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ELECTROACOUSTICS

The Analysis of Transduction, and Its Historical Background

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PREFACE

This monograph is concerned with three topics selected from the wide range of subject matter embraced by the general field of electroacoustics. The first of these is a long introduction devoted to the placement of electroacoustical transduction in its proper historical setting relative to the allied arts and to the basic sciences from which it derives. This is followed by three chapters that include the description of a new scheme for the analysis of both electrostatic and electromagnetic systems of electromechanical coupling in a single homogeneous frame of reference. This method of analysis is then illustrated in the succeeding chapters by examples of its application to three representative transducer systems.

Electric-circuit analogs have been widely exploited as a tool for the study of acoustical and mechanical systems. They have been less widely used, however, for the representation of electromechanical transducers owing to the disparity in the symmetry conditions pertaining to electromagnetic and electrostatic coupling. It has been standard practice to say that one type of analog recommends itself for use with one type of coupling, and that the "other" type must be used with the other — but never the twain could be connected back to back!

I had been experimenting pedagogically since about 1937 with a method for resolving this dilemma by using a *space operator* to import analytical symmetry into the electromechanical-coupling equations for the antireciprocal cases involving magnetic fields. After the war, when there was an opportunity to reëxamine the question, it became possible to resolve the basic issues more clearly and to establish, on sound physical grounds, the validity of using such a space operator to restore symmetry in the analysis of electromagnetic coupling. As a consequence, it now becomes possible to give a unified discussion of all types of electromechanical coupling, including magnetic, electric, and mixed transduction fields. I hope that the novelty of this unified approach will justify in part the publication of this material in advance of the completion of the textbook in whose context it was first drafted.

The ability to represent all transducer types with a single form of equivalent circuit makes it relatively more useful to invoke the methods of electric-impedance analysis for the study of transducer performance.

These methods, like the use of equivalent circuits, had already been widely exploited but they were still further developed during the war period. The account of this subject appearing in Chapter 4 leans heavily on the work carried out under NDRC auspices at the Harvard Underwater Sound Laboratory during the period 1941–1945. Although the relevant results of these studies are no longer classified, in the military sense, the research reports have not been generally available and their only summary was incorporated in another document that could receive only limited distribution. Most of the novel features of this work originated with Malcolm H. Hebb and Harvey Brooks, but Francis P. Bundy and many other members of the HUSL staff contributed significantly, and the cogency of the summary report owed much to Paul E. Sabine. In marshaling this material, I have attempted to act as spokesman for this group of wartime colleagues. None of them can be held responsible, however, for the form of presentation I have adopted, since substantial changes from the original have been introduced in order to adapt the procedures to the broadened frame of reference.

The primary generic types of electromechanical coupling include two that make use of a magnetic field and one that uses an electric field. These are exemplified by movable conductors in a fixed magnetic field, by fixed conductors linking a variable magnetic field, and by movable conductors bearing fixed or variable electric charges. The last two categories embrace both lumped-constant systems, such as the moving-armature earphone and the electrostatic loudspeaker, and distributed-constant systems, such as magnetostriction and piezoelectric transducers. Although the methods of analysis presented here are equally applicable to all these transducer types, the gamut of analytical procedures can be illustrated adequately, and a good bit more succinctly, in terms of the lumped-constant systems. This is fortunate, since an adequate discussion of magnetostriction and piezoelectric transducers could not have been included in any case without far exceeding the dimensional limitations of the monograph format. As a consequence, the consideration of these distributed systems, in which electromechanical coupling is effected through body forces, is perforce relegated to a later monograph or other publication.

In the original form of these notes, a few "firsts" had been mentioned casually as an introduction to the various sections devoted to specific mechanisms of transduction. The process of recasting the material in the form of a monograph provided an opportunity to broaden the scope of these historical allusions and to draw them together into a coherent introduction designed to exhibit electroacoustical transduction in its relevant historical context. There is a close parallelism between electroacoustics and the science of electrical communication, and the mushroom expansion of the latter industry has provided incentive for the publication of many accounts dealing with the history of its growth. Some of these accounts contain useful material bearing on electroacoustics, but I had been well coached about not relying on such secondary sources except as an auxiliary guide in prospecting for original source material. For better or worse, these historical notes are based on the cited primary sources, and while it may not be fluent history, I can at least guarantee that every bibliographical reference has been verified at first hand.

Fortunately, most of the needed source material was available in the rich collections of the Harvard College Library, but a few items (identified by [LC]) had to be run to ground in the Library of Congress, a few in the Engineering Societies Library (New York) [NNE], and a few in the Vail Library of the Massachusetts Institute of Technology [MCM]. I am also indebted to Mr. David P. Wheatland for graciously making available from his private collection the choice items listed in notes 10, 20, 21, and 68 to Chapter 1. The almost complete files of United States, British, and German patents maintained by the Boston Public Library were also invaluable.

Some readers may be surprised by the prominent role played by patent references in the documentation of a history of transduction. However one may feel about the probity of scientists applying for letters patent, if one wishes to be realistic it is necessary to recognize that electroacoustical transduction is an applied science that presents both electricity and acoustics in their working clothes. It follows that many of the most significant gains in know-how, as well as in basic understanding, have made their earliest public appearance — and some, their only appearance — as publications of the Patent Office. On the basis of my experience in assembling the material for Chapter 1, I am persuaded that a good many scientists and most of the science historians have paid too little attention to this class of source material.

I feel overwhelmed by the inadequacy of any acknowledgment I can record here of my indebtedness to others. Since this material has been accumulating throughout most of my adult life, the list needs to start with Professors G. W. Pierce and E. L. Chaffee, who initiated me into these mysteries a good many years ago. The history chapter presented many problems that were novel, at least to me, but generous help came from many quarters. Professor I Bernard Cohen was always ready with wise guidance, kindly criticism, and warm encouragement. Mr. David Rines, patent expert extraordinary, deepened my long-standing obligation to him by making available documents, briefs, his collection of patents, and much good advice. I am also indebted to several makers of this history who were kind enough to read and criticize relevant portions of the manuscript. Among these were Robert W. Boyle, Willoughby G. Cady, Edward W. Kellogg, Edward C. Wente, Raymond L. Wegel, Hugh S. Knowles, and Harry F. Olson. I owe special thanks to Mr. Fred J. Harbaugh for comments and many helpful leads to the patent literature on dynamic loudspeakers.

To the students of many classes, and to my colleagues in our Acoustics Research Laboratory, I am deeply grateful for their patient forebearance through many long discussions of points and viewpoints. Professor Philippe Le Corbeiller has been a gracious tutor and a stout foil, and his careful reading and criticism of this manuscript now puts me further in his debt.

I am in no position to deny that completing a first book has its painful moments, alike for the author and for his wife and son. Without their unfailing devotion and indulgence this book probably never would have been finished.

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CHAPTER 1

Introduction – Historical Context

Electroacoustics is as old and as familiar as thunder and lightning, but the knowledge that is the power to control such modes of energy conversion is still a fresh conquest of science not yet fully consolidated. Like many other frontiers of acoustics, this one could only be attacked by flanking movements. Acoustical manifestations of electricity were in the forefront of notice throughout the shocking and crackling adolescence of static electricity during the 18th century, yet before a satisfying measure of control of these effects could be achieved, there had to be sought first an understanding of the underlying electrical phenomena. This was not to be the only course of evolution, however, for human needs sometimes assert themselves with irresistible insistence without waiting for calm scientific inquiry to run its own well-ordered course.

Throughout man's history, his progress as a social being has been marked by ceaseless efforts to improve the means for moving about from place to place and for satisfying the universal urge to communicate. Common speech and the written word are still the staunchest bulwarks against isolation, but to extend the one and speed the other is a goal that challenges perpetually man's best creative effort. Since ancient times, men of practical science have sought to nourish this basic need for the sharing of perception by making available ever more useful instrumentalities for communication. Signal fires and smoke, the gleam of reflected sunlight, the beat of drums and flight of pigeons — every means for producing observable effects at a distance was bent in its own time and within its limitations to the task of serving man, as Hermes, the messenger and bearer of tidings, had served the gods.

The momentous discovery,[1] in 1729, that some substances "would

[1] Stephen Gray, "A Letter to Cromwell Mortimer, M. D., Secr. R. S. containing several Experiments concerning Electricity," *Phil.*[osophical] *Trans.*[actions of the] *Roy.*[al] *Soc.*[iety] (*London*) **37,** 18–44 (1731–1732).

carry the electrical vertue" while others would not, established almost at once the unique fitness of electricity as an agency for signal transmission. Few discoveries can be said to have had more profound influence on the course of history than this one, which established that electric energy could be transmitted from a point of origin to some other place where "the vertue" could be utilized. The subsequent history of discovery in electricity revealed many examples of electrical action — audible, visible, tactile, mechanical, and electrochemical, to mention only the simple ones. Patient study of such effects provided objectives for a century-long pursuit of theoretical understanding; but each novel effect was also greeted eagerly by those — and there were always some — who saw in each a new vehicle for the transmission of intelligence. The story of this dual search for utility and understanding, and of the proposals both fanciful and practical for exploiting one within the limitations of the other — this is the transducer story.

The word *transducer* is now used as a generic term denoting, in its broadest sense, any device or agency that serves the function of converting one form of energy into some other form. The nature of the energy exchange is often indicated by prefixing to the generic term a self-defining compound modifier, as may be illustrated by defining an *electroacoustic transducer* as a device for converting electric energy into acoustic energy, or vice versa. The generality of this definition is greater than might be required if such devices had no other function than to serve as "terminal transducers" for communication systems, but such a limitation is implicitly denied. It is indeed to be acknowledged — proudly claimed, in fact — that the historical origins of electroacoustical transduction are inseparably linked with the early history of electrical communication. This close relationship continues to account for most, by far, of the transducers now in service throughout the world. The breadth and vigor of this market, awesome as it is in point of numbers,[2] should not, however, divert attention from the vital role played by a smaller class of specialized transducers that allow sound energy to serve directly in physical research and for the needs of industry.

[2] The Radio-Television Manufacturers Association estimates that more than 206 million receivers have been made and sold by manufacturers in the United States alone during the thirty years 1922–1952, and that 130 million of these are currently in use. To these must be added the 168 million transducers accounted for by the 84 million telephones estimated by the American Telephone and Telegraph Company to be in public service throughout the world by the end of 1952. These figures do not include the transducers that have been required for military and miscellaneous end use.

Exciting new frontiers have been opened up for exploration by the 20th-century renaissance of physical acoustics. In the area of fundamental research, these frontiers often lie in zones of overlap with other disciplines, as illustrated by the use of sound in studies of such diverse topics as the behavior of viscous polymers, the structure of liquids and of metals, the distribution of temperature in the upper atmosphere or of fish in the sea, and the topography of ocean bottoms.

The frontiers of applied acoustics are just as widely diversified. Modest beginnings have been made in exploring the use of sound waves, at both low and ultrasonic frequencies, for such operations as non-destructive testing, emulsification, flocculation, cleaning, and process control; and in the area of medical therapy. An even wider field for exploitation is suggested by the use of sound-wave agitation as a more effective agency than stirring for promotion of chemical reactions. One common feature of this catalog commands attention. It is that every novel application requires a source of sound especially adapted to the circumstances of use. The pioneer is thus confronted at the outset, and at every reappearance of a speculative gleam in his eye, with a novel problem of transducer design. The moral is obvious, though hardly new. Professor Joseph Henry pointed it out to Alexander Graham Bell, who had consulted him in connection with his telephone experiments in 1875 and had lamented his "lack of electrical knowledge". Henry's advice [3] was sympathetic but brief; he said, "Get it."

Terminology

Before coming to grips with the detailed analysis of mechanisms of transduction, it may be useful, or at least diverting, to extend these introductory remarks by surveying briefly the historical background of electroacoustical transduction. The kinship between the old and the new can be made more pointed, however, if the present nomenclature is first established. It is a secondary consequence of choosing a broad definition of electroacoustic transducers that a few acoustical orphans are accidentally included in the family, such as domestic or industrial machinery that produces sound or noise only as a by-product of normal operation. These can easily be excluded, however, by defining and applying additional criteria of electroacoustical performance, such as ***linearity***, ***passivity***, and ***reversibility***.

[3] Incident related by Thomas Coulson in *Joseph Henry, His Life and Work*, p. 314 (Princeton, Princeton University Press, 1950). See also 126 U. S. 297 (cf. note 56 below).

Transducers are *linear* if the principal variables describing their output, such as sound pressure and particle velocity (or electromotive force and current), are substantially linear functions of the related quantities describing the transducer input. The qualifying term "substantially" suggests that minor departures from linearity will not alter the classification, and that it is both proper and desirable to speak of evaluating the nonlinear (harmonic) distortion occurring in a transducer otherwise described as "linear." Transducers are *passive* if all the energy delivered to the electric (or acoustic) load is obtained from the energy accepted by the transducer from the acoustic (or electric) source. The term *reversible* indicates primarily the ability of a transducer to convert energy in either direction between the acoustic and electric forms, but the concept of reversibility is also used frequently in a more specialized sense to imply that energy conversion in either direction takes place with equal efficiency.

Transducers used primarily to receive sound energy and deliver electric signals were, for a long time, referred to as *transmitters* in the specialized jargon of telephony, and their companion instruments for the converse transformation were called *receivers*. These designations are often ambiguous, however, and the ambiguity is enhanced when one or both instruments are inherently reversible; hence, such usage is now deprecated, except where it may be required for maintaining contact with previous literature. Transducers that function as sources or sinks for sound in air are now designated, in general conformity with American Standard Terminology,[4] as *earphones*, *loudspeakers*, or *microphones;* and their companion instruments for use in water or liquids are called *projectors* or *hydrophones*.

A good many sound generators, such as bells, automobile horns, and sirens, are not reversible; and although these sources are usually driven electrically and have a sound output that is roughly proportional to the electric input, they are not linear in the sense intended here since there is no correspondence of wave form between the electric input and the acoustic output. The carbon microphone, which has the distinction of being the only "bad connection" tolerated in the telephone system, is neither passive nor reversible, but prolonged development effort has endowed it with a relatively high degree of linearity, and it is still uni-

[4] *American Standard Acoustical Terminology, Z24.1–1951*, sponsored by the Acoustical Society of America and the Institute of Radio Engineers, and published by the American Standards Association, New York.

versally used throughout the telephone system. The thermophone, the hot-wire microphone, and the ionization microphone are examples of another class of transducers to which only a limited kind of reversibility can be ascribed. While the principles on which these devices operate can indeed be adapted for energy conversion or the control of energy flow in either direction, the design requirements for serving one function usually preclude the use of the same instrument for the converse function. Of course, the oldest of all the mechanisms of electroacoustics is one that generates impulsive sound by the sudden expansion of air heated by the energy released in an electric discharge — in short, the thunder and lightning referred to in the opening line. This one can certainly not be classed as reversible, although one might claim for it a distant-cousin relationship to the ionization microphone and the "ionic" loudspeaker.

Another novel transducer that is not linear, not very reversible, and most certainly not passive, is the one based on the discovery that a musical note can be perceived when the ear is placed close to the arm or chest of a person through whose body is passing the intermittent current from a Ruhmkorff induction coil. One can surmise that there was little contest of the monopoly duly granted for the use of this transducer mechanism by a British patent[5] issued as recently as 1874!

It is an almost universal feature of the conversion of electric energy into acoustic energy that the electric energy is first converted into the mechanical motion of a surface in contact with the acoustic medium. The "unconventional" transducers mentioned above are obvious exceptions, and the ingenious can undoubtedly (and did) invent others; but this author is not familiar with any exceptions that satisfy the joint conditions of passivity, linearity, and reversibility. Energy conversion in the reverse direction similarly involves the mechanical motion of a surface that is coupled to the electrical system and is driven by the forces arising in the acoustic medium. It is convenient, therefore, to assume that the transducer problem can be divided so that the electromechanical coupling and the coupling between the mechanical system and the sound radiation field can each be considered separately. In dealing only with the first of these problems, it will be presumed that a solution of the second is available,[6] so that the radiation loading of the mechanical system can

[5] Elisha Gray, represented by John Henry Johnson, in whose name British Pat. No. 2646 was issued 23 October 1874 (complete specification filed 29 July 1874).

[6] See, for example, L. L. Beranek, *Acoustics* (New York, McGraw-Hill, 1954); or H. F. Olson, *Elements of Acoustical Engineering*, 2nd ed. (New York, D. Van Nostrand, 1947).

be adequately represented by a generalized mechanical radiation impedance connected, in effect, at the output terminals of the electromechanical system.

Classification of the Mechanisms of Transduction

The electromechanical coupling problem is the venerable one of the electric motor or the electric generator, here specialized to the case of linear vibration rather than rotation. Methods of coupling can be broadly classified according to whether the mechanical forces are produced by the action of *electric fields* on electric charges, or by the interaction of *magnetic fields* and electric currents. Each of these classes may be further subdivided, and in this way the five most important motor mechanisms involved in linear electroacoustic transducers can be characterized as follows.

(*a*) *Electrodynamic* (dynamic): Motor and generator action are produced by the current in, or the motion of, an electric conductor located in a fixed transverse magnetic field.

(*b*) *Electrostatic:* Motor action is produced by variations of the mechanical stress established by maintaining a potential difference between two or more electrodes, one of which is movable and usually comprises a very light, conducting diaphragm from which sound is radiated directly. The electric output of a *condenser microphone* comprises the variable charging current arising when the capacitance between a fixed electrode and the diaphragm changes as the diaphragm moves under the influence of a sound wave.

(*c*) *Magnetic:* Motor action is produced by variations of the tractive force tending to close the air gap in a ferromagnetic circuit. Generated voltages appear in fixed coils linked with the magnetic circuit when the flux is changed by variations in the reluctance of the magnetic circuit.

(*d*) *Magnetostriction:* Motor and generator action are derived from the direct and converse magnetostriction effect — an effect arising in a variety of ferromagnetic materials whereby magnetic polarization gives rise to elastic strain, and vice versa.

(*e*) *Piezoelectric* (crystal): Motor and generator action are derived from the direct and converse piezoelectric effect — an effect arising in a variety of nonconducting crystals whereby dielectric polarization gives rise to elastic strain, and vice versa.

The ingenuity of designers has led to the production of each of these transducer types in a wide variety of modifications, many of which have been given descriptive designations. For example, electrostatic transducers are available in "push-pull" or "single-sided" versions; magnetic transducers in "balanced-armature" and "ring-armature" types, as well as in the form of the familiar bipolar earphone or "telephone receiver." Piezoelectric transducers may use various crystal "cuts" that can operate in longitudinal, thickness, or shear vibration; or they may use composite "bimorphs" operating as "benders" or "twisters." Magnetostriction vibrators may occur as rods, tubes, scrolls, rings, or laminated stacks, and may use longitudinal, flexural, or radial vibrations. Electrodynamic coupling may involve "moving coil" or "ribbon" conductors which may be either conductively or inductively connected in external circuits.

18th-Century Electrostatic Transduction

The electric machines of the 18th century, with their whirling globes of glass or brimstone, provided experimenters with ample opportunity to become familiar with the loud impulsive sounds that accompany spark discharges in air. Accumulating the charge on a condenser or Leyden jar still further enhanced these noisy discharges. When the main spark could be caused to occur at some remote point, however, thus removing the primary acoustical distraction, it was usually possible to observe a faint clicking sound that seemed to emanate from the Leyden jar itself at the moment of discharge. This effect can now be identified as a shock excitation of compressional waves in the material of the jar, produced by the sudden release of electrostrictive stresses established by the electric charge. A ringing musical tone corresponding to the frequencies of mechanical resonance of the Leyden jar might have been expected to be elicited by this type of excitation, but the resonance vibrations died out so quickly, presumably as a result of the damping introduced by the foil electrodes, that only the click remained. Owing to a lack of the kind of incentive that would have been provided by identifying the source of these clicks, little further attention was devoted to the phenomenon. A similar clicking sound issuing at the discharge of a flat-plate condenser was observed much later, in 1863, by Lord Kelvin,[7] who correctly inferred

[7] Sir William Thomson (Lord Kelvin), in a letter to Professor P. G. Tait, dated 10 October 1863; reprinted in Kelvin's *Papers on Electrostatics and Magnetism*, §§ 302–304 (London, Macmillan & Co., 1872, 1884). [Can any reader supply an 18th-century reference to this phenomenon? I feel sure I have seen one and several of my friends think they have too, but I have not been able to relocate it. As for the phenomenon, I'm sure it exists, because I have heard the clicks myself. F.V.H.]

that the cause of the effect must be closely related to the electrostatic stresses about which Faraday had speculated.

Not long after the Leyden jar itself had been invented, Benjamin Franklin used one for an experiment that provides the first exemplar of controlled electromechanical transduction. When a terminal connected to the outer coating of the jar is brought near the central terminal, a light cork ball suspended between them will be attracted to one, will share its charge on impact, and will then be repelled from it and attracted toward the other terminal. Thus, as Franklin described the action, the ball "will play incessantly from one to the other, 'till the bottle is no longer electrised; that is, it fetches and carries fire from the top to the bottom [that is, from the inside to the outside coating] of the bottle, 'till the equilibrium is restored." [8a] Franklin was primarily concerned with the demonstration this afforded of the equality of the charges on the inner and outer coatings of the Leyden jar. With characteristic promptness, however, the ingenious Mr. Franklin soon found an application for the motive principle in a multipole arrangement adapted for producing continuous rotation of a wheel. He called this an "electrical jack," and suggested that "if a large fowl were spitted on the upright shaft, it would be carried round before a fire with a motion fit for roasting." [8b]

Once the principle of this relaxation-type oscillator had been made known, Franklin regarded its electro*acoustical* modification as "a contrivance obvious to every electrician," [8c] since it involved no more than mounting a bell on each terminal and substituting a light metal striker for the cork ball. When one bell is grounded and the other connected to an electrical machine, they would continue to sound as long as the potential difference was maintained. De Laborde proposed to use this striking mechanism as the basis for an "electrical piano" [8d] in 1761, and similar "electrical chimes" were enjoyed as an electroacoustical toy throughout the following half century of waiting for electromagnetism to be discovered. Franklin had already made better use of the effect by

[8a] Benjamin Franklin, *Experiments and Observations on Electricity*, edited, with a critical and historical introduction, by I Bernard Cohen, p. 183 [in *Letter III* of 28 July 1747] and p. 189 (Cambridge, Harvard University Press, 1941).

[8b] *Ibid.*, pp. 194–197.

[8c] *Ibid.*, p. 268.

[8d] R. P. [Jean Baptiste] De Laborde, *Le clavessin électrique; avec une nouvelle théorie du méchanisme et des phénomènes de l'électricité* (Paris, H. L. Guerin & L. F. deLatour, 1761).

arranging for such a pair of bells to signal the appearance of high potentials on the otherwise-ungrounded lightning rod he had installed on his house for experimental purposes in 1752.[8e] When his family finally tired of hearing the portentous ringing of these bells during Franklin's absences abroad, he sent to them from London a suggestion [8f] that still retains its effectiveness as a means of evading electroacoustical insult — that a short piece of wire be firmly connected across the electrical terminals of the transducer!

The Sympathetic Telegraph

The earliest proposals for harnessing electricity in man's service took the form of primitive schemes that were suggested for realizing an electric telegraph. The basic concept of the telegraph itself is a very old one that sprang up long before science had made available the instrumentalities for realizing it in practice. The primitive notion usually took the form of a "sympathetic-needle" telegraph, and Fahie [9] has found references to the idea dating as far back as the 4th century. The first clear allusion to it, however, is probably that given in several places by Porta,[10] who simply stated with disarming presumption, "And to a friend that is at a far distance . . . we may relate our minds; which I doubt not may be done by two Mariners Compasses, having the Alphabet writ about them."

A fuller description of this bit of science fancy, and one that came to be widely copied, was given a little later by Famianus Strada, who wrote in 1617 of two friends who maintained rapport by carrying

[8e] A full account in I B. Cohen, "The Two Hundredth Anniversary of Benjamin Franklin's Two Lightning Experiments and the Introduction of the Lightning Rod," *Proceedings of the American Philosophical Society* **96**, 331–366 (June 1952), p. 352.

[8f] Albert Henry Smyth, *The writings of Benjamin Franklin*, vol. 3, pp. 438–443 (in 10 vols., New York, Macmillan, 1907).

[9] J. J. Fahie, *A History of Electric Telegraphy to the year 1837*, pp. 20–25 (London, E. & F. N. Spon, 1884). For a tolerably complete summary of references, early and late, to the "sympathetic telegraph" idea, see also the Appendix, pp. 409–418 of vol. II, of *Catalogue of the Wheeler Gift of Books, Pamphlets and Periodicals* [the Latimer Clark collection] *in the Library of the American Institute of Electrical Engineers* [New York], edited by Wm. D. Weaver (in 2 vols., New York, American Institute of Electrical Engineers, 1909).

[10] Giambattista della Porta, *Magiae Naturalis, sive de miraculis rerum naturalium, Libri IIII*, in Lib. II, Cap. XXI, p. 89 (1st ed., small folio, Neapoli, Matthiam Cancer, 1558); also in *Magiae Naturalis, Libri XX*, in preface to Lib. VII (1st ed., small folio, Neapoli, Horatium Saluianum, D.D.LXXXVIIII. [*recte* 1589]); among the many later editions was one in English, *Natural Magick: in twenty books* (small folio, London, Thomas Young and Samuel Speed, 1658).

"sympathetic loadstones" having dial plates inscribed with the letters of the alphabet.[11] When one friend turned the point of his compass needle to a selected letter, the other's instrument responded, as with

> . . . fond spontaneous sympathy;
> While his own steel in like rotation flies,
> And bids the gradual syllables arise:
> Each word he marks to full perfection brought,
> And eyes th' expressive point, interpreter of thought.

No respecter of distance, this mode of communication! As Strada puts it, in the lyrical "Student" translation,

> Thus, if at Rome thy hand the steel applies,
> Tho' seas may roll between, or mountains rise,
> To this some sister needle will incline,
> Such nature's mystic pow'r, and dark design!

Addison brought forward his translation of Strada's proposal as a suggested remedy for the plight of a wife who felt herself widowed by a husband's absence. Apparently he could not resist adding the suggestion that a good bit of time might be saved by including on the dial plate "several entire words which have always a place in passionate epistles" — a suggestion that has been not only accepted but extended by modern telegraph companies who offer reduced rates for the transmission of stylized greetings.

The Electrostatic Telegraph

More realistic proposals for communication by means of signals transmitted over wires began to appear during the middle of the 18th century, not long after Stephen Gray [1] had discovered that some materials would conduct electricity, and that the electricity could be confined to these pathways by isolating or supporting the conductors with other substances which were nonconductors. Most of these proposals involved as many wires between the terminals as there were different letters or symbols to be transmitted; and each wire was to be terminated by some form of electromechanical transducer — usually a modification of the suspended-pith-ball electrometer — for indicating which symbol was being trans-

[11] Famianus Strada, *Prolusiones academicae oratoriae, historicae, poeticae, etc.*, pp. 351–352 (8°, Coloniae Agrippinae, 1617). The quoted passages are taken from the lyrical translation titled "The Sympathetic Loadstones" in *The Student, or, the Oxford and Cambridge Monthly Miscellany*, vol. 1, pp. 354–356 (Oxford, 1750); also freely translated by Jos. Addison in *The Spectator*, No. 241, December 6, 1711.

mitted. The first system of this kind to be constructively reduced to practice appears to be the one proposed, and said to have been set up at Geneva in 1774, by Georges-Louis Lesage.[12] Others followed, and before the turn of the century transmission was reported for distances as great as 26 miles.[13]

The curious fixation on the notion that a separate wire must be provided for each transmitted character adhered to most of the telegraph proposals made before 1830, although single-channel systems began to make their appearance as early as 1795. In that year, Tiberius Cavallo[14] experimented with such a system, and there is a prophecy of modern pulse-time modulation in his suggestion that "by sending a number of sparks at different intervals of time according to a settled plan, any sort of intelligence might be conveyed instantaneously". Another scheme involving use of the time interval between pulses for encoding the transmitted information was proposed by Harrison Gray Dyar[15] in 1828. This system was operated over a single-wire line a few miles long (strung around a racetrack on Long Island, in fact), and employed an electrochemical process (spark discoloration of moist litmus paper) as the receiving transducer. It thus became the first *recording* telegraph system.

The ancestry of the modern "ticker" telegraph can be traced back in a similar way to an experimental telegraph constructed by Sir Francis Ronalds[16] in 1816. In this system, rotating lettered dials at each end of the 8-mile line were kept in synchronism by mounting each one on the seconds shaft of a carefully regulated clock. The symbol to be transmitted was indicated by the response of an electrometer when a static charge was placed on the single-wire line just as the desired symbol passed the reference mark at each station.

[12] Lesage's telegraph is described in a letter of 22 June 1782, quoted by M. l'Abbé Moigno in *Traité de Télégraphie Electrique*, 2nd ed., part ii, p. 59 (Paris, A. Franck, 1852); Fahie (see note 9) questions whether this telegraph was actually built and his skepticism seems to be supported by the brief contemporary notice in *Journal des Sçavans*, pp. 637–638 (1782).

[13] This evidence is also questionable: see the discussion in Laurence Turnbull, *The Electro-Magnetic Telegraph*, 2nd ed., pp. 21–22 (Philadelphia, A. Hart, 1853).

[14] Tiberius Cavallo, *A Complete Treatise on Electricity*, vol. 3, p. 295 (London, C. Dilly, 3d ed. in 2 vols., 1786; vol. 3 added 1795).

[15] Harrison Gray Dyar, quoted in G. B. Prescott, *History of the Electric Telegraph*, pp. 427–428 (Boston, Ticknor and Fields, 1860).

[16] (Sir) Francis Ronalds, *Descriptions of an electrical telegraph, and of some other electrical apparatus*, pp. 1–24 (8°, London, R. Hunter, 1823).