Helmholtz

This 19th-century German was a deep and versatile investigator. Although he had been trained as a physician, he made important contributions to physics, physiology and the theory of knowledge

by A. C. Crombie

"My mind absorbed avidly, like a revelation, the first law I knew to possess absolute, universal validity, independently from all human agency: the principle of the conservation of energy."

These words are from the *Scientific Autobiography* of the great German physicist Max Planck. The law to which they refer—which says essentially that energy, like matter, cannot be created or destroyed but only transformed—was indeed a revelation to scientists of the mid-19th century. Its implications and the problems it posed dominated physics in the period between the electromagnetic researches of Faraday and Maxwell and the introduction of the quantum theory by Planck in 1900. It is certainly one of the most important ideas in the history of physical science.

Like many great scientific discoveries, the law of the conservation of energy was arrived at independently by several men. Its broadest and most definitive formulation was given by the German physicist, physiologist and philosopher Hermann von Helmholtz. Yet at the time he published his account of energy conservation he was not a professional scientist but a young doctor practicing in the Prussian army.

Helmholtz's scientific accomplishments were extraordinarily wide in range. To physics he contributed not only his work on the conservation of energy but some of the most important germinal ideas on the electrical theory of matter and of light and radio waves. In physiology he carried out the first systematic experimental investigation of the sense organs, especially the eye and ear. These investigations in physiology led him to epistemology and the philosophy of science. Here his genius played a major part in turning German philosophy from its resolute preoccupation with philology and history toward a concern with science.

The remarkable breadth of his achievements is a testimonial to the advantages of forcing a man of genius to consider problems outside his usual field of interest. By natural bent Helmholtz was a theoretical physicist and mathematician. His father, however, could not afford to give him a university education; to obtain a government scholarship Helmholtz had to take up the study of medicine. As a medical student and army surgeon he was forced to look at scientific problems from an unusual point of view and to enrich and discipline his unifying mathematical and physical intuitions by contact with concrete and particular facts.

Hermann Helmholtz (the "von" was added when he was ennobled many years later) was born at Potsdam in 1821. His father was a master at the Potsdam Gymnasium; his mother was the daughter of an army officer and a direct descendant of William Penn. As a young child Helmholtz was delicate and seems to have learned slowly; a relative, writing to reassure his ambitious parents, reminded them that the great Alexander von Humboldt had learned nothing before he was eight. Nonetheless when Helmholtz entered school at seven he is said to have astonished his teachers with his intuitive grasp of geometry, learned from playing with toy blocks.

Geometry appealed to the young Helmholtz because of its orderliness. He had a bad memory for disconnected facts and was hopeless at history. But geometry failed to satisfy him for long. As he said many years later: "It dealt exclusively with abstract forms of space, and I delighted in complete reality." The first fragments of physics which he learned at the Gymnasium revealed to him "the mighty fullness of Nature, to be brought under the dominion of a mentally apprehended law." The prospect of winning "intellectual mastery over Nature" was to fascinate him for the rest of his life.

Helmholtz's first attempts to generalize reality had been cast in geometrical terms. The study of physics soon shifted his thinking to "a kind of mechanical mode of view." He discovered with delight that he had an intuitive grasp of the distribution of strains and stresses in any mechanical arrangement. Experienced mechanics and machine-builders also have this sort of intuitive understanding, but, as Helmholtz later put it, "I had the advantage over them in being able to make complicated and specially important relations clear by means of theoretical analysis."

In 1838, when he was 17, Helmholtz entered the Friedrich-Wilhelm Institute of Medicine and Surgery in Berlin. Its professor of physiology—the first man to hold that title in any country—was Johannes Müller. Through Müller's influence Helmholtz soon became interested in seeking out physicochemical explanations for biological processes. His first original contribution to science, published soon after his graduation, was in the field of anatomy; it showed that the nerve fibers of invertebrates originate in ganglion cells. For relaxation from his medical and physiological studies he read mathematical works by Euler, Bernoulli and d'Alembert, along with the poetry of Goethe and the philosophy of Kant.

As a scholarship student at the Institute Helmholtz had had to agree to serve 10 years as an army surgeon. Fortunately he was able to continue his physiological researches in a laboratory fitted up in the Potsdam barracks where he was stationed. These researches, which were to lead him to the law of the conservation of energy, were inspired by the controversy over "vitalism" that stirred all workers in the life sciences in the first half of the 19th century.

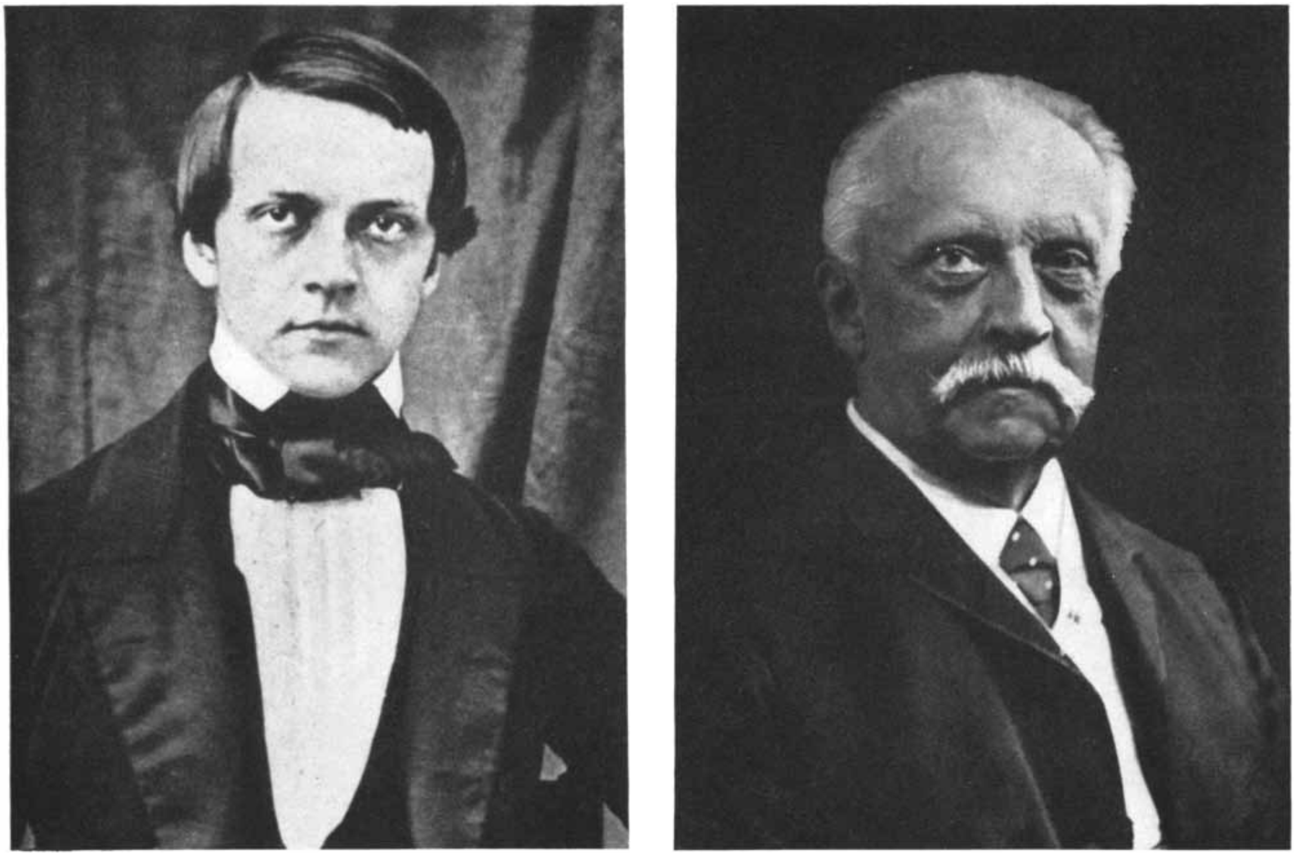
As Helmholtz himself put it: "Most physiologists had at that time adopted G. E. Stahl's way out of the difficulty, that while it is the physical and chemical forces of organs and substances of the living body which act on it, there is an indwelling vital soul or force which could bind or loose the activity of these forces; that after death the free action of these forces produces decomposition, while during life their action is continually being controlled by the soul of life." He went on to say: "I had a misgiving that there was something against nature in this explanation; but it took me a good deal of trouble to state my misgiving in the form of a definite question."

It was the great German chemist Justus von Liebig who succeeded in formulating the question. Are the mechanical energy and heat produced by an organism, he asked, entirely the product of its own metabolism? Helmholtz, in his barracks laboratory, set out to discover the answer. His first investigations into the metabolism of muscle showed that the heat of the body comes entirely from the foodstuff and oxygen supplied to it. The heat given off by an animal, he found, was equal to that produced by burning the animal's food in a calorimeter. There was none left over to indicate the operation of a vital force.

Now Bernoulli, d'Alembert and other 18th-century mathematicians had already developed Newton's law of the conservation of momentum to show that machines cannot originate energy, but can only convert the energy they receive from without into various forms of motion. Thus a man may give potential energy to a weight-powered clock by winding up the weight; as the weight falls this potential energy will be converted into the kinetic energy of the clock-mechanism. But when the weight reaches the bottom, the clock will stop. A perpetual-motion machine, which works without input of energy, is impossible. "Stahl's theory," Helmholtz later wrote, "ascribed to every living body the nature of a *perpetuum mobile*." The concept of a vital force that could engender and direct physical forces without consuming energy struck Helmholtz as a paradox.

The resolution of this paradox stimulated Helmholtz, already able to move with ease in many different branches of science, to apply his powerful mathematical vision to a general solution of the whole problem of energy transformation. In 1847 he was able to present his theoretical solution to the Physical Society in Berlin, in his famous paper "On the Conservation of Energy."

Assuming that perpetual motion is impossible, he asked what the relations between the various known forces of nature must then be. His answer was that these forces cannot arise out of nothing. Mechanical energy cannot be generated in any natural process without a corresponding expenditure of energy. But neither can energy disappear. A quantity of energy may be lost to a particular machine (as in the clock when the weight reaches the bottom) but not to the universe as a whole (the kinetic energy of the clock's mechanism is converted into an equivalent quantity



HELMHOLTZ is shown as a young man and at the age of 60. The daguerreotype at left was made about 1842, the year he graduated from medical school. The photograph at right was made in 1881, when he was professor of physics at the University of Berlin.

of heat). "Nature as a whole," Helmholtz wrote, "possesses a store of energy which cannot in any wise be added to or subtracted from. . . ." The quantity of energy is as eternal as the quantity of matter, the indestructibility of which had been established by Lavoisier.

Helmholtz went on to examine the implications of his thesis. The atomic and molecular theories, already well-secured as scientific principles, held that matter consists of elementary particles with unalterable properties, and that chemical changes involve merely the redistribution of these particles in space. To this conception Helmholtz added the postulate that all forces can be analyzed into mechanical forces acting between these elementary particles; even heat is due to atomic or molecular motion. All forms of energy are ultimately kinetic; the final aim of natural science must be to reduce itself to mechanics, with mass and energy as the fundamental, indestructible quantities.

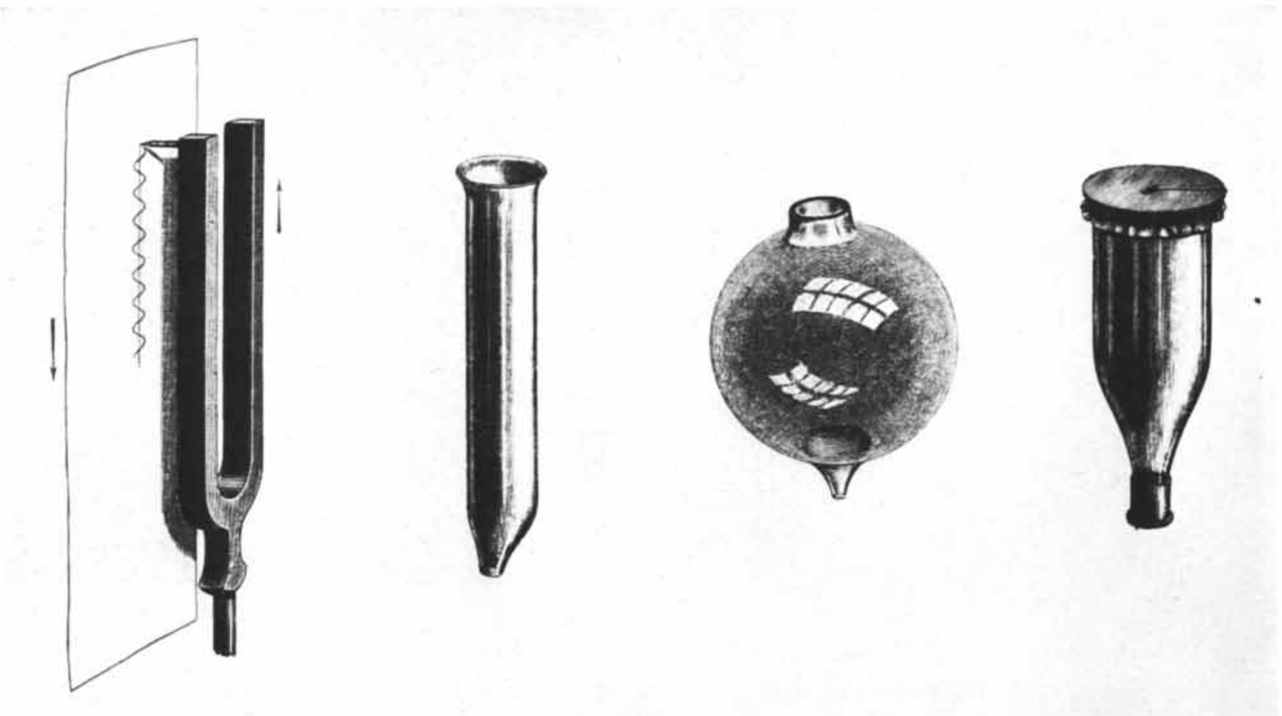
Applying his principle in detail, Helmholtz showed how to compare the kinetic energy of a moving body, the electrical energy produced by a thermocouple, the energy of a magnet moved by electricity, and simple heat energy. This could be done by reducing each form of energy to the amount of mechanical work it could do. Chemical reactions, he pointed out, also conserved energy: the German chemist G. H. Hess had proved only a few years before that the heat liberated when two or more elements united to form a given compound was the same no matter what intermediate stages preceded the final result. Whatever the mode of transformation of one into another, all forms of energy were an exactly measurable equivalent of the kinetic energy of matter in motion.

"I think that in the foregoing," he concluded, "I have proved that the above-mentioned law does not contradict any hitherto known facts of natural science, but is supported by them in a striking manner." Complete experimental confirmation of the law, he added prophetically, "must be regarded as one of the principal problems of the natural philosophy of the future."

Helmholtz was not the first to formulate the law of the conservation of energy; he soon found that Julius Robert von Mayer, another German physician, and the English physicist James Joule had both anticipated him. But it was undoubtedly Helmholtz who saw and presented mathematically the law's profound general implications.

The law of the conservation of energy revolutionized many branches of science. In physiology it helped to eliminate vitalism and opened up new areas of research by regarding the body as a machine which converts food and oxygen into heat and work. It provided the main program for physics during the rest of the 19th century. From then on, as Helmholtz's most brilliant pupil Heinrich Hertz later wrote, the physicist's object was "to refer all phenomena . . . to the laws which govern the transformation of energy." From Helmholtz's original conception Clausius, Boltzmann, Kelvin and other physicists were able during the next 50 years to construct the imposing structure of modern thermodynamics. Helmholtz himself helped to clarify the concept of entropy, the basis of all subsequent cosmological systems. He even delivered a lecture on the ethical consequences of the assertion that the universe is tending toward a "heat death" of uniform temperature and eternal rest.

Helmholtz's paper, despite the incredulity which at first greeted it (the leading German journal of physics refused to print it), soon launched him on the academic career for which he had long hoped. Two years after its publication (as a pamphlet) Müller was able to extract him from the army and get him appointed lecturer in anatomy at the Berlin Academy of Arts. The following year he was appointed professor of physiology at Königsberg. Immediately on receiving this appointment he married



PHYSICS OF SOUND was studied by Helmholtz with the aid of a tuning fork (*left*), which traced its vibrations on a moving sheet of paper. He devised glass resonators of various shapes as a means of analyzing complex musical tones into their constituent parts.

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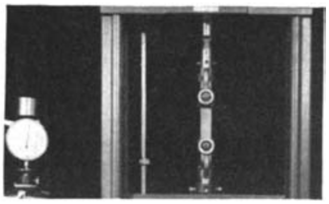

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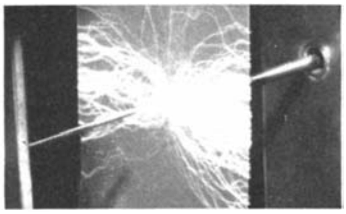

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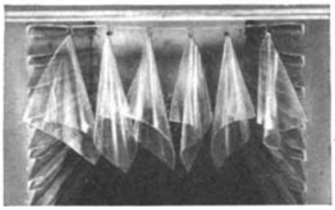

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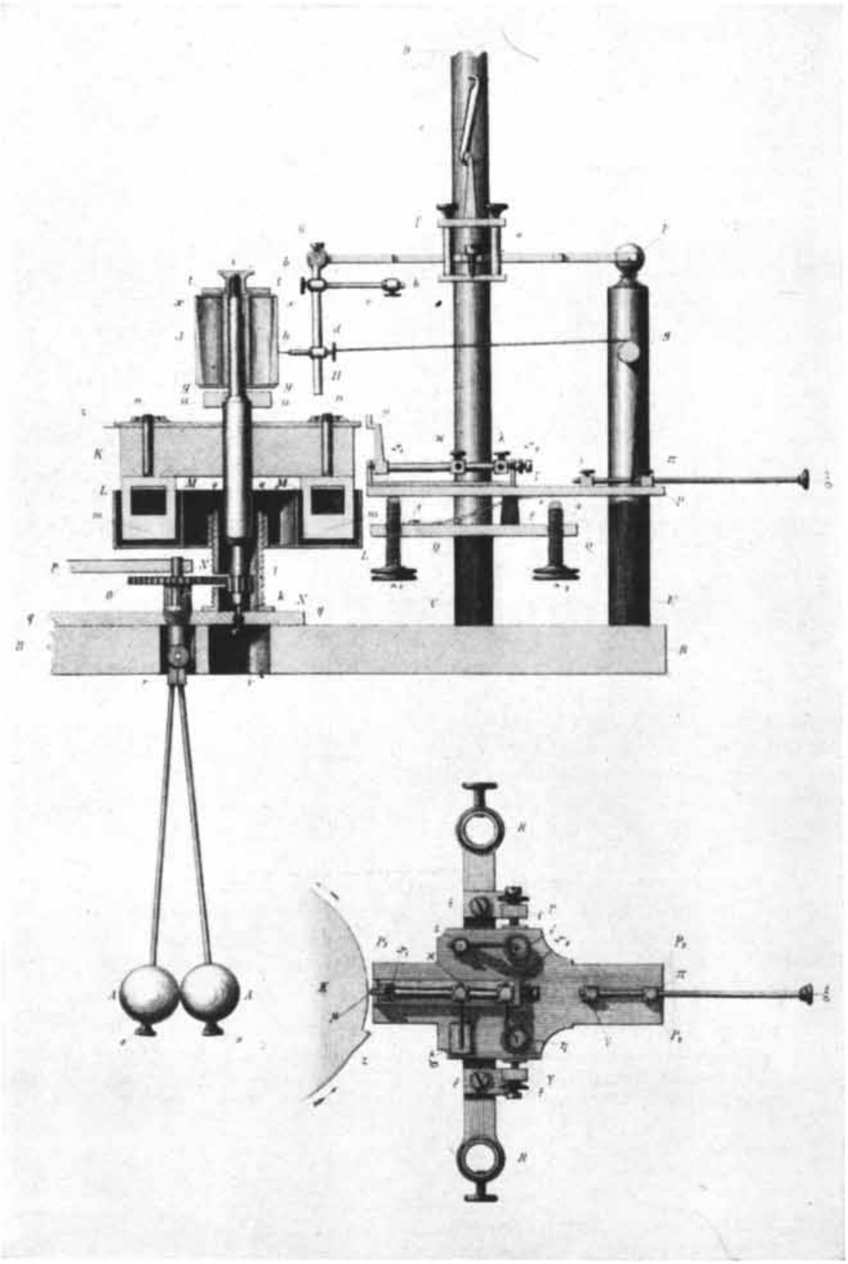
Olga von Velten, whose father, an army surgeon, had been one of Helmholtz's superiors at Potsdam. In 1855 Helmholtz moved to Bonn as professor of anatomy; the young couple's home there, with its terrace overlooking the Rhine, became the center of a distinguished group of friends. In 1858 the Helmholtzes moved to Heidelberg, where Hermann was to spend 13 years as professor of physiology. In 1859 Olga died after a long illness; two years later Helmholtz married Anna von Mohl, whom he described with affectionate irony as having had the benefit of a "fashionable" education.

It was at Königsberg that Helmholtz began the investigations which were to lead him toward the other great question that guided his life's work: the origin of human knowledge. Again he began with the experimental study of a highly specific question and ended with broad, general conclusions. As his studies of vitalism had given birth to the law of the conservation of energy, so his theory of knowledge emerged from a lengthy and exact investigation of the nervous system and sense organs.

In 1850 little was known about what actually happens in the nervous system. Nervous activity was thought to be somehow related to electricity; Helmholtz's friend Emil Du Bois-Reymond had already described the electrical changes which accompany a nerve impulse. Helmholtz carried this work an important step further. By hitching a pointer to a frog's leg he was able to record on a smoked-glass plate its twitchings under electrical stimulation. By timing the interval between stimulus and twitch, he was able to make the first measurement of the speed of a nerve impulse. He made similar experiments on his own arms and those of his assistants. He was able to show that whatever passed along the nerves to deliver messages to the brain was a material change, moving with a definite speed; nerve fibers thus resembled the wires of an electric telegraph.



MUSCLE CONTRACTIONS under electrical stimulation were timed by Helmholtz with this apparatus. By means of it he was able to measure the speed of impulses in the nerves.

Turning to the special sense organs which receive impulses from the outside world, he made a thorough study of the eye, investigating the path of light in that organ, the resulting impulses in the optic nerve and their interpretation in the brain. While preparing an anatomical demonstration for one of his classes, he invented the ophthalmoscope. This instrument, which makes possible the examination of the living retina, quickly became essential equipment for every eye doctor.

He measured variations in the curvature of the lens in close and distant vision and explained the muscular mechanisms by which the eye focuses itself on near and far objects, as well as the way in which the two eyes secure a single image from two different stimuli. He reestablished the theory of color vision advanced half a century earlier by Thomas Young, according to whom all colors are perceived by three primary sensations—red, green and violet—received by three different systems of optic nerves. Helmholtz used this theory to explain the different kinds of color blindness.

The result of these investigations, *Physiological Optics*, was published in three parts between 1856 and 1867. It is one of the great landmarks of 19th-century science.

Helmholtz next turned to the ear. Beginning with an investigation of the physics of sound, to which he made important original contributions, he looked into the way in which different sounds excite the cochlea. He studied differences in tone qualities (such as distinguish one musical instrument from another) and explained them in terms of the relative strength of overtones. His discussion of this point, involving de-

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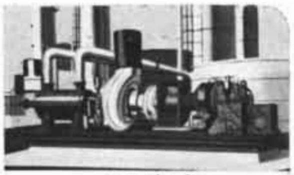

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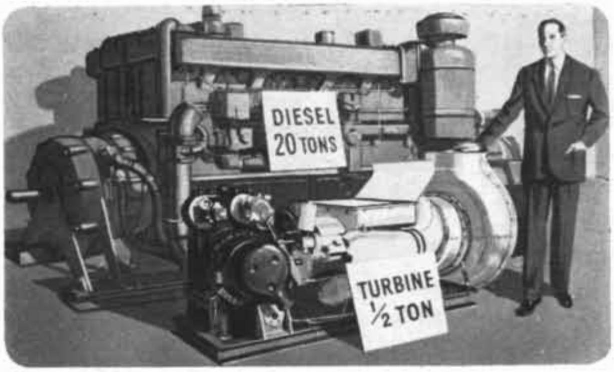

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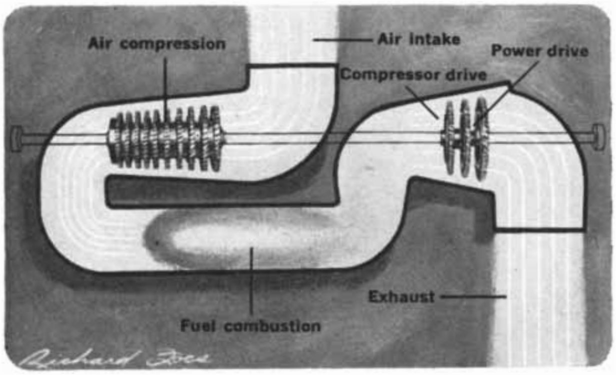

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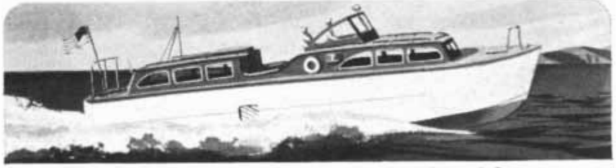

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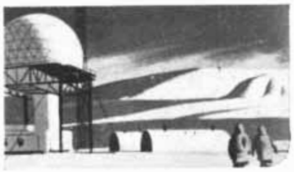

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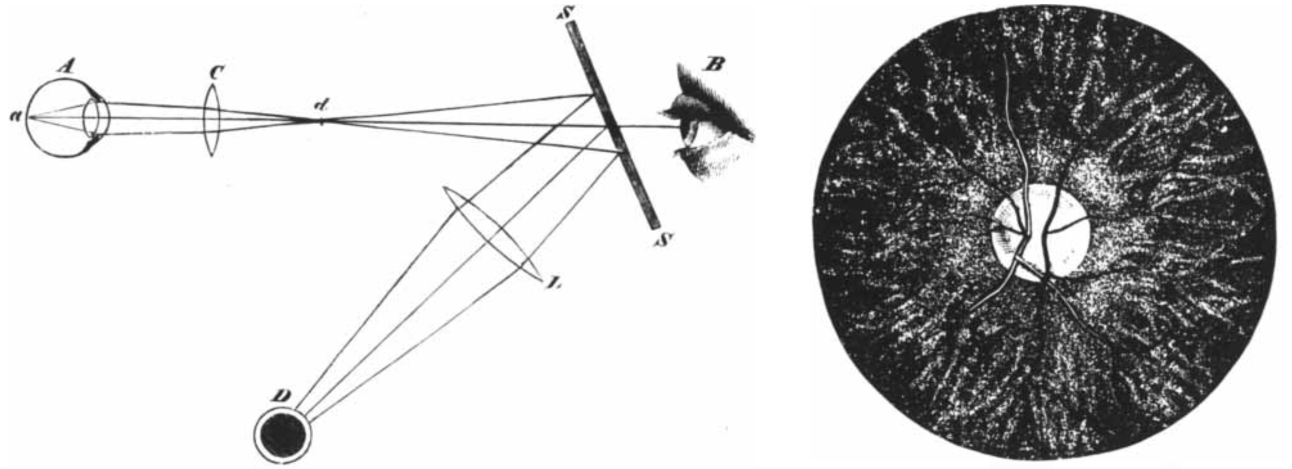


THE OPHTHALMOSCOPE, invented by Helmholtz, uses lenses (*C and L*) and a mirror (*S*) to focus a beam of light and reflect it into the eye (*A*). The observer (*B*) can then examine retina (*shown at right in drawing by Helmholtz*) through hole in mirror.

tailed studies of scales in Eastern and Western music and a theory of vowel tones, is evidence of his own love of music; it is one of the most charming marriages of science and esthetics. Later he made an equally interesting study of the relation of optics to painting.

From these detailed physiological researches Helmholtz now began to evolve his theory of knowledge. Sense perception—the process by which we know external things—he had already analyzed into two stages. The first stage he held to encompass the physical processes through which stimuli are received by the sense organs and transmitted to the brain; the second concerned the interpretation of the messages of "knowledge" by the mind.

Müller, Helmholtz's teacher, had already noted that there is no one-to-one correspondence between a sensory stimulus and the sensation it produces. A given nerve tends to produce the same type of sensation no matter how it is stimulated (for example, pressure on the eyeball in a dark room will stimulate the optic nerve to produce the sensation of light). Müller explained this fact by postulating physiological differences between the various sensory nerves.

Helmholtz further developed this principle in his studies of what is now called "color constancy." He noted that the same subjective sensation of color can be produced by light of quite different physical composition (for example, this page would look green if it was illuminated either by pure green light or by a mixture of blue and yellow light). From this and similar facts Helmholtz concluded that "our sensations are, as regards their quality, only *signs* of external objects, and in no sense *images* of any degree of resemblance." The only connection between the sensation and the external object which produces it is the fact that both appear simultaneously.

Our sensations, then, do not resemble the objects they symbolize, any more than the letters on this page resemble the sounds they represent. Sensations are "signs that we have *learned to decipher*, . . . a language given us with our organization by which external objects discourse to us." Our ability to understand this language, Helmholtz believed, is not inborn. Like any other language it is learned "by practice and experience."

Thus Helmholtz's theory of knowledge derived from his factual approach through empirical physiology. This approach, born of the fusion of medicine and mathematics that had formed his mind, is well illustrated by his analysis of the origin and significance of geometrical axioms.

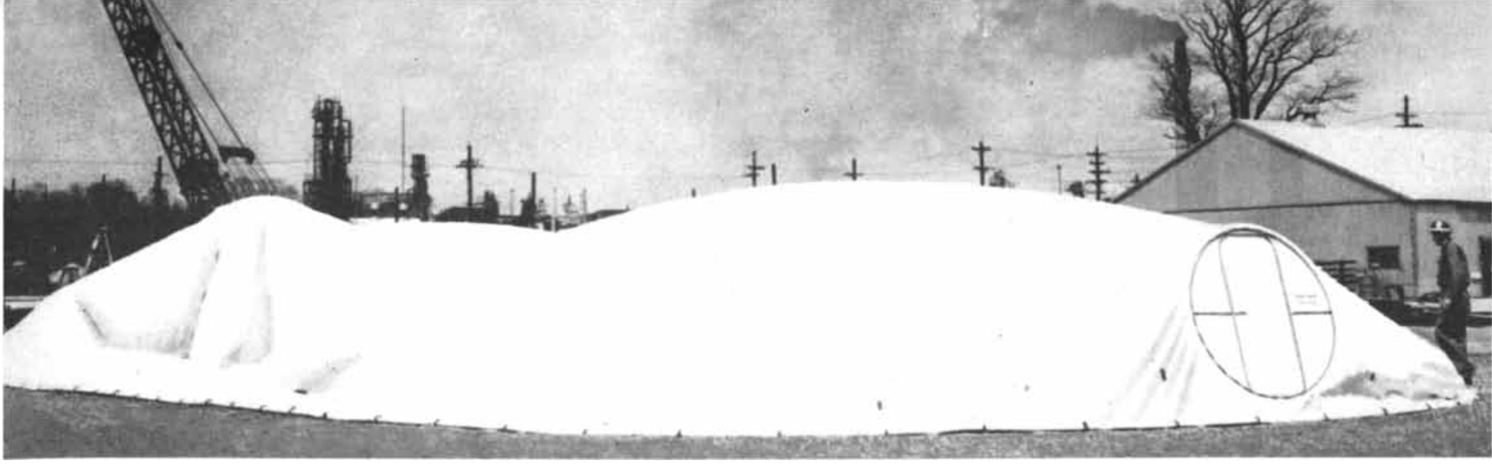
Kant had supposed that these axioms were innate *a priori* determinants of all our conceptions of space. Helmholtz, approaching the problem quite differently, asked under what conditions we arrive at our knowledge of these axioms. He concluded that they were not innate but rather the result of our perceptions of space as mediated by the spatial extension of the retina. Since they were not intuitive but the fruit of observation, they could be tested by observation and replaced if they proved incorrect.

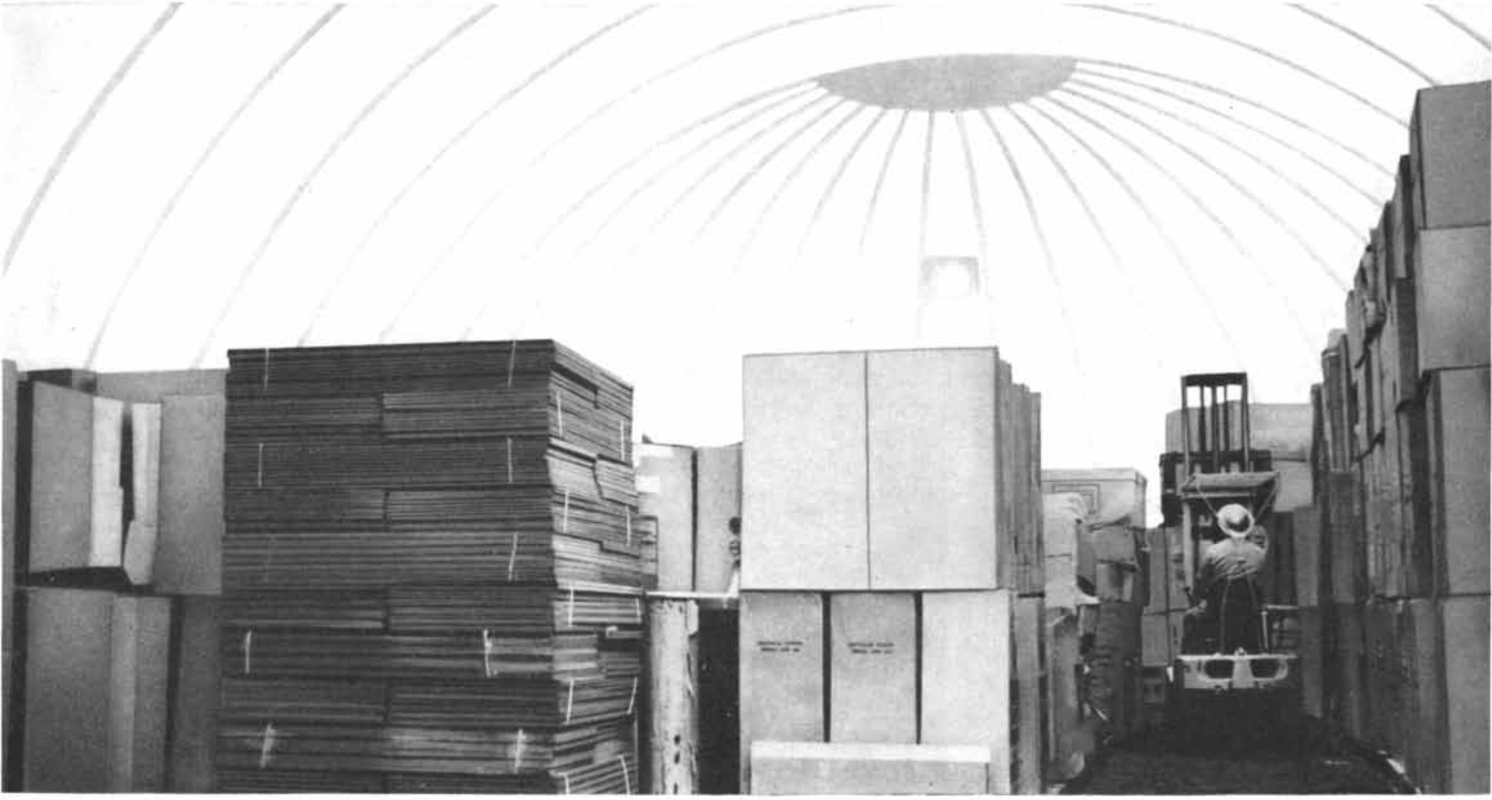
With this view of geometrical axioms, it is not surprising that Helmholtz—albeit with some initial hesitation—came to applaud the non-Euclidean geometries of Lobachevsky, Gauss and Riemann. His own work in geometry, dating from 1870, became, along with that of Riemann, the basis of the important developments in the field which took place toward the end of the century.

Helmholtz's empirical investigations into philosophy made him increasingly dissatisfied with the school of metaphysical idealism which then dominated German philosophy. This school had been founded at the beginning of the 19th century by Hegel, who held that a purely speculative philosophy could replace all the other sciences. To Helmholtz, the experimentalist, this notion seemed absurd. As early as 1859 he wrote his father, from whom he had acquired his interest in philosophy, that Hegel "diverted philosophy from its proper scope and gave it problems it can never accomplish." The task of philosophy, he held, was not to try to replace science but to supplement it by investigating the source and functions of knowledge, after the example of Kant and his disciple Johann Fichte.

"I believe," Helmholtz declared, "that philosophy will only be reinstated when it turns with zeal and energy to the investigation of epistemological processes and of scientific methods. There it has a real and legitimate task. The construction of metaphysical hypotheses is vanity. Most essential of all in this critical investigation is the exact knowledge of the processes of sense perception." He added: "I believe that any German university which had the courage to appoint a scientific man with an inclination to philosophy to its chair of philosophy would confer a lasting benefit on German science."

Helmholtz's crusade to reform philosophy along empirical lines entitles him





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to be numbered among the fathers of the modern philosophy of science. Though he himself was apt to declare that too much philosophy made one vague, his own writings on the philosophy of science have all the confident feel of reality that only a scientist can give.

Though Helmholtz during his later years became increasingly preoccupied with physiology and philosophy, his contributions to physics did not end. Indeed, the culmination of his academic career came with his appointment as professor of physics at Berlin in 1871, and his appointment as president of the State Institute of Physics and Technology in 1888.

During these years he pursued experimentally and theoretically ever more remote applications of the conception of matter in motion. He made a mathematical study of the analogy between the motion of fluids and the electromagnetic action of electrical currents in wires. The equations he produced inspired Kelvin to conceive of an atom as a vortex in the ether, in which different chemical properties were associated with different combinations of vortex rings.

Later he developed Faraday's conception that the bonds between chemical elements are electrical in character. From experiments on the electrolysis of substances in solution he was able to calculate the equivalence of electrical, chemical and mechanical forces. His work on this subject was a fundamental contribution to the theory that matter consists of electrically charged atoms and to the whole conception of valency on which modern chemistry is based.

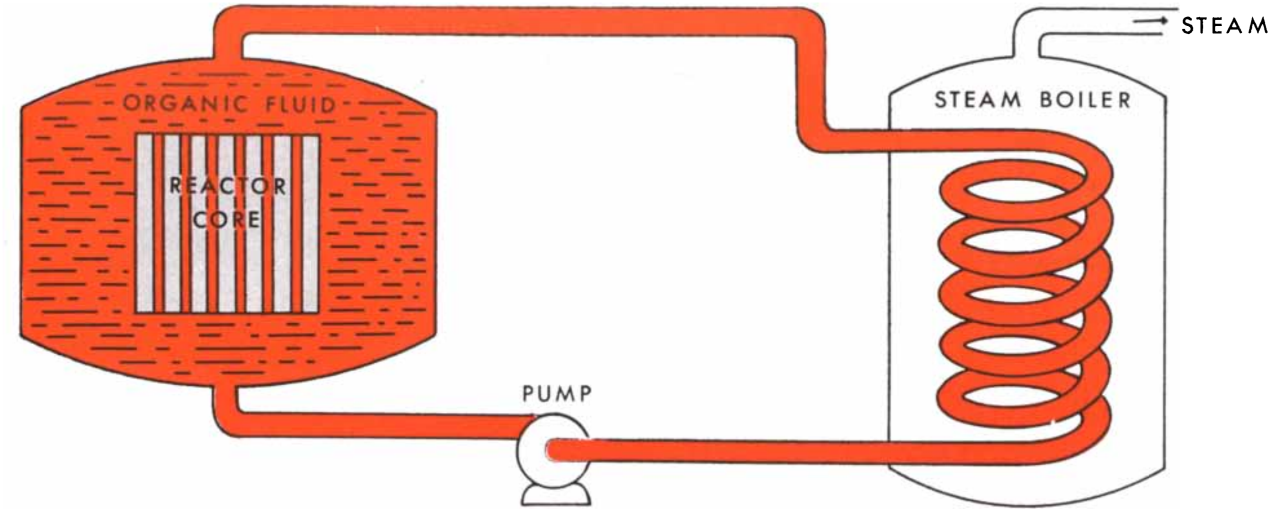
The most far-reaching later manifestations of Helmholtz's mathematical insight were concerned with the nature of electrical and magnetic forces. Here we have the vision of the mathematician, strained to its utmost, combined with the practical logic of the experimenter to penetrate the structure of the physical world. Faced with three rival theories of electromagnetic forces, Helmholtz showed that all three were special cases of a more general mathematical theory, and devised theoretical and experimental tests to determine which special theory was to be adopted. Two of the three were eliminated, and Helmholtz was left with the theory of Faraday and Maxwell, according to which electrical and magnetic forces are propagated through an all-pervading ether. Helmholtz's mathematical interpretation of Maxwell's theory that light is another form of electromagnetic wave in the ether stimulated Hertz to make his famous experiments in electromagnetic radiation. These not only established Maxwell's theory of light, but made possible the development of radio communication.

Helmholtz's genius was remarkably original, versatile and productive. In this article I have tried to indicate the main lines of his thought and to relate them to the chief qualities of mind from which his discoveries seem to spring. He himself became deeply interested in the processes of scientific discovery; his essays on the subject, drawing heavily on his own experiences, are among the most interesting of his philosophical writings. Here is an example from a lecture, "On Thought in Medicine," which he delivered in 1877. If it leads some readers back to Helmholtz's own writings, the main purpose of this article will have been fulfilled:

"In speaking against the empty manufacture of hypotheses, do not by any means suppose that I wish to diminish the real value of original thoughts. The first discovery of a new law is the discovery of a similarity which has hitherto been concealed in the course of natural processes. It is a manifestation of that which our forefathers in a serious sense described as 'wit'; it is the same quality as the highest performances of artistic perception in the discovery of new types of expression. It is something which cannot be forced, and which cannot be acquired by any known method. . . .

"When we fancy that we have arrived at a law, the business of deduction commences. It is then our duty to develop the consequences of our laws as completely as may be, but in the first place only to apply to them the test of experience, so far as they can be tested, and then to decide by this test whether the law holds and to what extent. This is a test which never really ceases. The true natural philosopher reflects at each new phenomenon whether the best-established laws of the best-known forces may not experience a change; it can of course only be a question of a change which does not contradict the whole store of our previously collected experiences. It never thus attains unconditional truth, but such a high degree of probability that it is practically equal to certainty."

It is not as common as one could hope for creative minds, whether in science or in art, to be so conscious of their mental processes and so well equipped to criticize logically the results of these processes. The combination of these gifts makes Helmholtz all the more worthy of our study.



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"Burning" fuel in the core of a nuclear reactor—theoretically—is as easy as firing coal in a furnace. The hard, practical problem has been to capture heat from the reactor and transfer it at low cost to a steam generator. Now, new test results with Monsanto synthetic fluids indicate that organic chemicals can transfer heat more economically than other materials.

Unique properties of these synthetics from Monsanto's storehouse of functional fluids break the barrier to lower costs in reactor construction. Their low vapor pressure at high temperatures eliminates the need for high-pressure equipment. Since they do not corrode common construction materials, such as mild steel and aluminum, costly metals are not required in equipment. And because these organic fluids do not emit gamma radiation even while under neutron bombardment, thick secondary shielding is unnecessary for safety.

Work by Atomics International at the National Reactor Testing Station in Idaho has already spurred plans for a commercial power reactor with Monsanto terphenyl compounds as the "coolant-moderator." Meanwhile, researchers are studying other Monsanto organic fluids, such as isopropyl biphenyl and biphenyl, which may be more desirable in certain types of reactors. Some engineers believe a mixture of organic liquids may prove to be the best coolant of all. Whichever proves best, Monsanto organic fluids promise to help ease the cost pinch on atomic power.

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