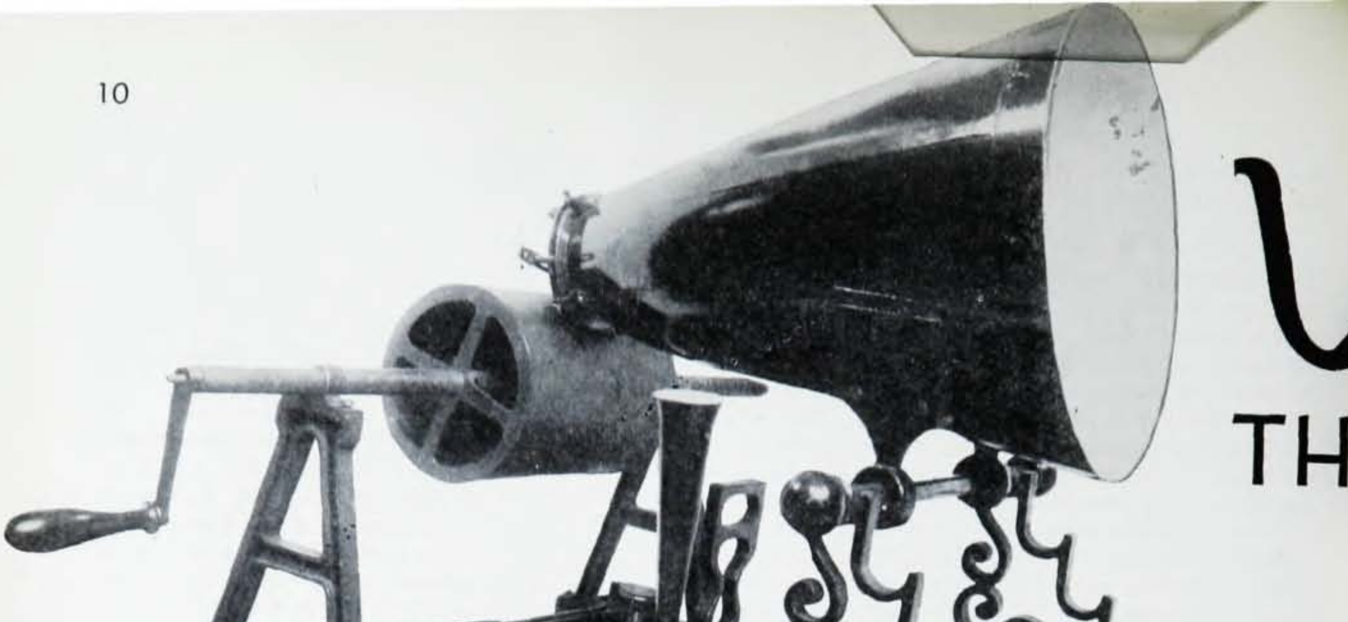

Sound reproduction has undergone many revolutionary changes since the invention in 1865 of Scott's phonautograph, shown in this Smithsonian Institution photo.

*By* ***Edgar M. Villchur***

SEVENTY-FIVE YEARS AGO, in the autumn of 1877, Thomas Edison cranked out a weak, distorted imitation of his own voice reciting *Mary Had a Little Lamb*. It was the first time in history that a record of the instantaneous excursions of a source of sound had been used to re-create the original sound at will. Edison designed the necessary apparatus with great mechanical ingenuity, but his phonograph was only the final model, perhaps already overdue, of a series of acoustical devices which had been built in physics laboratories over a period of almost a century.

Newton had clearly pointed out the vibratory nature of sound, describing the source of a sound wave as a "tremulous body" which radiated alternate impulses of compression and rarefaction. The study of changing quantities already utilized, in Newton's age, the technique of symbolizing a series of variations in time by a static graph. The advance and retreat of particles stimulated by sound energy, and the shifting pressure states in the conducting medium, were therefore represented on paper by a sinuous curve plotted on a scale whose dimensions were proportional to time intervals. Once this translation from temporal to spatial units was introduced it was possible to conceive of a dumb machine to perform the operation automatically. Such a translation is the sum and substance of sound recording; alternations of atmospheric pressure, successive in time, are converted to alternations of groove dimension, magnetization, or light value, laid out in spatial sequence.

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# REPRODUCTION OF SOUND

The first extensive experiments in the direct formation of graphical patterns by sound energy were performed in the late 18th century by Ernst Chladni. Chladni scattered dry sand on a metal plate, induced vibrations in the plate by drawing a violin bow across its edge, and observed the patterns into which the nodes and antinodes of standing waves arranged the dancing particles of sand. The designs produced by vibrations of various characteristics were published and carefully analyzed as clues to the nature of sound.

Thomas Young, the physicist who introduced the modulus of elasticity in current use, revealed the principle of permanent sound recording in "A Course of Lectures on Natural Philosophy and the Mechanical Arts", published in 1807. He wrote:

"The situation of a particle at any time may be represented by supposing it to mark its path, on a surface sliding uniformly along in a transverse direction. Thus, if we fix a small pencil in a vibrating rod, and draw a sheet of paper along, against the point of the pencil, an undulated line will be marked on the paper, and will correctly represent the progress of the vibration."

Young developed this idea in the design of a mechanical recording device which held the stylus pressed against the surface of a cylinder, so that when the cylinder was rotated about its longitudinal axis the stylus marked or scored a line along the circumference. Vibrations could then be induced in the stylus by touching it with a "sounding body", and the line became a rhythmic graph of instantaneous source displacement versus time, a graph traced by the source of sound itself rather than by the hand of a draftsman.

This machine was intended to aid in the study of oscillatory or other types of motion. In addition it was meant to serve as a practical recorder, through its ability to measure very small intervals of time taken up between successive stimuli applied to the stylus. The surface of the cylinder could be calibrated in hundredths or even thousandths of a second by reference to the speed of rotation.

Experiments were made in the years following with apparatus based upon Young's design by acoustical workers such as Duhamel and Wertheim. Duhamel's vibrograph of 1840, for example, recorded the vibrations of a source of sound by scratching white lines on a cylinder coated with lampblack. As in the case of all the other recording devices built during this period direct connection between the stylus and the vibrating source was required. The first device which could record sound from the air without such a connection was built in 1856 by Léon Scott de Martinville. The recording stylus of Scott's instrument, instead of being coupled mechanically to the source of sound, was attached to an intermediary parchment diaphragm stretched across the narrow throat of an acoustical horn. The recording medium was the same as that of the vibrograph, a cylindrical surface coated with lampblack.

Scott named his instrument the phonautograph, or self-writer of sound.* Within its limitations it was able to capture the characteristics of any sound or group of sounds, their frequency, wave form, and dynamic range. Fairly lengthy records could be made since the cylinder shaft was mounted on a feed screw, adding lateral motion to the cylinder's rotation and causing the stylus to trace a helical rather than a circular path. The instrument was manufactured commercially by a Paris firm as a sort of mechanical oscilloscope for laboratory use, and shipped to various parts of the world.

A PARALLEL DEVELOPMENT had been going on in European acoustical laboratories related to investigations into the nature of speech. The era's intense curiosity about how the human body worked, coupled with the mechanic's delight in machines which could imitate human activity, led to the construction of pneumatic devices that talked. The most successful of these was a keyboard operated machine designed by Josef Faber of Vienna, which could be made to speak intelligibly in any of the common European languages by means of a complicated and ingenious mechanism consisting of bellows, adjustable air cavities, a fan wheel to roll its *R*'s, and rubber lips and tongue. This talking machine represented the application of an entirely different branch of acoustical research from that which produced sound recorders, but it probably stimulated thought in the direction of retranslating phonautograph recordings back into sound.

In order to reconvert the graphically recorded data to a time sequence it was necessary that a reproducing mechanism, sensitive to the variations imprinted in the recording medium, be made to scan the symbolic pat-

* It is interesting to note that both Scott and Young were deeply interested in the symbols of writing; Scott wrote a book on stenographic systems, and Young made important contributions to the field of Egyptian hieroglyphics.

tern. This principle was suggested in several periodicals, but it was not until twenty years after the invention of the phonautograph that reproduction was actually achieved. The problem which had to be solved was quantitative, not qualitative; the phonautograph would have worked as a reproducing instrument if there had been any records with traces rigid and deep enough to force the stylus to follow them.

A recorder to inscribe the wave forms of sound had to be a sensitive device if the only driving force was to be provided by the sound itself. It was for this reason that the scratching of lines in lampblack, an operation creating very little resistance to motion of the stylus, was chosen as the recording system. But a groove from which reproduction could take place had to be stiff enough so that when a compliant stylus was dragged through it the stylus and not the groove walls would give. At that time it was not possible to make accurate measurements of acoustical pressure, and the ability of sound energy to carve its record into solid material was underestimated.

Charles Cros devised a solution to the problem in April, 1877. He proposed to make photoengravings of lampblack recordings on metal. Cros deposited a sealed copy of the description of his system with the Académie des Sciences, but didn't actually construct a working model. A translated extract from his description follows:

"Speaking generally, my process consists in obtaining traces of the movement to and fro of a vibrating membrane, and in using this tracing to reproduce the same movement, with its intrinsic relations of duration and intensity, either on the same membrane, or on one adapted to give out the sounds which result from this series of movements.

"It is therefore necessary that an extremely delicate tracing, such as may be obtained by passing a needle over a surface blackened by fire, should be transformed into a tracing, capable of sufficient resistance to guide an index which will transmit its movements to the membrane of sound.

". . . . By a well known photographic process, a transparent tracing of the modulations of the spiral can be represented by a line of similar dimensions on some resisting substance—tempered steel, for example."

Edison, like Cros, realized the mechanical necessity for a stiff groove. He tried a compromise solution by using a recording material which was neither very soft nor very hard, tinfoil. A sheet of this material was wrapped around a pre-grooved brass cylinder, and the recording stylus was mounted in such a way that it could indent the tinfoil in varying degree into the depressions of the brass threads. Although the recorded groove was deformed with each playback it retained enough of its original shape to reproduce intelligible speech. This retention of shape was possible because of the severe loss in acoustical energy from recording to playback; the resisting force of the stylus in reproducing was much less than the recording force that had been applied.

The tinfoil phonograph was demonstrated to the Académie des Sciences in 1878. Scientific caution, and perhaps a resemblance between the tone of the instrument and the voice of a ventriloquist, led to suspicion of deception. Some of the members even claimed that the demonstrator seemed to be moving his lips as he cranked the machine. Théodose du Moncel, the academy member through whom the presentation was being made, was asked from the floor to make a recording himself. To the satisfaction of the doubters (as recounted by du Moncel) his first attempt failed, but a small group then retired to the Secretary's office where a successful recording was made under carefully controlled conditions.

One academician noted, almost justifiably, that Edison's invention consisted of the sheet of tinfoil. The use of a compromise material was not a very satisfactory way to reconcile the necessary sensitivity of the recording mechanism with the need for a stiff groove. In 1886 Sumner Tainter and Chichester Bell (a cousin of Alexander) improved on Edison's system by introducing a basic difference between the recording and the reproducing processes. Their record groove was not embossed, but cut into wax by a knife edge on the recording stylus, while the groove was protected from damage during playback by the fact that the reproducing stylus had a rounded tip. The basic idea of the Bell-Tainter system for disc recording has never been abandoned. The separation between recording and reproducing was widened by the introduction of records cast from a mold, and very recently the system has been further refined by electrical heating of the stylus for a smoother cut.

MUCH OF THE HISTORY of phonograph development from this point consists of the application of principles and devices borrowed from other fields. The motive power of the hand driven machines was succeeded by that of electric motors, water motors with hose connections to the local faucet, and treadles modelled after sewing machine designs. A few years later all of these methods were replaced by regulated spring motors copied from the clockmaker's art.

The power and tonal fidelity of the reproduced sound was to a large extent dependent upon the efficiency of acoustical coupling between the vibrating needle and the air. The necessity for augmenting the small radiating area of the stylus with that of the reproducing diaphragm was understood from the first, and many changes were subsequently made in the material and design of the stylus-diaphragm assembly for optimum results. A diaphragm by itself, however, cannot efficiently radiate energy into the open space of a room, as it does not engage the relatively large volume of air which must be moved at lower frequencies. A horn acting as an acoustical transformer was therefore inserted between the diaphragm and the room, enabling the source of sound to get a better bite of its load. Since each cross-sectional layer of air in the horn is intimately associated with its adjacent layers, a vibrating body at the narrow throat is engaged to and moves all of the air in the horn instead of cutting a swath through the middle, and the effective radiating area of the source is increased towards that of the horn's mouth.

Significant improvements resulted from remodelling phonograph horns along the lines of certain musical instruments. The constant rate of flare of the conical form was replaced by a flare which followed an exponential function, giving the horn the appearance and the name of a morning glory. The coils of the bass tuba, which enable a long, gradually flaring horn (the design best suited for good acoustical coupling at bass frequencies) to occupy a reasonable space, were imitated by folding the phonograph horn back on itself. Then, instead of allowing this bulky structure to follow the stylus and diaphragm across the record the horn was made rigid with respect to the cabinet, and was coupled to the reproducing head by a flexible joint and a tapered tone arm which itself formed part of the flare. When the tortuous passages of the folded horn were enclosed by the cabinet the era of the "hornless" phonograph had begun.

The most revolutionary change in phonograph technique after the adoption of the Bell-Tainter system was the introduction of amplification, originally referred to as the "relay" method of reproduction. The development of direct mechanical-acoustical systems had not taken long to reach a dead end. The mechanical reproducing system subjected to forced oscillation is a device which must vibrate in imitation of many different voices despite its own values of mass and elasticity, and it has inherent limitations. The natural resonances of such a device must be subdued by damping or by design which shifts the main resonant frequency to a less annoying region, if possible subsonic, but these same measures drastically reduce efficiency. Such a loss of efficiency can only be tolerated if the mechanical energy shaped by the record groove, rather than being consumed as the final product, is used to direct an independent source of greater energy.

The modern reproducing stylus assembly is not designed to radiate mechanically into the air but to control an electronic amplifier, a system foreshadowed by pneumatic and mechanical amplifiers which were produced commercially during the 1900's. In the pneumatic "auxetophone" the reproducing needle was made to modulate a flow of air supplied by a motor driven compressor. The mechanical or friction amplifier employed the principle of the ship's capstan; the reproducing needle was coupled to the diaphragm by means of a string and friction shoe which passed over a rotating drum, and the extra energy picked up from the drum aided in varying tension on the diaphragm.

Electronic amplification of oscillatory energy was developed primarily in connection with radio, and later applied to the phonograph. Electronics has become a third and increasingly powerful partner to acoustics and mechanics in the field of sound reproduction. The output of modern amplifiers designed for the audio-frequency spectrum can be made to conform closely to the input signal, within a tolerance of error which compares favorably with perceptible hearing differences. On the other hand electro-acoustic transducers which interchange acoustical, mechanical, and electrical energy have ample room for improvement, and will probably undergo radical changes.

Quantitative analysis of mechanical or acoustical oscillatory systems has powerful tools at its command today, making possible design for predictable behavior rather than design by pure cut-and-try methods. Such systems follow the same fundamental laws that apply to alternating electrical currents. The same equations accurately describe system behavior, the same complex quantities made up of real and imaginary components are used in these equations, and mechanical and acoustical impedances are measured in ohmic units. For example, the expression:

$$E = I\left[R + j\left(\omega L - \frac{1}{\omega C}\right)\right]$$

describing the relationship between voltage, current and a complex impedance across which the voltage source is connected, applies equally well to an acoustical system, in which pressure is analagous to voltage, volume velocity (the rate of flow of the conducting medium) to current, viscosity to resistance, acoustical mass to inductance, and acoustical compliance to capacitance.

The most important transducing link between electrical and acoustical energy is the electromagnetic or electrostatic field, whose movement in space can be controlled and harnessed. The harnessing agent has usually been some form of pivoted or suspended machine, a diaphragm, moving coil, or similar device. But the use of intermediary mechanical systems whose natural behavior must always be suppressed is no longer considered a necessary evil; electro-mechanical transducers are being replaced by devices which require no mechanical moving parts. The tape recording and reproducing head make the pivoted stylus unnecessary, and a new development from France, the "ionic" speaker, by-passes the electro-mechanical stage of the loudspeaker by ionizing and directly controlling molecules of air in an electrostatic field. Thus the generation of sound, which had been considered an inherently mechanical function, can be freed from the trammels of suspensions and diaphragms, and the same principles will undoubtedly be applicable to the reverse function performed by microphones.

The reproduction of sound has matured from a novelty field to one which is a serious adjunct of musical performance. Most of the music played today is passed through at least one recording or nonacoustical transmission medium before it reaches the ears of its listeners. The goal of audio and acoustical engineers is ultimately to efface the imprint of the transmission, so that the original perceived quality is re-created. As in the past, engineering development is following the course of more basic physical research.