in favor of engagement and relevance. Case in point: Physics for Poets has become Physics for Future Presidents. Poets don’t need much physics, or at least they don’t think they do; modern presidents do.

The connection between length proportions on a string and pleasing musical intervals is attributed to Pythagoras. According to the legend, Pythagoras as early as 600 BCE used a monochord, a stretched string over a resonator, to connect intervals like the octave and the fifth with length ratios of 2:1 and 3:2, respectively. This reinforced deep mysticism about the fundamental connection between small whole numbers and the clockwork of the heavens. It is said that Pythagoras’ followers believed only he could hear the music of the spheres, the divine harmonies of small integers governing the motion of the planets and the heavens. In 1618, English physician and mystic Robert Fludd wrote *De Musica Mundana*, which included a compelling illustration of the divine monochord (figure P.1), elevating the monochord to the governing engine of the universe.

This idea of a “vibratory universe” has not died away. If you Google that phrase, you will get many websites physicists think of as crackpot; the mysticism side of this idea is as strong as ever. In fact, the vibrating plates of Chladni became enormously popular around 1800. These are taken up in section 15.4 and seem to have provided a segue between the scientific and the mystical that has lasted to this day. It is well-known that Hans Christian Ørsted, the discoverer of electromagnetism and an unassailably brilliant scientist, took off in a mystical direction for quite a while after he saw and heard Chladni plate vibrations.

The vibratory universe idea has not been entirely left to mystics, however. Indeed, I cannot think of any aspect of the physical universe that is not vibratory at some level. Quantum mechanics teaches us that matter is actually made of waves, which have the usual properties of wavelength and frequency; the evidence of this is abundantly clear, but of course we can’t go into it here. Light, microwaves, radio waves, and so on exhibit obvious vibratory wavelike properties. Cosmologists tell us that the whole universe is still vibrating in various modes as a remnant of the Big Bang. Even the most modern and abstruse corner of theoretical physics, string theory, supposes that the different particles found in nature are distinct vibratory modes of tiny stringlike objects. I am not a mystic, but I do believe the universe is vibratory.

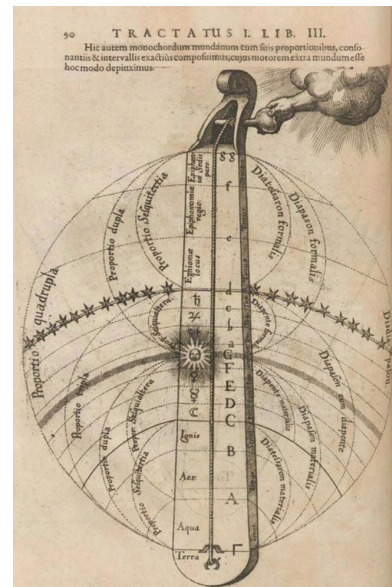


Figure P.1

Illustration of the divine monochord, in the book *De Musica Mundana*, by Robert Fludd. Notice the hand of God tuning the monochord.

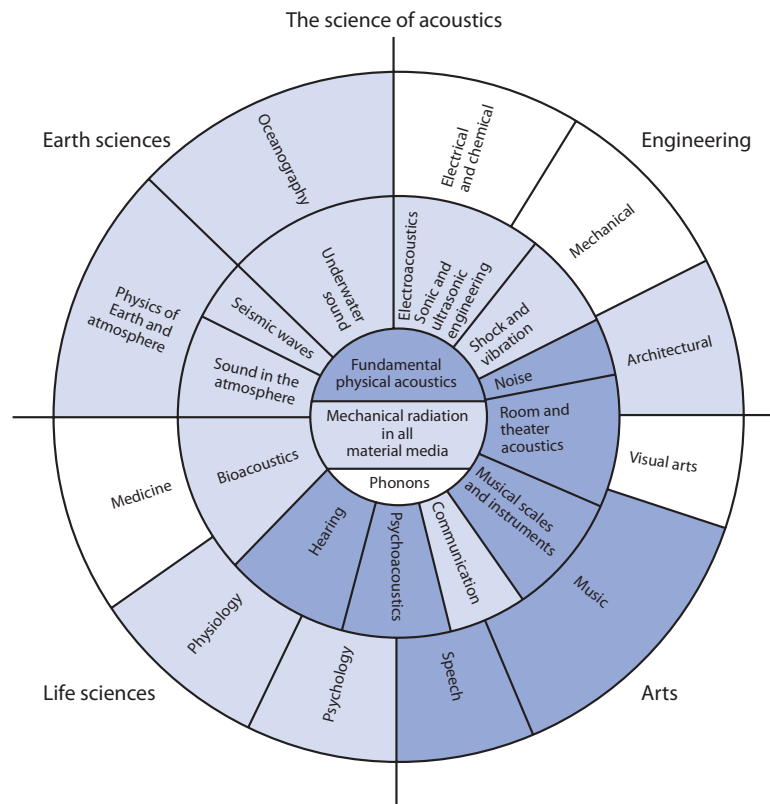


Figure P.2

A figure by R. Bruce Lindsay showing the range and breadth of the field of acoustics. Subjects treated extensively in this book are highlighted in darker blue; subjects partially treated are shown in lighter blue. Adapted from R. Bruce Lindsay, *Acoustics: Historical and Philosophical Development*, Dowden, Hutchinson, and Ross, Stroudsburg, PA, 1973.

This universality is another reason for studying sound, the most accessible of all vibrational and wavelike manifestations, for in doing so you are studying the clockwork of the universe. Perhaps this is simply a less poetic way of expressing the idea of music of the spheres, which so captivated Pythagoras and those after him.

R. Bruce Lindsay, the late professor at Brown University, understood the universality of acoustics in a more practical way. In the introduction to his marvelous book of reprints of some of the seminal works and papers on acoustics in the past few thousand years, *Acoustics: Historical and Philosophical Development*, Professor Lindsay created a graphic that makes clear the vast range of applications of acoustics and some relations among them. A modified version is shown in figure P.2. Topics that are key to this book are highlighted in dark blue; some related areas that we touch upon are shown in lighter blue.

How to Use This Book

The book was written with a wide range of interests and musical/acoustical backgrounds in mind, from neophyte to professional. Students, musicians, sound engineers, psychologists, phonetics and audiology professionals, and anyone wanting or needing to know more about sound and music generation and perception can expect to emerge with a real understanding of sound, because the real story is told. Not much prior technical sophistication is demanded, yet teachers, musicians, acoustical engineers, and scientists will recognize a fresh perspective and hopefully be entertained on almost every page. The book is designed so that students of the subject are not hindered by the subtext for the insider. Rather, students are presented the truth and pretty much the whole truth at the minimum possible level of technical sophistication.

There is too much material here for a one-semester undergraduate course. The book makes various pathways through parts of the subject possible. An instructor can steer a course (several are suggested here) through the material, confident that curious students with an interest in something not specifically covered in class can find it in this book. The website paired with the book, whyyouhearwhatyouhear.com, is an essential addition to the package and a multifaceted resource.

The book is heavily cross-referenced to help smooth the way for creative pathways through the material. Many of the chapters and parts are mostly self-contained—some are almost books in themselves. This is partly a consequence of the spiral learning approach, so that concepts introduced earlier keep reappearing, not just mentioned in passing but brought up anew in a context that enriches understanding. These facts make it quite possible and even recommended to read the book on a “need-to-know” basis. For example, if you play the violin, start with that chapter, and follow all the cross-references to the violin from other chapters. If you find you are fascinated by the bridge hill resonance and the reason for its existence, you might find yourself reading the chapters devoted mainly to the concept

of resonance and impulse response. Before long, you might put a little piece of putty on a violin string to see what happens (you'll be surprised). To understand the drastic result, you might end up reading about the Helmholtz wave, harmonic vibrations on a string, and stick-slip motion of bow and string. Next you might buy a cheap, tiny accelerometer (there's one in every smart phone), attach it to your violin and then to your laptop, and start making measurements on your own violin. Free sound capture software will record and analyze all the data you need. Who cares if you read the whole book? You're on your way to acoustical discovery.

The psychophysics chapters are another good place to start; they are rather self-contained in some respects, but definitely enriched by all the material before and after if you choose to explore further. For example, dive into the chorus effect (section 4.6), and branch out from there. You'll read about autocorrelation. Now you have a reason to know what autocorrelation is, in order to understand how a chorus can have a definite pitch even through every singer is a little bit off pitch, or doing vibrato, and so on.

Musically inclined readers might want to start with psychophysics and especially pitch perception, moving into the theory of dissonance and the chapters on systems of musical scales, finishing with chapters on musical instruments and the acoustics of musical spaces. Forays into other cross-referenced sections of the book would be required for the best understanding, but reading the whole book would not be required.

If singing, phonetics, and voice are a special interest, it is possible to start in chapter 17, backtracking to sound in tubes and sound from turbulence as the topics arise.

A more conventional and "safe" approach for a college class would be to introduce qualitative ideas in part I (chapters 1 and 2), further develop the language and analysis tools in part II, and then introduce resonance through the effects of walls and horns, jumping over the more technical aspects of resonance and impulse response, and then proceeding directly to musical instruments (part IV) or psychoacoustics (part V), backtracking cross-references where necessary. Individual or class projects could be assigned as forays into the chapters on impulse response or architectural acoustics, for example.

A casual reader will find much material of historical and human interest, including the culture of acoustics and waves. Fascinating characters like Ernst Chladni and Sophie Germain enliven the subject, as do scientific curiosities, matters of importance to society, and so on. For example, why was Moodus, Connecticut, named by the Indians for sonic booms long before settlers arrived? What could cause pieces of sod weighing several tons and resembling cookies from a giant cookie cutter to wind up 75 feet from the hole they left behind, as has happened in several places in the world? How do whales communicate over thousands of miles by diving down almost a kilometer? Why is it that you can easily be heard when you

shout downwind, but you can't hear what anyone says when they shout upwind back to you? On which side of a busy highway would you prefer to live? These and many other stories and examples are to be found within the pages of this book.

The chapters can be read and appreciated without the use of a computer to download and play sound files, run demonstrations, and measure and analyze sound, but it is highly recommended that you get interactive to best assimilate the subject matter. Descriptions, screen shots, and the like are provided, but nothing beats the hands-on, ears-open experience of trying and testing the concepts for yourself. Some experiments, like pitch or phantom tone perception, are done *on* yourself. Your perceptions may differ from the norm, and with the ears-open approach you will find yourself listening for and able to hear new aspects of sound. If you are a performer, you will become aware of new aspects of sound that you may be able to control.