SOUND & HEARING

A CONCEPTUAL INTRODUCTION

R. DUNCAN LUCE

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Preface for Instructors

This text has evolved during the past decade in an attempt to convey something about scientific thinking, as evidenced in the domain of sounds and their perception, to students whose primary focus is not science. It tries to do so using a minimum of mathematics without, it is hoped, seriously compromising scientific integrity.

Its origins were in the then new Harvard University Core Curriculum. All undergraduates were required to take two semesters of science, the choices being grouped into two categories unrevealingly labeled A and B. Roughly, A courses were to correspond to scientific basics, such as particle physics and microbiology, and B courses to the more complex sciences, such as geology and biology of systems. (In practice, this partitioning was less clear-cut, which probably accounts for the fact that word labels never came to replace A and B.) David M. Green and I from the Department of Psychology and Social Relations and R. Victor Jones from the Department of Applied Physics laid out a plan for a two-semester course to fulfill both requirements: Sound and Hearing followed by Light and Seeing. The physics of the course would meet the A requirement, whereas the physiology and psychology satisfied the B requirement. Green and Jones gave the entire sequence once. Because Green did not find doing it very rewarding, he relinquished it to Jones and me. We gave Sound and Hearing the next year, but not Light and Seeing. After that I gave Sound and Hearing alone several times. As a single course it was, to my surprise, classed as A rather than B.

Since coming to the University of California, Irvine, I have given it twice to, primarily, psychology majors. As many of these students do not intend to do graduate work, and often have a decidedly limited interest in the scientific aspects of psychology, the conceptual flavor of the course has not changed greatly from its origins at Harvard.

It is safe to say that although quite a few students have taken the course—50–75 each time it was given at Harvard and somewhat fewer at Irvine—it has never been judged a popular success. At Harvard this was due in part to the fact that the classes were full of nonscience majors who hoped it would be a relatively painless way to fulfill their Science A requirement. It was never sufficiently painless. In part this was because we made them do problems both as homework and in exams. And in part it was because many of these students were "big picture" types, and hearing, although personally important and valuable, hardly has the pizzazz of world history or cosmology or sociobiology. Yet it does serve as a neat vehicle for learning some basic physical ideas of wave motion, a bit of neurophysiology, some perception, and how these three work together. Its lack of popular acclaim was, I must acknowledge, also due to my not being a charismatic teacher.

One may ask: Why bother writing a new book on the topic? Why not just use one of the existing texts, such as Green's (1976) or Yost and Nielsen's (1985) admirable treatments? At the onset, all three of us felt that the handling of the physics in the psychology texts was insufficiently detailed and elementary for the students with whom we were dealing. So at Jones' suggestion we used Johnson, Walker, and Cutnell (1981) to cover the physics of waves, and I continued to use it until the Spring Quarter of 1991. That book, despite its being excellent and at the appropriate level, does not take up topics in my preferred order and, given its title *The Science of Hi-Fidelity,* understandably includes a great deal of material on audio equipment that is irrelevant to hearing, as such. So it seemed reasonable to incorporate the needed physics into a text whose focus is as much on hearing as on sound.

For the physiology and psychology, I have tried several of the psychology texts, the most successful proving to be Yost and Nielsen. Still, I found I had to supplement whatever book I used by various handouts. Things were patched together from various sources, something that never seems popular in elementary courses. For the physiology of the ear, the existing texts seem very satisfactory, although typically rather more detailed than I could afford to be. For the psychology, things seemed poorly organized from my perspective. One goal of the course was to make as clear as possible which phenomena can be accounted for by the physics of sine waves; then those for which the physics alone provides no explanation, but properties of the ear and the peripheral auditory nerve do; and finally those that, although well-established psychologically, have not been reduced to what we *currently* know about physics and neurons. In general, the latter phenomena are believed to be more heavily mediated by central processing than by the periphery alone. Beyond that, I wanted to segregate issues that could be studied using just single pure tones from those that necessarily involve more complex waveforms, such as harmonics and noise. In part, this was to partition a fairly substantial dose of physics into two segments separated by some physiology and psychology. To do this in the existing texts required jumping about a great deal, always bumping into inconvenient cross-references. So gradually the handouts grew in number and size, and increasingly they supplanted the text materials until in 1991 I operated solely from the notes that led to this text.

The material covered is what I covered in one semester at Harvard and in one quarter at Irvine, both of which involve 10 weeks of lectures. The course involves 28 lectures plus two 1-hour exams. The schedule that I followed, with slight adjustments for holidays, has been:

Week	*Sections*
1	I, II.1–4
2	II.5–10
3	II.11–12, III.1–2
4	III.3–5
5	Hour exam, IV.1–3
6	IV.4, V.1–2
7	V.3–5, VI.1–2
8	Hour exam, VI.3–4
9	VI.5–6
10	VI.7–8, review

For a course with more lectures, supplementary material will have to be added, which is certainly not hard to do because I have ignored many topics. To some degree, binaural hearing has been slighted, in part because the demonstrations, which mostly require earphones, create special classroom problems that I elected not to confront. Usually binaural phenomena are grouped together, but in this text they are separated depending on whether they are understood primarily physically, physiologically, or psychologically. Among the many topics not covered are pulsation thresholds, the dependence of pitch perception on duration, the circularity of pitch, and properties of timbre, musical scales, and various click phenomena.

The issue of classroom demonstrations is always a problem. As the course was first devised, a number were prepared and used for the physics part. I have come to abandon most of these, in part because so many of the relevant phenomena are well known to the students from their experience with water waves, ropes, pendulums, and springs. And partially because for qualitatively unfamiliar ideas, such as spectral analysis, the demonstrations seemed more confusing than illuminating. These demonstrations just did not seem to be worth the effort and time for students with little technical background.

Most of the auditory demonstrations came originally from the series of tapes prepared by David M. Green that were disseminated to professionals in the field and, no doubt, widely copied. Later, many (but unfortunately not all) of these plus some additional or modified ones were released as a compact disc by Phillips, 1126-061, which is currently available from the Acoustical Society of America. Because this disc is not very strong on some of the complex fusing and streaming phenomena, the induction of missing sounds, and various aspects of speech, I supplemented it with some of Green's tapes and with a tape prepared by A. Bregman and M. Kubovy. I am grateful to the copyright holders, A.J.M. Houtsma, T.D. Rossing, W.M. Wagenaars, Albert S. Bregman, and David M. Green, for their assistance in the preparation of the various materials for the demonstration disc, and for their permission to use those materials. The demonstrations used in this text are all on a compact disc entitled *Sound & Hearing Demonstration Disc* that is available from Lawrence Erlbaum Associates. A technical description is provided at the end of this text beginning on page 297.

My major debts are, first, to Green and Jones, with whom the initial course was developed. I have subsequently made a number of changes from that original plan; I have lost sight of just how many. And second, to Phillip Kelleher who was my head teaching assistant three times at Harvard. He was a fine source of feedback about problems in the course, an excellent instructor, and most conscientious in helping students and preparing supplementary materials. Kelleher was especially effective in preparing problems for homework and exams, and a substantial portion of the included exercises are his handiwork. In the final phase of preparation Courtney Crowther assembled the figures both from original and secondary sources and by computer generation. Dr. Bruce Berg carefully read the entire manuscript, and his comments have been extremely useful in reducing error and unclarity in the text, for which I am deeply indebted. My wife, Carolyn Scheer, has helped me in many ways, the most directly relevant being to simplify my writing.

R. Duncan Luce

Preface for Students

GOALS

The major aim of this text is to give you some idea about the ways in which scientists approach and think about a phenomenon—hearing—that intersects three quite distinct disciplines. Usually we take hearing for granted. Unless afflicted by hearing loss of one sort or another, we rarely think about it, any more than we think about how we see or talk or walk. The disciplines involved are the physics of sound sources and the propagation of sound through air and other materials, the anatomy and physiology of the transformation of the physical sound into neural activity in the brain, and the psychology of the perception that we call hearing. Physics, biology, and psychology each play a role in understanding how and what we hear.

One problem that a scientist in this area must repeatedly try to untangle is this: Given a particular phenomenon of hearing—for example, the localization of sounds—to what degree can we understand it simply in terms of the physics of sounds? Or do we need also to know something about what the ear does? Or is the phenomenon also dependent on something in the brain and psychology that lies beyond the ear and the peripheral auditory nervous system, that is, in what we refer to as the central system? We encounter examples of each.

In this text we use our gradually developing understanding of the three disciplines to try to untangle various auditory puzzles. Let it be clear at the onset that some puzzles are too complex for a text at this level to tackle and there are others that no one yet understands. Nonetheless, within our limits, there are a number of phenomena that, most likely, you do not now understand but will by the end of the text.

One aspect of these puzzles is auditory illusions. These are much like visual illusions in the sense that what one hears differs from what is physically present: something not present is heard or something that is present is not heard. The main difference is that auditory illusions typically go unnoticed by the uninitiated, whereas many visual ones are clearly paradoxical. For example, did you know that telephone communication is based in substantial part on an illusion? You hear what is in fact not physically there; more on that in Section VI.4. There is another illusion that is easier to demonstrate; yet it is one in which you, the hearer, fail to hear what is in fact there. This occurs all of the time because you are unaware of the many echos that always exist. You can hear this in Demonstration 1[1] in which various recorded sounds are played in the usual way following which they are played backward. In the backward version you will be aware of a long "shish" preceding the major sound itself. These are echos from the walls of the room in which the sounds were made, echos that one fails to hear in the forward version. In this case the listener unconsciously suppresses a sound; it is something we do all of the time unless the echos of the sound are sufficiently delayed, as in a canyon. Nevertheless, it is an auditory illusion.

PREREQUISITES

The major prerequisite is your interest in learning how science tries to provide some understanding of a basic, but nonetheless complex sensory process. The text is not intended to be the basis of a "gut" course. It involves an accumulation of knowledge and requires you to think about different ways in which that knowledge can be put together. On the other hand, the course does not presuppose that you already have a strong background in physics, biology, psychology, or mathematics.

Let me be precise about the mathematical requirements:

Elementary algebra is used freely. For example, you are expected to be able to get readily from one side of the following equation to the other:

$$1/x + 1/y = (x + y)/xy$$

Note the distinction between $1/x + 1/y$ and $1/(x + 1/y) = y/(xy + 1)$.

The only *functions* that appear as equations are:

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[1] The demonstrations are available on the CD, *Sound & Hearing Demonstraction Disc*, from Lawrence Erlbaum Associates.

$$y = A \sin x,\ y = ax + b,\ y = ax^c,\ y = \log_{10}x.$$

The relationships represented by such equations appear often in the context of specific empirical problems. As each one is introduced, you are reminded of its basic properties.

Graphs of various types serve as effective means for summarizing a lot of information—both qualitative and quantitative. In particular, you are expected to go back and forth between the four functions listed and their corresponding graphs. (You are reminded about this as we go along.) In addition, many data are presented in graphical form. By the end of the text you will have been exposed to a least six quite different types of graphs. One goal is for you to understand and to know how to interpret data in each of these different modes of presentation, which skill is useful beyond the present subject matter.

Equipment is not much emhasized although, in fact, moderately elaborate electronic equipment is essential for carrying out original research in this area. Auditory phenomena can be demonstrated using a CD player and the demonstration disc described in footnote 1. Some of the binaural (two-ear) demonstrations on the disc can only be appreciated using earphones.

Some of the material on waves is nicely demonstrated on a computer, but I have not prepared such programs to accompany the text. In part, it seemed futile to do so given the large number of possible software packages available.

HOMEWORK

Homework problems are essential for understanding this kind of science, and a number are provided. In general, they are not multiple choice. Some involve calculations using equations you have encountered, but few can be solved by simply searching for the right formula and substituting the numbers. Rather, they require some understanding of which concepts are relevant, and only than will it be apparent what calculations to carry out.

GENERAL STRUCTURE OF THIS TEXT

Part I describes in very general terms something of the problem faced by any organism in finding out about its environment. There are similarities and differences in the several sense modalities, and some of the more important of these are cited. Part II develops the physical description of the simplest sound signals, and some important phenomena are explained. Next, Part III examines some of the anatomical, mechanical, and electromechanical properties of the inner ear. Within that framework we examine how the sound arriving at the ear is "transduced" through the inner ear and is recoded as electrical pulses on the auditory nerve. These findings play a role in Part IV, which explores some of the psychophysical (behavioral) results about these simplest sound signals. To deal with sounds of greater complexity, we examine some of the physics of more complex sounds in Part V. Finally, Part VI takes up some of the phenomena that arise with more complex signals, including several that are not really understood in terms of the physics of the signal or the physiology of the peripheral auditory neurons.

ADDITIONAL READINGS

Most of us get confused when trying to absorb a new subject, and any one presentation may confuse you to some degree. To crib a bit from Lincoln, no matter how authors try, they fail to communicate to some of the students some of the time, although presumably not all of the students all of the time. When you don't understand, often it helps to read what someone else has said about the same thing.

For the elementary physics of sound I recommend Johnson, Walker, and Cutnell (1981) as an excellent introduction. Rossing (1982) covers some of the same material plus a good deal of physiology and psychology, with a strong focus on music. Neither text uses any calculus.

For the physiology and psychology of hearing, the first reference to turn to is Yost and Nielsen (1985). Other, somewhat more advanced, alternatives are Hirsch (1952), Gluck, Gescheider, and Frisina (1989), Green (1976), Handel (1989), Moore (1982), Pickles (1988), Pierce (1983), Roederer (1975), Shiffman (1982), Stevens, Warshofsky, and Editors of *Life* (1965), Tobias (1970), or Warren (1982).

R. Duncan Luce

Greek Symbols

As in much scientific literature, there is a liberal sprinkling of Greek symbols, whose usage is deeply ingrained. They are summarized here with the section they are first introduced noted:

Symbol	*Case*	*Name*	*Section*	*Meaning*
α	lower	alpha	IV.3.3.3	exponent
β	lower	beta	IV.3.2.3	exponent
δ	lower	delta	IV.2.5	variable difference
Δ	upper	delta	II.8.3.1	fixed difference
γ	lower	gamma	IV.3.3.3	exponent
ϕ	lower	phi	II.2.1.4	phase angle
λ	lower	lambda	II.3.2.1	wavelength
μ	lower	mu	II.2.1.2	micro
ρ	lower	rho	II.7.1	density
θ	lower	theta	II.2.1	angle
τ	lower	tau	V.2.2.3	tension
ω	lower	omega	II.2.1	angular velocity

PART I

Transmission, Transduction, and Black Boxes

1. SIGNAL TRANSMISSION

For us to know about the world outside ourselves, events at some distance from us must impact one or more of the sense organs underlying the sensations known as sight, sound, taste, smell, touch, pain, and so forth. So, before information reaches the sense organ, something external must happen: A signal must be produced and that signal must be transmitted in some way to the sense organ.

What are the possible modes of transmission? Scientists know of three distinct types of transmission.

(i) A physical object can simply move from the source to the receiver—from the external site to the sense organ.

The crudest example is some form of projectile, such as a stone or a bullet, although neither is often used to transmit information in any usual sense. An informative projectile is a letter, but of course it requires some additional (visual) transmission once it is sufficiently near the intended recipient.

A more subtle example is light transmission. One of the great discoveries of the early 20th century is that light moves about in tiny packets of energy (and mass) called light quanta, which in some respects may be treated simply as projectiles. In particular, this mode of transmission does not depend on there being a physical connection—medium—between the source and the receiver. Light, for example, traverses a vacuum.

(ii) Impulses that are transmitted in a medium.

In this case, the source of a signal and the sense organ receiving it are usually bathed in the same medium,[1] and the signal moves as a pulse through the medium. Perhaps the simplest, most visible example is a surface wave on water that is generated simply by touching the surface of still water, for example, by dropping a pebble into a pond. Note that no material object is moved from the source to the receiver. For example, if a cork is floating in the pond, it will bob up and down as the impulse arising from the stone passes it, but on average it will be no closer to the receiver after the pulse has passed than it was before. Nothing but the ephemeral pulse moves through the medium.

For the purposes of this text, the key example is sound pulses that are transmitted in various materials, including air, water, and solids. Again, this is done without any particle moving from one place to another. Only the sound propagates, which may be thought of as a wave somewhat analogous to a water wave. Note that this method of transmission is not possible in a vacuum, such as outer space.

(iii) Transmission as a field, which acts somewhat like a medium, but is not.

The two most prominent examples of this form of transmission are gravity and electromagnetism. We are all very familiar with both gravitation and magnetic fields (compasses). The exact nature of fields has been the source of some controversy because, from some points of view, they act much like wave transmission, without any medium.[2] (Until the late 19th century, a medium called ether was postulated for electromagnetic transmission, until experiments established that it would have to have impossible properties.) In addition to gravity and electromagnetism, two other types of fields have been discovered called the strong and weak forces, and one of the concerns of modern physics is how these forces relate. Gravity, despite its being the first known, seems isolated from the other three. Indeed, despite major efforts to detect gravity waves, it remains unclear whether gravity exhibits a wave motion.

We focus solely on pressure impulses and waves in a medium, for it is these changes in pressure that we perceive as sound. Part II is devoted to the physics of generating and transmitting such pressure waves.

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[1] This is not strictly necessary. For example, sounds originating in air can be rather poorly received by a person under water because, as we explore in Section II.8, some, but not a great deal, of the sound produced in air is transmitted through the air-water interface. Transmission is best when the source and receiver are in the same medium.

[2] Depending on the question asked, light, which is a special form of electromagnetism, acts either as a particle or a wave. This is known as the duality of light. Some scientists believe that gravity may ultimately be shown to exhibit the same duality.

2. SIGNAL RECEPTION

What is involved when a signal arrives at a sense organ? At the least, the person must be made aware by the sense organ that the signal has arrived. A basic generalization can be made about all such perception:

Only physical *changes* are perceived. Anything that is truly constant is never perceived.

Three examples illustrate this fact:

- Most of the time you are unaware that your entire body is under atmospheric pressure (of about 14.7 lbs/in^2). But in a rapidly moving elevator or descending airplane the external pressure can change far more rapidly than does your internal pressure, which is somewhat slower to respond, and you become (often acutely) aware of the pressure change.
- You do not notice an image that is held in a fixed location on the retina (the neural receptors at the back) of the eye. This is a difficult experiment to perform because, without any conscious awareness, the eye moves in small jumps—called saccades—several times a second. So some subtle technique and apparatus is needed to take the saccades into account in order to maintain an image at a fixed location on the retina. But when done, the fixed image rapidly disappears. (Is this assertion inconsistent with your subjective impression that you can fixate on something and it does not disappear?)
- You do not notice when there is a high level of static electricity on your body until it is rapidly discharged (preferably not into a computer), at which point you feel an electric shock. This phenomenon is very familiar to those who live in cold, dry climates; it occurs infrequently in southern California.

A corollary of this proposition states that anything perceived as a steady signal must, despite the compelling impression of steadiness, involve some change at the sense organ. Either

- **the sense organ must induce continual change, or**
- **the seeming constancy of the stimulus must be an illusion, and it really is not constant.**

As noted earlier, the eye is an example of a sense organ that induces continual change. When you gaze steadily at an unmoving object, the saccades, mentioned earlier, cause the needed change.

As an example of the second, consider a steady sound, such as a pure tone often used to test audio equipment. It sounds completely constant, but that is an illusion. A pure tone actually involves very rapid, very small changes of air pressure at the ear. They are so fast you do not notice them at a conscious level, but without them you would hear nothing.

So, each sense organ must be a device that responds to a certain class of physical changes: the eye to aspects of the light quanta impinging on it, and the ear to the changes in the pressure waves. But if they are just simple detectors of change, one can ask:

In order to understand sound and hearing (and light and seeing) why isn't it sufficient to understand the physics of the sound stimulus?

This is not a silly question. Indeed, until about 100 to 125 years ago, many scientists thought that understanding the physics of sound would be sufficient. Among those who pursued this approach were three of the most famous physicists, Newton, Fourier, and Helmholtz. They first showed how complex light and sound signals can be decomposed into a sum of very simple components: in the case of light, into the spectrum formed in a rainbow. We look into such decomposition of sound waves in Part V. Next, they postulated that if we understand how the human being responds to each of these components, then the total effect of the signal would simply be the sum of the several effects from the components. This is known as the **linear systems** approach.

Their strategy did not work because the eye and the ear do a far more complex job of processing complex signals than was realized at first. We encounter some of this processing in Part III.

Such complexity is illustrated by the existence of perceptual illusions. These were first recognized in vision, and you are no doubt familiar with some. There are auditory illusions as well, but most of us are less aware of them. The existence of illusions means that the ear and eye do a lot more than passively "transduce" the physical signal, which is discussed in some detail in the next section.

3. TRANSDUCERS

We just spoke of the ear and eye as doing more than "passively transducing" the signal. What does this term *transduce* mean?

DEFINITION: A **transducer** is any device whose (primary) function is to convert energy from one form to another while retaining information about the amount of energy involved.

The term *device* is intentionally vague, because transducers come in many guises. Some familiar examples listed in Table I.1 illustrate the breath of the concept.

TABLE I.1
Types of Transducers

Name of Device	*Conversion*
MICROPHONE:	sound pressure into electrical current
LOUDSPEAKER:	electrical current into sound pressure
PHOTOCELL:	light into electrical current
LIGHT BULB:	electrical current into light (+ heat)
GENERATOR:	mechanical rotation into electrical current
MOTOR:	electrical current into mechanical rotation
EAR (outer, middle, inner):	sound pressure into neural activity
VOCAL CORDS + MOUTH:	neural activity into sound
RETINA:	light into neural activity
– – –:	neural activity into light

Note that transducers mostly come in pairs, the one being, in effect, the inverse conversion of the other, except that in each case some of the energy is dissipated in the form of heat loss. Thus, for example, we use a flow of water or steam in a turbine to rotate a generator that converts some of that mechanical (flow) energy into electricity, which is then transmitted to a site, such as one's home, where some of it is used to run motors (in fans, vacuum cleaners, turntables, etc.) that once again provide mechanical power. In both conversions, heat is also generated and lost.

The major exception to such pairing is the last. Mammals simply do not generate light. Of course, some fish and some insects, such as fire flies, do.

4. BLACK AND NOT-SO-BLACK BOXES

4.1 The Black-Box Approach

In describing transducers, we speak of them in a functional way: as devices that perform a task of converting energy from one form to another. We often need to describe the exact nature (i.e., functional form) of that conversion in great detail. For example, an ideal microphone or loudspeaker has an output that is directly proportional to input, that is, if x denotes a numerical measure of the input and y a numerical measure of the output, then proportionality means that there is a positive constant c such that $y = cx$. Few microphones or loudspeakers live up to such an ideal, but usually proportionality is the goal and, roughly, it is accomplished to a degree that tends to correspond closely to the cost of the transducer. (As is pointed out later, proportionality may well not be an ideal goal for a hearing aid.) For many purposes, such a functional description may be all we need to know about the transducer. Of course, a person designing, building, or repairing a transducer needs to understand the internal structure that gives rise to the overall behavior, but few people who use transducers need to know more than the functional description.

Treating a complex device as a unitary object of known characteristics has come to be called the "black-box" approach. This image arises from the dull, usually inelegant, black casings that often housed scientific electronic devices just before and after World War II. When attention was paid only to their input-output relations, they were referred to as "black boxes." The term has been generalized. For most of us, most of the devices we encounter are treated as black boxes: TVs, computers, calculators, automobiles, locks, and so forth. Most of us usually do not care or need to know more about a device than its functional properties.

4.2 Why and When Does One Take a Black-Box Approach?

The answer to this question depends on the situation.

- The behavior of the box may be functionally much simpler than its inner mechanisms, and the external description may suffice for the purposes at hand. A good amplifier is a case in point. All it does is effect a proportional change, taking a weak electrical signal and making it strong enough to drive a transducer such as a loudspeaker. Nothing could be simpler—except that it is extremely difficult to achieve such proportionality over a wide range of inputs. To do so took years of research and development.
- We simply may not care in the slightest about how the behavior of the box is generated—unless it needs repair or it badly confuses us. The latter is often the situation facing a scientist who is trying to understand something complex, such as human behavior or earthquakes.
- Opening the black box may be infeasible (e.g., ethically), impossible (e.g., opening it destroys its function), or dangerous (e.g., opening it will release noxious substances). Obviously, there are all sorts of feasibility and ethical problems when people and their sense organs are at issue. We simply cannot take apart a human sense organ in order to learn more about how it works.
- Usually it is a good idea to have clear-cut behavioral questions before looking at the "jungle" inside a black box. Imagine trying to figure out what a computer does with neither a manual nor a wiring diagram, but just by opening it and measuring its electrical activity. That analogy is not too far

from the task facing scientists who study the relations between human behavior and neural activity.

4.3 The Black-Box Approach in Psychology

As has been hinted at in some of these examples, experimental psychology treats the person as a black box in the following sense. It tries to describe outputs, **responses**, as a function of external events (often past ones), which are usually classed into at least one of the following categories:

- **Signals** are external events of concern to the receiver.
- **Noise** is other energy in the same modality as the signal, especially energy that makes reception of the signal significantly more difficult. What is noise to one receiver may be signal to another, for example, people talking at a party.
- **Instructions** are explanations to the subject about what is to be treated as signals and how to respond to them.
- **Reinforcements** involve feedback of information about the accuracy of responses. Sometimes the feedback is accompanied by rewards, such as money or food pellets for animals, or punishments that depend on the accuracy of the responding to the signals. With animals, reinforcements are the way that instruction is communicated about what behavior the experimenter wants; it also serves to keep the animal motivated in responding differentially.
- **Social manipulations** of the subject's environment occur in some experiments, although not in many perceptual ones. One social factor that is always present and sometimes significant is the interaction between the subject and the experimenter.

There are other features of the human black box over which the experimenter has no control except by selecting subjects to meet certain criteria. These features may prove important in gaining a full understanding of the observations. Two of the most important are:

- **Cultural backgrounds** of subjects may have an impact on experimental outcomes. To the degree that this has been studied, which is not a great deal, it does not seem to be as major a factor in sensory experiments as in some others.
- **Genetic differences** may underlie some of the individual differences seen in the behavior of subjects. Of the genetic differences, the most prominent and easiest to study is sex, and studies sometimes partition the data by the sex of the subjects. This is most common when it is obvious that

it makes a big difference as, for example, in hearing loss with age (see Section IV.2.6.3).

To some extent these differences can be determined from external observation, such as sex and certain aspects of ethnic background. Other, more subtle genetic differences, such as certain chromosome patterns, can only be determined by intrusive methods. Presumably, the deep impact of culture on people is somehow stored as nearly permanent features of the brain, but at the present time we do not know what internal observations to make and we are restricted to gross external characteristics.

One example of such a black box approach that is relevant to sound and hearing is shown in Fig. I.1.

This figure, to a degree, suggests the organization of the text into the physics of the sound signal (Parts II and V), the anatomy and physiology of the ear, which is the major transducer of sound pressure into electrical activity on the neurons (Part III), and the overall stimulus-response psychology of hearing (Parts IV and VI). We follow this strategy:

We first undertake to gain some understanding of the transmission of

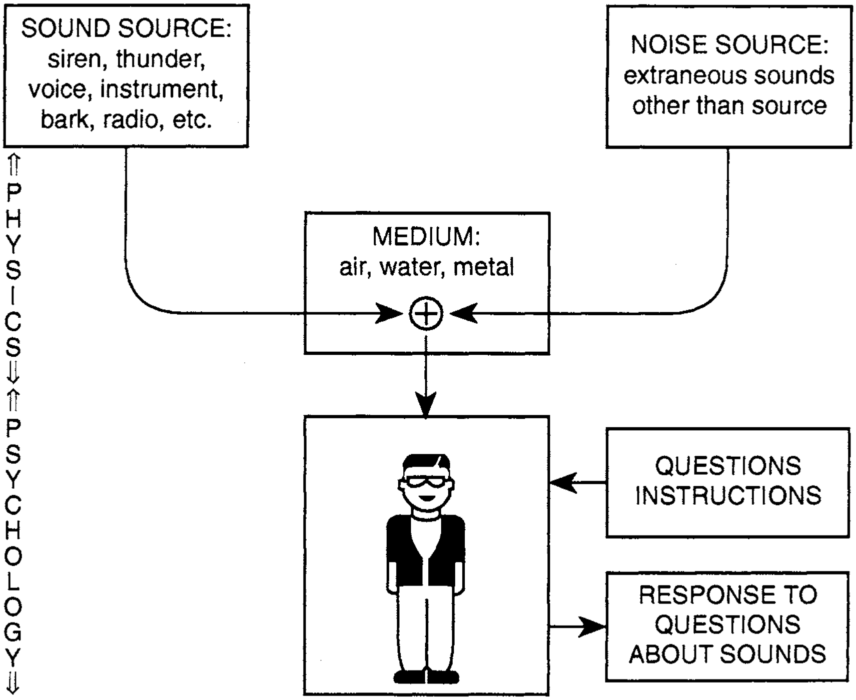

FIG. I.1 The black-box view of a person who, under instructions, is responding to a sound source in the presence of noise.

sound, and as we do so we cite examples where the physical properties of the stimulus are sufficient to account for our perceptions. For example, Part II provides an explanation for the fact that when a police car approaches with its siren blaring, the pitch of the siren changes as it passes us. And Part V explains physically why beating, which is used by piano tuners, occurs. If it cannot be explained physically, the next question is whether by opening the black box we can gain a better understanding.

4.4 Partially Opening the Black Box

Psychology, itself, does not necessarily try to open the black box to explore the internal mechanisms that lead to individuals' behavior or, in the case of sounds, to their perceptions. That is the province of neuroscience and physiology. These fields "open" (at least partially) the black box and try to understand the nature of the processes that underlie aspects of behavior—in our case, those having to do with hearing. They try to understand the mechanical, chemical, and neural-electrical activities that appear to give rise to the observed behavior.

The need to open the black box arises, in particular, when the transducer is complex in what it does. Had the ear been simply a proportionality device, like an amplifier, then the purely physical approach to hearing would have worked and there would have been little reason for psychologists to worry about what goes on in the ear. However, the ear is not much like an amplifier, although it is partially one, and so it became essential to study carefully what exactly the ear does in transducing the signal. This is taken up in Part III.

In opening the black box, one replaces it with several other black boxes at a finer level of observation. For example, we study the level of electrical activity on individual neural fibers in the auditory, or so called eighth nerve[3] coming off the inner ear, but we treat the individual neuron itself as a black box. We do not ask about the processes that go on within the nerve cell that allow electrical activity to be propagated along the nerve. Of course, there are biologists who study such matters. Each of the processes in the cell may, in turn, be taken apart further into component black boxes. This process terminates at the ultimate black box, currently thought to be a family of elementary particles and four forces (fields) among them. We stop far, far short of that.

So, for example, our first level decomposition for hearing can be diagrammed as in Fig. I.2. Further decomposition is necessary to understand the inner ear. We examine its structure in some detail, finding components that themselves will be treated as black boxes.

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[3] In the technical literature this is usually written VIIIth nerve.

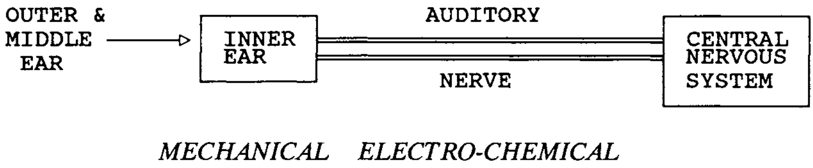

FIG. I.2 A first "opening" of the overall black box into a series of component black boxes: the inner ear, the auditory nerve, and the central nervous system. Each of these can, and will, be decomposed into systems of more basic black boxes.

Having acquired some idea about the nature of the transduction effected by the ear, we then return to psychology, in Parts IV and VI. Here we describe some of the phenomena that psychologists have discovered, and we ask the degree to which we understand them either in terms of the physics of the signal or in terms of the peripheral physiology. If neither, then presumably the explanation lies in activities higher up in the brain. Although a great deal of research has and is being carried out on the neurophysiology of brain function, at the present time it does little to illuminate the psychological phenomena we encounter, and so it is not summarized here.

5. REDUCTIONISM IN SCIENCE

This, then, illustrates the *partially reductionist* strategy of the sciences.

Going between levels of analysis typically is difficult—in particular, detailed knowledge at one level does not always translate readily into predictions at an adjacent level. Probably it does not surprise you that knowledge at a higher level fails to implicate precisely the underlying processes at the next lower level, but many people seem to expect that it will be comparatively easy to pass from lower level knowledge to predictions about the higher level. Some scientists feel that when we understand enough neuroscience, then we will be able to predict the psychological processes in great detail. Perhaps that will happen in the long run, although there are sound reasons to doubt even that. But certainly matters are currently not so simple. The structure and function found at the lower level is often overwhelmingly complex, and without the behavior discovered by psychologists partially guiding the search for relevant neural processes, one simply does not have any idea what is behaviorally significant.

We turn in the next three parts to the generation and transmission of simple physical sounds, their transduction by the ear into neural activity, and to some of the basic sensory behavior that is partially illuminated by the physics and physiology.