Hermann Ludwig Ferdinand Von Helmholtz | Encyclopedia.com

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energetics, physiological acoustics, physiological optics, epistemology, hydrodynamics, electrodynamics

Helmholtz was the oldest of four children. From his mother, Caroline Penn, the daughter of a Hannoverian artillery officer, he inherited the placidity and reserve which marked his character in later life. His father, August Ferdinand Julius Helmholtz, was the typical product of a romantic era. Ferdinand Helmholtz had served with distinction in Prussia's war of liberation against Napoleon and had studied philology and philosophy at the new University of Berlin before accepting a poorly paid post at the Potsdam Gymnasium. A passionate, romantic figure, he possessed an acute aesthetic sensitivity which he transmitted to his son: a profound concern with music and painting underlay much of Helmholtz' later work in sensory physiology. Ferdinand also fervently admired the philosophers Kant and J. G. Fichte; Fichte's son Immanuel Hermann Fichte was his close friend and a frequent visitor. Helmholtz' own lifelong devotion to epistemological issues was motivated by the intense philosophical discussions to which he had listened as a boy.

At the Potsdam Gymnasium Helmholtz' interests turned very early to physics, but his father did not have the money to send Helmholtz to the university, and he persuaded his son to turn to medicine, for which there existed the prospect of state financial aid. In 1837 Helmholtz obtained a government stipend for five years' study at the Königlich Medizinisch-chirurgische Friedrich-Wilhelms-Institut in Berlin. In return he committed himself to eight years' service as an army surgeon. He passed his *Abitur* with distinction and left for Berlin in September 1838.

While at the Friedrich Wilhelm Institute, Helmholtz took many courses at the University of Berlin. He studied chemistry under Eilhardt Mitscherlich, clinical medicine under Lucas Schönlein, and physiology under Johannes Müller. Although he took no courses in mathematics, he read privately the works of Laplace, Biot, and Daniel Bernoulli as well as the philosophical works of Kant. During the winter of 1841 Helmholtz began research for his dissertation under Johannes Müller and later moved into the circle of Müller's students. Chief among these were Ernst Brücke and Emil du Bois-Reymond. Confident and sophisticated, du Bois-Reymond seems to have taken the younger Helmholtz as his protégé. He and Brücke quickly won Helmholtz to their program for the advancement of physiology. With Karl Ludwig the three made up the "1847 school" of physiology. Their program reacted sharply against German physiology of previous decades. Philosophically they rejected any explanation of life processes which appealed to nonphysical vital properties or forces. Methodologically they aimed at founding physiology upon the techniques of physics and chemistry. All of Helmholtz' minor papers published between 1843 and 1847, most of which treated problems of animal heat and muscle contraction, clearly reflect the mechanistic tenets of the school.

Helmholtz received the M.D. degree in November 1842. After completing the state medical examinations he was appointed surgeon to the regiment at Potsdam. He maintained his Berlin connections, though, and in 1845 du Bois-Reymond brought the shy young doctor into the newly founded Physikalische Gesellschaft. On 23 July 1847 Helmholtz read to the society his epic memoir "Über die Erhaltung der Kraft," in which he set forth the mathematical principles of the conservation of energy.

In 1848 Brücke resigned his chair of physiology at Königsberg to accept a post at Vienna. When du Bois-Reymond refused the vacant post, Helmholtz was released from his military duty and appointed associate professor of physiology at Königsberg. Before leaving Potsdam he married Olga von Velten on 26 August 1849

From that time on, Helmholtz led a quiet professional life of tireless labor at his research. At Königsberg he measured the velocity of the nerve impulse, published his first papers on physiological optics and acoustics, and won a European reputation with his invention of the ophthalmoscope in 1851. Both scientifically and socially the early 1850's were a period of widening horizons for Helmholtz. In 1851 he toured the German universities, inspecting physiological institutes on behalf of the Prussian government. In 1853 he made the first of many visits to England, where he formed lasting friendships with various English physicists, especially William Thomson. Despite his success at Königsberg, his situation there was not altogether happy; his wife's already delicate health was further impaired by the cold climate, and he experienced minor priority conflicts with Franz Neumann. In 1855, with the help of Alexander von Humboldt, Helmholtz obtained a transfer to the vacant chair of anatomy and physiology at Bonn.

At Bonn, Helmholtz continued his research into sensory physiology, publishing in 1856 volume I of his massive *Handbuch der physiologischen Optik*. His work took a wholly new turn with his seminal paper on the hydrodynamics of vortex motion of 1858. Helmholtz' philosophical views had begun very early to diverge from his father's idealist position, and from 1855 he began to develop these views publicly in various popular lectures. Although father and son shared epistemological interests and even held common views on the subjective nature of sensory perception, Ferdinand nevertheless remained intensely suspicious of his son's physical and empirical methods. During his years at Bonn this divergence created a strain in their frequent correspondence, although Helmholtz' letters remained dutiful and submissive.

Helmholtz was never satisfied at Bonn. Anatomy was an unfamiliar subject, and there were whispered reports to the minister of education that his anatomy lectures were incompetent. Helmholtz angrily dismissed these reports as the grumblings of medical traditionalists who opposed his mechanistic-physiological approach. At the same time he was becoming the most famous young scientist in Germany. In 1857 the Baden government offered Helmholtz a chair at Heidelberg, then at the peak of its fame as a scientific center. The promise of a new physiology institute convinced Helmholtz to accept in 1858. At the last moment the prince of Prussia intervened to persuade him to stay, but in vain.

The following thirteen years at Heidelberg were among the most productive of Helmholtz' career. He carried on his research in sensory physiology, publishing in 1862 his influential *Die Lehre von den Tonempfindungen als physiologische Gnundlage für die Theorie der Musik*. His treatises on physics included "Über Luftschwingungen in Röhren mit offenen Enden" (1859) and his analysis of the motion of violin strings. The Heidelberg years also brought important changes to Helmholtz' personal life. His wife's health had declined steadily and she died on 28 December 1859, leaving Helmholtz with two small children. On 16 May 1861 he married Anna von Mohl, the daughter of Heidelberg professor Robert von Mohl. Anna, by whom Helmholtz later had three children, was an attractive, sophisticated woman considerably younger than her husband. The marriage opened a period of broader social contacts for Helmholtz. The community of physicists in England and the rest of Germany began gradually to displace the Berlin circle as the locus of his scientific interaction.

By 1860 Helmholtz had begun research for volume III of his *Handbuch der physiologischen Optik* in which visual judgments of depth and magnitude were to be treated. The study led him directly into the nativistempiricist controversy and inaugurated a decade of intense concern with epistemological issues. The death of his father in 1858 had eliminated Helmholtz' reluctance to develop the empiricist position latent in his earlier work. He began that development in volume III of the *Handbuch* (1867), which was an extended defense of the empirical theory of visual perception. In 1868 and 1869 Helmholtz carried that position still further in his work on the foundations of geometry. He summarized his epistemology in the famous popular lecture of 1878, "Die Thatsachen in der Wahrnehmung."

By 1866 Helmholtz had completed his great treatises on sensory physiology and was contemplating abandoning physiology for physics. The scope of physiology had already become too great for any individual to encompass, he wrote in 1868, and while a flourishing school of physiology existed in Germany, German physics was stagnating for lack of well-trained young recruits. When Gustav Magnus' death in 1870 left vacant the prestigious chair of physics at Berlin, Helmholtz and G. R. Kirchhoff, his colleague at Heidelberg, became the primary candidates for the post. The Berlin philosophical faculty preferred Kirchhoff, whom they regarded as the superior teacher. When he refused the post, the nomination went to Helmholtz. Helmholtz' price was high: 4,000 taler yearly plus the construction of a new physics institute to be under his full control. Prussia readily agreed to his terms, for it was widely recognized that his call possessed great political as well as scientific significance in Prussia's bid for the leadership of southern Germany. He accepted the Berlin post early in 1871.

Helmholtz inaugurated his new position with a series of papers critically assessing the various competing theories of electrodynamic action. This work first brought Maxwell's field theory to the attention of Continental physicists and inspired the later reearch of Helmholtz' pupil Heinrich Hertz, who entered the Berlin institute in 1878. After 1876 Helmholtz contributed papers on the galvanic cell, the thermodynamics of chemical processes, and meteorology. He devoted the last decade before his death in 1894 to an unsuccessful attempt at founding not only mechanics but all of physics on a single universal principle, that of least action.

By 1885 Helmholtz had become the patriarch of German science and the state's foremost adviser on scientific affairs. This position was recognized in 1887, when Helmholtz assumed the presidency of the newly founded Physikalisch-technische Reichsanstalt for research in the exact sciences and precision technology. Helmholtz' friend, the industrialist Werner von Siemens, had donated 500,000 marks to the project, and he himself had been among its foremost advocates. Under his administration the Reichsanstalt stressed purely scientific research.

Although Helmholtz' productivity did not wane, his health began to fail after 1885. He had always suffered from migraine, from which he sought relief in music and mountaineering in the Alps. In old age he began to experience fits of depression which only long vacations could cure. On 12 July 1894 he suffered what appeared to be a paralytic stroke, and he died on 8 September.

Energetics . Before 1847 Helmholtz' interest in force conversions had been motivated largely by physiological concerns. The mechanistic school to which he belonged demanded that the hypothesis of a unique "vital force" within the animal body be rejected as the first step to refounding physiology on chemical and physical principles. Assuming such a vital force, Helmholtz believed, was tantamount to assuming a *perpetuum mobile*. Consequently, its refutation necessitated proving that all the body heat and all the muscle force produced by the animal could be derived ultimately from the chemical force released by oxidation of its foodstuffs, with no recourse to a vital force. In this belief Helmholtz had been greatly influenced by the chemist Justus Liebig's *Die Thierchemie* (1842), in which Liebig had attempted to argue away experiments of Pierre Dulong and Cáezar Despretz which seemed to refute the chemical theory of animal heat. In 1845 Helmholtz noted that these experiments were invalidated by their assumption that the heats of combustion of complex foodstuffs were equivalent to the summated heats of combustion of their constituent carbon and hydrogen. In 1845 he proved experimentally that chemical changes occur in the working muscle and, in 1848, that heat is generated by muscle contraction.

"Ueber die Erhaltung der Kraft" (1847) set forth the philosophical and physical basis of the conservation of energy. It drew heavily on the works of Sadi Carnot, Clapeyron, Holtzmann, and Joule, although it was far more comprehensive than those previous treatises. The philosophical introduction clearly illustrated the influence of Kantianism on Helmholtz' thought. Science, he began, views the world in terms of two abstractions, matter and force. The goal of science is to trace phenomena to their ultimate causes in accordance with the law of causality; such ultimate causes are unchangeable forces. We can, Helmholtz implied, know the nature of such forces virtually a priori. If we imagine matter dispersed into its ultimate elements, then the only conceivable change which can occur in the relationship of those elements is spatial. Ultimate forces, then, must be moving forces radially directed. Only the reduction of phenomena to such forces constitutes an explanation to which we may ascribe the status of "objective truth" (from the translation in Richard Taylor's *Scientific Memoirs* [London, 1853], p. 118).

That ultimate forces must be of this nature can also be inferred from the impossibility of producing work continually from nothing. That impossibility, Helmholtz demonstrated, is equivalent to the well-known principle of the conservation of *vis viva*. Assuming that principle to hold for a system of bodies in motion, Helmholtz attempted to prove that the forces under which those bodies move must be functions only of position (and hence not of velocity or acceleration) and also radially directed. If a particle m is acted on by a central force of intensity ϕ emanating from a fixed center of force and moves freely from a distance r to a distance R from that force center, then

where Q is the velocity of m at R and q its velocity at r. The left-hand side of equation (1) is clearly one-half the difference of the *vires vivae*; Helmholtz calls the right-hand integral the "sum of the tension forces" (*Spannkäfte*) between the distances R and r. Equation (1) remains valid when summed over the entire system of bodies and hence expresses the most general form of the principle of the conservation of energy.

Helmholtz then demonstrated how the conservation principle could be applied to various physical phenomena. The principle of the conservation of *vis viva* had already been applied to gravitation, wave motion, and inelastic collision. Previously an absolute loss of force had been assumed in inelastic collision and friction. Helmholtz argued to the contrary that the *vis viva* apparently lost in such cases is merely converted to tension forces or heat; on the latter assumption Joule had recently measured a mechanical equivalent of heat equal to 521' meter-kilograms per calorie in mks units. Helmholtz then proceeded to an extended defense of the dynamic theory of heat against the caloric theory, arguing that the free heat of a body consists in the microscopic motion of its particles, its latent heat in the tension forces between its atoms. He then introduced the equations of Clapeyron and Holtzmann for the expansion of gases. The derivation of Clapeyron's equations, he pointed out, rests upon the untenable assumption that no heat is lost when work is done by a gas in expanding. He concluded by applying the conservation principle to electrostatic, galvanic, and electrodynamic phenomena.

After 1847 Helmholtz' research interests turned for some time to sensory physiology, and he took no direct part in the subsequent development of the entropy concept or kinetic theory. Late in his career, though, he turned again to research into energy processes, this time those of the galvanic and electrolytic apparatus. In 1872 he showed that convection currents within a polarized electrolytic cell can sustain a feeble current even at voltages too low to sustain electrolytic decomposition. That phenomenon had previously seemed to violate either the conservation of energy or Faraday's laws of electrolysis. In 1877 Helmholtz attempted to predict theoretically the electromotive force of a galvanic cell for different concentrations of a salt solution. Under certain conditions the cell can be treated as a reversible cycle and the laws of Carnot and Clapeyron applied to it. The theory was in substantial agreement with experimental data by James Moser.

Helmholtz' research in physical chemistry culminated in his 1882 memoir, "Die Thermodynamik chemiseher Vörgange." Thermochemistry, especially that of Thomsen and Berthelot, assumed that the heat evolved in reactions is a direct measure of the chemical affinities at work. The occurrence of spontaneous, endothermic reactions had always presented an anomaly in this tradition, for such reactions seemed to act against the forces of chemical affinity. In 1882 Helmholtz distinguished between "bound" and "free" energy in reactions. The former is the portion of the total energy which, in accordance with the entropy principle, is obtainable only as heat; the latter is that which can be freely converted to other forms of energy. From Clasius' equations Helmholtz derived the "Gibbs-Helmholtz equation,"

where F is the free energy, U the total energy,T the absolute temperature, and where $\partial F/\partial T$ yields the entropy. In any spontaneous reaction occurring at constant temperature and volume the free energy must decrease. Hence the free energy, not the total energy change measured by the evolution of heat, determines the direction of any reaction. Helmholtz' research had been anticipated by J. W. Gibbs, in whose formulation U in equation (2) must be replaced by the enthalpy.

This research led Helmholtz directly to his investigations into the statics of monocyclic systems and the principle of least action. In the former (1884) he demonstrated that it is possible to define certain mechanical systems the internal motions of which can be shown to obey Clausius' entropy equations. In response to an attack by Clausius he emphasized that the vibrational motion of heat does not rigorously satisfy the conditions of such a system; hence the paper constituted no mechanical derivation of the second law of thermodynamics. In the latter study (1886) he attempted to derive not only all of mechanics, but also thermodynamics and electrodynamics, from the principle of least action as formulated by Sir W. Rowan Hamilton. Although the problem dominated his attention until his death in 1894, Helmholtz achieved no satisfactory derivation. The importance of these studies lies chiefly in their influence upon Heinrich Hertz, who acknowledged his debt to Helmholtz in his *Die Principien der Mechanik* (1894).

Physiological Acoustics . Helmholtz' research in sensory physiology began in 1850, when he determined the velocity of the nerve impulse in the sciatic nerve of the frog. In 1852 he obtained more precise results through his invention of the myograph. This device, in which the muscle traces the motion of its contraction upon a rotating drum, permitted more exact measurement of the small time intervals involved than any previous method. Helmholtz' measurements yielded not only a finite velocity for nerve propagation but also the surprisingly slow one of about ninety feet per second. The result was considered a victory for the mechanistic school, for it seemed to confirm du Bois-Reymond's hypothesis that the nerve impulse consisted in the progressive rearrangement of ponderable molecules.

At the conclusion of these experiments, Helmholtz' interest turned immediately to physiological acoustics. Physicists had long known that a vibrating string produces not only a tone of its fundamental frequency *f*1 but also a series of harmonics $2f_1$, $3f_1$, and so on. They also knew that two similar tones *f*1, and *f*2, when sounded together, would produce beats of frequency $f_1 - f_2$ After 1750 a third phenomenon had come to light: Tartini's tones, or difference tones. If tones f^1 *and* f_2 are sounded together, then the acute ear can sometimes hear a third tone $f_1 - f_2$ which is not a harmonic. Romieu, Lagrange, and Thomas Young all advanced the obyious "beat theory of difference tones," which held that the difference tone is a beat frequency so great that it has become a tone in itself. In 1832 G. G. Hällström noted that the harmonics of f_1 and f_2 should also beat; that is, one should hear beats or difference tones $2f_1 - f_2$, $- 2f_2 - 2f_2$, $3f_1f_2$ and so on. These, however had never been observed. Finally in 1843 G. S. Ohm advanced his law of acoustics, which asserts that the ear perceives only simple harmonic vibrations. The ear, according to Ohm, decomposes the complex sound waves which it receives into the same simple harmonic waves obtainable mathematically from Fourier analysis.

The perception of beats and difference tones seems to contradict Ohm's law, a fact which perhaps attracted Helmholtz' attention. In 1856 he demonstrated the use of resonators to isolate and reinforce upper partial tones and thus showed the existence of the higher-order difference tones predicted by Hällström. He also proved that in addition to the difference tones mf_1-nf_2, there exist also very faint summation tones m*f*1+ nf_2 Because summation tones cannot be predicted from the beat theory, Helmholtz regarded it as decisively disproved and advanced his own transformation theory. In simple harmonic motion the restoring force *k* on a particle *m* is proportional to its displacement *x*; but if the square of the displacement is also sensible, then $k = ax + bx^2$. If two wave trains of force *f* sin *pt* and *g* sin (*qt* + *c*) act on *m*, then the equation of motion can be written and solved by series. Helmholtz showed that the series solution of that equation contains wave functions of all frequencies *mp*, *mq*, (*mp* - *nq*). (*mp* + *nq*). Hence combination tones result from inharmonic distortions of the wave form, either externally in resonators (as Helmholtz showed) or in the ear at the drum-malleus junction (as Helmholtz believed); hence they do not violate Ohm's law.

Obviously all sounds of the same pitch and intensity do not sound alike. Helmholtz attributed this difference in timbre *(Klangfarbe)* mainly to the different patterns of upper partial tones, which depend on how the fundamental is produced. He advanced this theory first in connection with his fixed-pitch theory of vowel sounds. The vowel *A* sung at pitch f_1 differs from the vowel *E* sung at f_1 by the same individual, Helmholtz argued, only because the mouth serves as a variable resonator. At the vocal cords, both *A* and *E* have the same pattern of upper partials, but the different shapes of the mouth cavity reinforce different ranges of partials, giving *A* and *E* different timbres. Helmholtz also argued that timbre is independent of phase differences among the upper partial tones.

Helmholtz' greatest achievement in physiological acoustics lay in formulating the resonance theory of hearing. Like so much of his physiology, that theory rested upon Johannes Müller's law of specific nerve energies. Müller taught That the nature of the impulse carried to the sensorium by a given nerve is unique and independent of the nature of the external stimulus. Rigidly interpreted, the law seemed to require each just noticeable difference of any sensory quality to possess its own sensory receptor. Between 1850 and 1855 the microscopic anatomy of the cochlea first became known. Among the structures revealed were the rods of Corti strung out in gradually increasing size along the length of the cochlea—analogous, Helmholtz insisted, to the tuned wires of a piano. In 1857 Helmholtz boldly hypothesized that these rods function as tuned resonators. A complex sound wave transmitted to the cochlea fluid sets in sympathetic vibration those rods tuned to the frequency of its simple harmonic components. These rods in turn excite adjacent nerve endings, which transmit the impulse to the sensorium. Hence the resonance theory satisfies Mõller's law and provides a physiological explanation of Ohm's law. In 1869 the experiments of Victor Hensen convinced Helmholtz that the transverse fibers of the basilar membrane, not the rods of Corti, are the cochlea resonators. With this modification the theory survived virtually unchallenged until after 1885.

Helmholtz incorporated all these results in his great work *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (18631 in which he applied his discoveries to music theory. Musicians had long known that the most perfect consonances are those whose frequencies are small whole-number ratios. Helmholtz explained this by noting that such consonances have the greatest number of coincident upper partial tones. Less perfect consonances have many slightly different upper partials, and these produce beats which are perceived as dissonance. Later editions of *Tonempfindungen* also incorporated the results of two studies of the ossicular bones carried out in 1867 and 1869, in which Helmholtz evaluated the efficiency and linearity of the ossicular chain as a transformer.

Physiological Optics . Helmholtz inaugurated his study of physiological optics with his invention of the ophthalmoscope in 1851. His friend Ernst Brücke had recently shown how the human eye could be made to glow with diffusely reflected light, like the eyes of many animals. In preparing a lecture demonstration of the phenomenon, Helmholtz realized that by means of a simple optical apparatus this reflected light could be obtained as a magnified, sharply focused image of the subject's retina. He published the mathematical theory of the ophthalmoscope with an account of the improved instrument in 1851.

Helmholtz turned to the intricate problems of color vision in 1852 with an attack on Sir David Brewster's new theory of light. Brewster had maintained the objective reality of three primary colors by supposing, in opposition to Newton, that there exist three distinct kinds of light, each of which excites in the eye one of the sensations red, yellow, or blue. Helmholtz regarded the theory as still another confusion of physical stimulus and subjective response. The experiments by which Brewster claimed to have verified his theory, Helmholtz argued, had actually led Brewster astray, for he had failed to obtain pure spectra.

In conjunction with his attack on Brewster's theory Helmholtz conducted spectrum experiments of his own. To his surprise a mixture of blue and yellow spectral lights yielded a green-tinted white, although a mixture of blue and yellow pigments yields green. From this anomaly Helmholtz elaborated the important distinction between additive and subtractive color mixtures, which he announced in 1852. Yet the same experiments led Helmholtz into serious error. When he attempted to produce white by mixing the pairs of colors which Newton's color theory predicted to be complementary, he succeeded in obtaining pure white only with yellow and indigo. He concluded that this is the only pair of complementaries and rejected Newton's color theory. This aspect of his 1852 paper was immediately attacked by H. G. Grassmann, who, like Maxwell, was attempting to develop a mathematical theory of Newton's color chart. In 1855 Helmholtz acknowledged the experimental error of his earlier paper and announced new experiments which yielded the sets of complementary colors demanded by Newton's theory.

In his paper of 1852 Helmholtz also revived Thomas Young's forgotten theory of color vision. In 1801 Young had hypothesized that each retinal nerve ending possesses three distinct color receptors, each primarily sensitive to one frequency of light. When stimulated, each receptor yields one of the subjective color sensations red, green, or violet. Hence all color sensations except the three primary ones are physiological mixtures. Ironically, Helmholtz revived Young's theory in 1852 only to refute it. He had discovered that spectral colors, when mixed, always yield a duller color of less-than-spectral saturation. Therefore the whole idea that all colors may be obtained from mixtures of three primary colors must be incorrect, he concluded, for the spectral colors, at least, can never be obtained in their full saturation by mixing any three of their number. That fact seemed to refute Young's theory; for if Young's physiological primaries are assumed to be spectral red, green, and violet, then that theory cannot explain how other spectral colors are seen in their full prismatic saturation.

Although Helmholtz dismissed Young's theory in 1852, by 1858 he had changed his mind and become its foremost advocate. In order to save Young's theory from the objections of the 1852 treatise, Helmholtz assumed that Young's physiological primaries are not spectral colors at all, but colors of far greaterthan-spectral saturation. Mixtures of the three physiological primaries still undergo the loss of saturation which Helmholtz had noted in 1852, but this lower level of saturation is that of the spectral colors themselves. In this way all the spectral colors which we see can be mixed from three properly chosen physiological primaries, and Young's theory is saved.

Helmholtz' assertion that the physiological primaries possess greater-than-spectral saturation followed logically from another amendment to Young's theory. Helmholtz hypothesized that any wavelength of light, however strongly it excites one set of retinal receptors, always excites simultaneously the other two sets to a much weaker degree. It follows that any physical light, even a single wavelength corresponding to the most saturated color of the spectrum, evokes a color sensation which is not "pure" but a mixture. That mixture, even if it is a spectral color, must necessarily be less highly saturated than the physiological primaries from which it was mixed. In normal vision we never see one physiological primary color alone because there is no obvious way to stimulate one set of retinal receptors without simultaneously stimulating the other two. This fact accounts for the belief that the spectral colors are the most highly saturated which exist. In 1858, however, Helmholtz announced a method by which the pure physiological primaries could be observed approximately. In a paper on afterimages, Helmholtz pointed out that a prismatic color appears far more saturated when viewed after the retina has been fatigued by the complementary color. This fact is easily explained in the Young-Helmholtz theory by assuming that the retinal fatigue briefly inactivates two sets of color receptors. When the third set is then stimulated, we observe its corresponding color less mixed with the other two primaries than usual and hence see it as far more saturated than the spectral colors. Helmholtz regarded this experiment as striking confirmation of his amended version of Young's theory. In 1859 he further demonstrated the power of the theory by using it to explain red color blindness

Helmholtz incorporated all these results in his *Handbuch der physiologischen Optik*, a massive work which encompassed all previous research in the field. Volume I, which appeared in 1856, contained a detailed treatment of the dioptrics of the eye which was greatly dependent on J. B. Listing's previous works. In it Helmholtz treated the various imperfections of the lens system and announced the result that the visual axis of the eye does not correspond to its optical axis. Volume I also elaborated Helmholtz' theory of accommodation and his invention of the ophthalmometer, both announced in 1855.

In volume II, Helmholtz introduced Young's theory, calling it a special application of Johannes Müller's law of specific nerve energies. He also dealt with the complex phenomena of irradiation, afterimages, and contrast, which had dominated the interest of German physiologists since Goethe's *Farbenlehre* but could be investigated only through difficult and often dangerous subjective experiments. Helmholtz defended G. T. Fechner's explanation of afterimages by the fatigue of retinal elements and advanced his own theory that contrast phenomena arise from errors of judgment and have no physiological basis. He took pains to refute all theories which tried to explain these phenomena through synesthesia or retinal induction, particularly that of Joseph Plateau. Helmholtz took no part in the development of the duplicity theory of vision, which lay outside his main area of interest.

Eplstemology . Helmholtz often asserted that the task of modern philosophy is wholly epistemological, and he evinced a dislike for metaphysics. Kantianism exercised a strong influence on his thought as is obvious in his earliest papers. Later, through his physiological study, Helmholtz became convinced that sensory physiology, by revealing the processes of perception, was actually verifying and extending Kant's epistemological analysis. In Müller's law of specific nerve energies he recognized the great principle which explained the role of sense organs in transforming abstract, external stimuli into something wholly different: the immediate sensations of consciousness. Helmholtz' problem was to explain how, despite this radical transformation, we nevertheless have knowledge of the external world.

Helmholtz followed Kant in insisting that the law of causality is transcendental and a priori. In 1855 he asserted that the causal law underlies our belief in external objects, a proposition which prompted charges of plagiarism from Schopenhauer and hence cemented Helmholtz' distaste for metaphysicians. We have immediate experience, he observed, that changes occur in our sensations independent of our volitions. In order that this effect may have a cause, we postulate objects external to ourselves, which can be further analyzed into two categories: matter and force. Whether such objects actually exist must remain a metaphysical question, for both idealism and realism are wholly consistent systems. That the properties of matter and force are constant depends upon our assumption of the lawfulness of nature, which, in turn, rests upon the a priori status of the causal law. In our perception of the world, though, the conclusions we draw about the existence of external objects and forces and their interrelations do not depend upon reflection; they are instantaneous and unconscious. These highly controversial "unconscious conclusions" (*unbewusste Sehlüsse)* underlie all of Helmholtz' epistemology and reveal its debt to English associationist psychology.

Because all external stimuli are mediated and radically transformed by the sense organs, our sensations are not images of external reality but tokens or signs of it. We gain knowledge about the external world by experientially discovering how our volitions can alter our sensations. Visual perception of space and localization, for example, is built up in such a way. By willing to touch an object, walk around it, or merely move our gaze we discover experientially that we can alter the accompanying retinal sensations in very regular ways. Hence, through unconscious conclusions certain retinal patterns become associated with objects localized in space, the idea of space itself having first been built up through the sense of touch. The nature of that retinal pattern matters not at all, Helmholtz insisted. All that matters is that we be capable of distinguishing one retinal point from another (in R. H. Lotze's terminology, that each point have its own "local sign") and that the proper eye movements be always able to restore the same retinal pattern.

This empiricist theory of visual perception differed radically from the alternate nativist view. Nativists held that visual perception of space and localization was not wholly learned but was in some sense innate. Johannes Müller, himself a nativist, believed that we are directly aware of the retina's extension in space and that the local signs have an intrinsic spatial meaning. In the sophisticated theory of Ewald Hering, Helmholtz' great rival, the nativist theory was extended to depth perception as well. Helmholtz devoted volume III of his *Handbuch der physiologischen Optik* (1867) to proving that the empiricist theory could explain all the phenomena of visual perception and that nativist theories, especially Hering's, were incorrect or superfluous. Helmholtz first showed that Donder's and Listing's laws, the two basic laws of eye movement, could be easily explained on an empiricist basis in accordance with his own principle of easiest orientation. But Helmholtz organized his primary refutation of nativism around the phenomena of depth perception and binocular vision.

To deal with the problem of single and double vision Johannes Müller had hypothesized that the two retinas must possess paired or "corresponding" points and that each pair of corresponding points contributes to one point of the unified visual field. This hypothesis not only explains why we do not see two visual fields (one corresponding to each eye) but also explains the existence of single and double images. If the eyes fixate on a small object in space, that object will be seen single because its retinal images fall on corresponding retinal points. Many other objects, however, will be seen slightly double, for their retinal images do not correspond. The locus of all points in space which are seen single is called the horopter curve. Its exact determination occupied Helmholtz' attention, and he and Hering published its general mathematical form independently between 1862 and 1864.

Helmholtz regarded the way in which the disparate images of two corresponding points become united into one as the crux of the nativist–empiricist dispute. Understanding how visual perception of space originates also seemed to hang upon that issue, for Charles Wheatstone's invention of the stereoscope in 1833 had revealed the dependence of visual depth perception upon binocular double vision. Many nativists maintained that the nerve fibers leading from pairs of corresponding points become anatomically united before entering the sensorium, so that the resulting single image is an organic fusion of the two different images. Helmholtz and the empiricists believed that disparate images from corresponding retinal points enter the sensorium distinct and intact, and that their union into a single image is an unconscious act of judgment dependent upon prior experience. Against the hypothesis of any organic or anatomical union, upon which he believed all nativist theories must rest, Helmholtz marshaled various observations obtained from Wheatstone's stereoscope. The eyes show surprising ability to fuse the two halves of the steroscopic image, Helmholtz noted, even though these images are different and may fall on noncorresponding points. A still greater problem for nativist theories is the phenomenon of stereoscopic luster. If an area in one half of a stereoscopic drawing is shaded white and the same area in the other half black, the fused image appears not gray but lustrous. Empiricism explains this easily as a learned response to empirical situations in which lustrous objects reflect more light into one eye than into the other. Contrary to nativist principles, the sensations excited in corresponding points clearly yield not a fusion of each but a wholly different sensation. This, Helmholtz claimed, decisively disproved the anatomical union of corresponding points upon which nativist theories depended. The union of binocular images into a single perception of depth, he concluded. must be the result of learning and experience as predicted by the empiricist theory

Helmholtz' belief in the empirical origin of visual localization did not necessarily conflict with Kant's doctrine that space in general is a transcendental form of perception. But Helmholtz broke sharply with Kant over his claim that the axioms of geometry were also synthetic, a priori propositions. Motivated by his study of visual perception, throughout the mid-1860's Helmholtz investigated the most general analytic expressions of spatial relations. He formulated for himself the abstract mathematical concept of the extended *n*-ply manifold and became convinced that tacit assumptions of congruence and translation underlie the Euclidean axioms. In 1868, before publishing these results, he received a copy of G. F. B. Riemann's treatise of 1854, *Ueber die Hypothesen, welche der Geometrie zu Grunde liegen*, and discovered that most of his results had been anticipated. Nevertheless, he published his own work, emphasizing its one aspect that went beyond Riemann's treatment. Riemann had assumed that in any manifold the distance formula *ds* must be the square root of a homogeneous function of second degree in *dx, dy, dz*, and so on. Helmholtz, starting from the assumption of congruence, proved that Riemann's formula must follow necessarily from that assumption.

Helmholtz' interest in these problems was never that of the pure mathematician. He sought primarily to demonstrate that the Euclidean axioms presuppose the purely experiential facts of translation and congruence. Since geometries other than Euclidean can be developed from these facts, it follows that the Euclidean axioms cannot be the transcendental conditions for our perception of space, as Kant had claimed. Helmholtz' contribution to the development of non-Euclidean geometry was therefore a natural extension of his empiricist philosophical position.

Hydrodynamics . In 1858 Helmholtz published his seminal memoir "Ueber Integrale der hydrodynamischen Gleichungen, welche den Wirbelbewegungen entsprechen," important for both its physical results and its mathematical methods. His motivations for taking up this new research interest remain unclear. One motive seems, however, to have been his interest in frictional phenomena, carried over from his interest in energetics; another was his growing awareness of the power of Green's theorem.

Previously, Helmholtz began, hydrodynamics had assumed the existence of a velocity potential. Yet Euler had noted that there is fluid motion for which no velocity potential exists, including forms of rotary motion and frictional flow. If there exists a singlevalue velocity potential for a given fluid motion, then (in modern vector notation) $\nabla\phi = \mathbf{v}$ and $\nabla \times = 0$. These conditions, Helmholtz showed, exclude the possibility of vortex motion. In cases of fluid motion where rotary motion does occur, then $\nabla \times \mathbf{v} = 2\omega$ where ω is the angular velocity of a given element. From this fact and from the standard Eulerian equations of motion Helmholtz obtained

Hence, if the fluid is ever without rotation, that is, $\omega = 0$, then $d\omega/dt = 0$ and the fluid can never begin to rotate. This principle became known as the conservation of vortices.

Helmholtz defined the vortex line (*Wirbellinie)* as the locus of the instantaneous axes of rotation of a rotating particle of fluid. A given vortex line, he proved, is always composed of the same particles of fluid and hence shares their motion through the fluid. He defined vortex tubes (*Wirbelfinie)* as the tubes formed by the vortex lines drawn through all points on the circumference of an infinitely small surface within the fluid. The product of the velocity of rotation and the cross section at any point of a given tube is constant; it follows that such tubes must always be closed within the fluid or terminate on its boundaries.

Helmholtz proceeded to find $\mathbf{v}$ in terms of ω, subject to the three conditions $\nabla\cdot \omega = 0$, $\nabla\cdot \mathbf{v} = 0$, and $\nabla \times \mathbf{v} = 2\omega$ The solution, he asserted, is

Here *P* functions as a scalar potential while *L, M*, and *N* function as the components of the modern vector potential **A** . Hence Helmholtz had implicitly set out the Helmholtz theorem, that the velocity field is the sum of irrotational and solenoidal parts. But although Maxwell had introduced the vector potential explicitly in 1856, Helmholtz did not regard his *L, M*, and N as the components of any physical or mathematical entity. He defined each separately on a strict magnetic analogy. *L, M*, and N are the volume integrals over the fluid space of the magnetic potential exercised on an external point *x, y, z* by a magnetic fluid distributed with density ω/r. In other words,

P is defined analogously. It follows immediately for Helmholtz that

and from equation (4) that $\nabla \cdot \mathbf{A} = 0$. Hence solution (3) satisfies the necessary conditions.

Equations (3) allowed Helmholtz to calculate easily the velocity induced in a particle *a* by a rotating particle *b* at distance *r*. He obtained the striking result that

This formula, as Helmholtz pointed out, is exactly analogous to the Biot–Savart force law for the magnetic effect of currents. True to the rigorous, starkly mathematical tenor of the entire paper. Helmholtz regarded this as only a heuristic analogy; his own development was strictly kinematic and mathematical.

Although George Stokes had anticipated certain methods and results of Helmholtz, the 1858 memoir was nevertheless a tour de force; yet it seemed to attract little initial attention beyond involving Helmholtz in an insignificant controversy with Joseph Bertrand. In 1866, though, William Thomson (later Lord Kelvin) made it the basis of his theory of the vortex atom. Helmholtz had proved, Thomson, noted, that his vortices share with hard atoms the properties of being conserved, undergoing collision, exerting influence on other vortices at a distance, and possessing well-defined energies. In addition, vortices have suggestive properties not possessed by hard atoms, such as the electrical and magnetic analogies demonstrated by Helmholtz. For a decade Thomson tried to develop a physics based on the assumption that atoms are tiny vortices.

Helmholtz himself never returned to vortex theory, although his previous work did influence his important paper of 1868 on discontinuous fluid motion. Finally, in collaboration with Gustav von Piotrowski, he carried out a series of complex experimental determinations (1860) of the coefficient of internal friction for various fluids.

Electrodynamics . Although Helmholtz had published earlier papers on electrodynamic phenomena, the field began to dominate his research interests only after 1870. This new direction in his research seems to have been motivated chiefly by his desire to bring electrodynamic theory into harmony with the conservation of energy. Concomitant with this purpose, Helmholtz hoped to bring order to a field which he described in 1870 as a "pathless wilderness" of competing mathematical formulas and theories. He undertook his research with three aims in mind: (1) to test the consistency of each contending theory with accepted mechanical and dynamic principles, (2) to derive differing theoretical predictions from each theory, and (3) to carry out experiments in order to decide between competing theories.

In his 1847 memoir Helmholtz had argued that ultimate forces must be conservative. He had also argued that forces cannot be conservative if the force laws expressing them contain terms involving the velocity or acceleration of the ultimate particles between which the forces work. But this argument impugned the fundamental status claimed for Wilhelm Weber's law expressing the electrodynamic force acting between two charged particles *e* and *e′*. According to Weber's law

where *r* is the distance between *e* and *e′* and *c* is a constant. The formula involves not only the distance *r* but also its time derivatives; hence, according to Helmholtz, the force must violate the conservation of energy.

Helmholtz' criteria for force laws excited much opposition; his lifelong rival Clausius attacked them in 1853. The proofs upon which they rested were, in fact, incorrect; Helmholtz later acknowledged that force laws involving derivatives of distance can conserve energy, although they cannot be central and obey Newton's third law. Nevertheless, he continued to believe that the form of Weber's law implied physical inconsistencies if not explicit violation of the conservation principle. In 1870 he opened his critique of Weber's law, then the leading Continental formula for the prediction of electrodynamic effects. According to that law, Helmholtz showed, the energy of at least some systems of charges in motion is less than the energy of the same systems at rest. Hence at least some electrostatic equilibriums must be unstable. Furthermore, one can easily show from Weber's formula that two charges +*e* and −*e* can, under certain conditions, continue to accelerate spontaneously until their kinetic energy becomes infinite. Therefore, in both cases Weber's law predicts physical absurdities.

Helmholtz' critique provoked a running controversy, conducted with great bitterness by Weber's pupils, which lasted through the 1870's. The principals themselves found great difficulty in even understanding each other, for Helmholtz' conception was entirely of macroscopic phenomena; Weber's, of microscopic charges. The confrontation ultimately proved indecisive, yet it undermined the confidence of Continental physicists in Weber's theory and facilitated acceptance of Maxwell's theory, which replaced Weber's after 1880.

In cataloguing competing electrodynamic theories, Helmholtz also advanced a theory of his own which he believed would embrace many others as special cases. The intrinsic difficulties of electrodynamic force laws like Weber's dictated his decision to derive the force from a potential. In 1848 Franz Neumann had successfully derived all electrodynamic effects for closed currents from a potential. In 1870 Helmholtz showed that the most general form of Neumann's potential must be

In equation (5) *p* represents the potential which current element *d* s exercises upon element *d* s′ when *ds* carries current *i ds′* current *j*; **r** represents the distance between elements *ds* and *ds ′*, and $A = 1/c$, where *c* is an undetermined, constant velocity, In equation (5) *k* is also an undetermined constant. For $k = -1$. equation (5) becomes simply a form of Weber′s law; for $k = 1$, it becomes Neumann's potential; and $k = 0$ corresponds to Maxwell's theory. The parts of expression (5) which are multiplied by *k* can be written

This expression becomes zero when integrated around the full circuits *S* and *S*' if either is closed; hence for closed currents all the competing formulas are equivalent. Differences between formulas can arise only for open currents—those in which, according to Helmholtz, changes in the density of the "free electricity" occur. In 1870 there existed little experimental data on open currents.

The difficulties of open currents also arise in the propagation of electrodynamic effects in magnetic and dielectric media. Helmholtz' discussion of this topic necessitated a comparison of his theory with Maxwell's. In 1870 Maxwell's theory was little known on the Continent, for it differed radically from Continental theories. The latter assumed that a body exerted its electrodynamic action on another at a distance, independent of the intervening media. Maxwell's field theory rejected action at a distance and, as Helmholtz understood it, assumed all electrodynamic action to be propagated through contiguous, progressive polarization of a medium. On the assumption that the luminiferous ether itself is a magnetizable dielectric, Helmholtz noted, Maxwell's theory yields the striking result that electrodynamic disturbances propagate themselves in transversal waves possessing the velocity of light in free space. Like the English physicists, Helmholtz believed the existence of a dielectric ether to be strongly supported by the experiments of Faraday, especially those on diamagnetism.

Pursuing the comparison of the theories, Helmholtz first demonstrated that the derivation of a wave equation for electromagnetic propagation does not depend upon the particular assumptions of Maxwell's theory. If the polarization of the medium is taken into account and the polarization expression $\partial p/\partial t$ is introduced as one term of the current density, then Helmholtz showed how a wave equation could be derived from his own generalized potential law, even though that law rested upon the initial assumption of action at a distance. The velocity of the waves predicted by Helmho by z' wave equation depend upon the electrical and magnetic susceptibilities of free space. If these are assumed to be zero (that the ether is not a magnetizable, dielectric medium) then the velocities become infinite. If the susceptibilities are assumed to be large, then the wave velocities become finite. However, the further assumption that $k = 0$, the condition of Maxwell's theory, is required in order that the waves be wholly transverse and attain the exact velocity of light in free space. In this sense Maxwell's theory becomes a special, limiting case of Helmholtz' more general theory. Continental physicists first became acquainted with Maxwell's theory in this form, through Helmholtz' memoirs.

Like most of the Continental school, Helmholtz still distinguished in electrodynamics between inductive forces, those which tend to set in motion the electricity within a conductor, and ponderomotive forces, those which tend to set in motion the conductor itself. In 1874 he devoted a major paper to demonstrating that his generalized potential formula could serve as a potential for ponderomotive as well as for inductive forces. In this attempt he was merely generalizing and extending the earlier work of Franz Neumann. In 1845 Neumann had derived a simple induction law from Lenz's law and Ampère's expression for the ponderomotive force between current elements. Later, in 1848, he had published his more famous potential formula, equivalent to the induction law for closed currents. Neumann himself had shown that the potential formula could predict ponderomotive effects and had verified its agreement with Ampére's law for many simple cases. Helmholtz extended that verification to three-dimensional, deformable conductors and to cases of open currents.

In the course of the 1874 analysis Helmholtz discovered a feasible method through which the various theories could be tested experimentally. Ampère's law predicted ponderomotive forces only between infinitesimal elements of conductors carrying closed currents. The ponderomotive force law derived from Helmholtz' potential annexed to Ampère's expression other terms predicting ponderomotive effects due to the free electricity accumulating at the ends of open circuits. In 1874 Helmholtz and his student N. N. Schiller carried out experiments to determine whether the end of an open current, simulated by an electrostatic discharge, would produce ponderomotive effects. They observed none, and Helmholtz reluctantly concluded that the potential law must be incorrect or that the assumptions underlying it were incomplete. In the experiment Helmholtz noted that charge was continually removed from the discharge point of the electrostatic machine through the convective motion of air particles. The potential law denied that such convection currents produced any electrodynamic effects. But if this assumption were false, he pointed out, then in addition to the ponderomotive effects produced by the open current there would be other electrodynamic effects caused by the convection current. The potential law might not then be strictly false but merely incomplete as long as it failed to take into account that effect. In 1876 Henry Rowland conducted experiments in Helmholtz' laboratory which proved that convection currents produce electrodynamic effects. Helmholtz immediately pointed out that the results of both experiments can be predicted either from Maxwell's theory or from the generalized potential law with the dielectric ether. In 1875 Helmholtz had already conducted a different experiment with similar results. He had rotated the plates of a cylindrical capacitor aligned axially in a uniform magnetic field and had observed an induced electromotive force on the plates. This effect could be predicted from the generalized potential law only by assuming that the insulating space between the capacitor plates functioned like Maxwell's dielectric ether.

Logically, the experimental evidence remained inconclusive at the end of 1876. All the major results, Helmholtz noted, could be explained by Neumann's induction law without recourse to a dielectric ether. But although Helmholtz in 1875 presented the choice between theories as still open to experimental decision, in practice he had come gradually to regard the dielectric ether as a necessity and Maxwell's theory as correct. In the Faraday lecture of 1881 he predicted the decline of action at a distance on the Continent and lent full support to Maxwell's theory. His interest in electrodynamics waned after 1876, and his work was taken up by Heinrich Hertz.

Yet Helmholtz did not accept the Maxwellian view that all current consists of the polarization of media. After 1876 his electrical research turned almost entirely to the galvanic pile, and he became firmly convinced that electricity consisted ultimately of discrete charges. In the Faraday lecture of 1881 Helmholtz set out his theory of "atoms of electricity" and his conviction that chemical forces are ultimately electrical in nature.

Conclusion , Helmholtz exerted incalculable influence on nineteenth-century science, not only through the achievements of his research but also through his brilliant popular lectures and his activity as a teacher and administrator. Helmholtz witnessed the final transition of the German universities from purely pedagogical academies to institutions devoted to organized research.

The great laboratories built for him at Heidelberg and Berlin opened to him and his students possibilities for research unavailable anywhere in Europe before 1860. In many respects his career epitomized that of German science itself in his era, for during Helmholtz' lifetime German science, like the German empire, gained virtual supremacy on the Continent.

Helmholtz belonged to that brilliant and selfconscious generation of German scientists which arose in open reaction to the scientific romanticism of earlier decades. Yet—far more than they cared to admit—Helmholtz and his generation still harbored many of the preconceptions and even the program of the earlier science. Like many of his romantic predecessors, Helmholtz devoted his life to seeking the great unifying principles underlying nature. His career began with one such principle, that of energy, and concluded with another, that of least action. No less than the idealist generation before him, he longed to understand the ultimate, subjective sources of knowledge. That longing found expression in his determination to understand the role of the sense organs, as mediators of experience, in the synthesis of knowledge.

To this continuity with the past Helmholtz and his generation brought two new elements, a profound distaste for metaphysics and an undeviating reliance on mathematics and mechanism. Helmholtz owed the scope and depth characteristic of his greatest work largely to the mathematical and experimental expertise which he brought to his science. Especially in physiology that expertise, shared by few other physiologists of the day, made possible the imposing theoretical and experimental edifices that Helmholtz erected from the simplest of physiological principles. Although the biophysical program of the 1847 school did not prove wholly successful for physiology in general, in Helmholtz' field of sensory physiology it proved eminently so.

When Helmholtz abandoned physiology for physics in 1871, the former science, he complained, had already grown too complex for any individual to embrace in its entirety. At his death in 1894, that complexity had become true of virtually all fields. Helmholtz was the last scholar whose work, in the tradition of Leibniz, embraced all the sciences, as well as philosophy and the fine arts.

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