HISTORY OF PHYSICS

by MAX VON LAUE

translated by RALPH OESPER

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Mechanics

In the beginning was mechanics. As stated, the theory of equilibrium or statics extends far back into antiquity. It was brought into being by the practical importance of the lever, screw, block-and-tackle, and inclined plane as aids in heavy manual tasks. Such concepts as specific gravity and center of gravity were developed by the Greeks. The calculation of the center of gravity of a body of specified shape was a favorite mathematical exercise which required considerable skill as long as differential calculus was not available. Ancient statics reached its peak in the law of virtual displacements: multiply every force by the length of the path which the point of application traverses, provided a definite motion is produced. This motion will not ensue if the sum of these products (each given its appropriate sign) equals zero. Forces are measured here through weights; consequently, actions of gravity are always involved. The familiar law of the lever is a special case as is Archimedes' principle, which states that every solid body immersed in a liquid is buoyed up by force equal to the weight of the displaced liquid. The millennia before 1600 produced this knowledge at the cost of great labor. The last in the series of its creators was Simon Stevinus (1548-1620), who studied the equilibrium on the inclined plane in a brilliant, intuitive manner and thereby deduced the resolution of a force into components, i.e., he discovered the principle of the parallelogram of forces. The remainder of the mechanics taught by Aristotle, held to be incontrovertible truth through the entire scholastic period, proved to be nothing but the greatest of all the handicaps, which the budding science of the sixteenth century had to overcome.

The founding of the actual science of motion, i.e., dynamics, was due to Galileo Galilei (1564-1642); it was further developed by Christian Huygens; and brought to a certain degree of completion by Isaac Newton (1642-1727) in whose honor it is now known as Newtonian dynamics. Galilei's studies of falling bodies commenced soon after 1589; his chief work on mechanics *Discorsi e Dimonstrazioni matematiche intorno a due nuove Scienze attenenti alla Mecanica & Movimenti locali* was published in 1638; Newton's *Philosophiae naturalis principia* appeared in 1687. Hence the creation period of dynamics was just about a century in length.

The result of this magnificent achievement of the human mind is contained in two laws: The product of the mass of a mass point times its acceleration is equal to the force acting on it. (Acceleration and force are directed quantities, i.e., vectors, and the law assumes, among other things, the same direction for both of them.) The second law is that of the equality of action and reaction: The forces exerted by masses on each other are equal in magnitude but opposed as to direction.

These statements need analysis. As to acceleration, it had been cleared up, in essence, by Galilei when, with primitive mathematical tools, he studied the concept of variable velocity. Newton, who had available the calculus invented by him and also by Gottfried Wilhelm von Leibniz (1646-1716), was able to lighten the task for himself. Acceleration is the change in velocity per unit time, the derivative of the velocity with respect to time, and hence the second derivative, with respect to time, of the radius vector drawn from a chosen starting point to the place at which the mass point is located. If the location and the elapsed time are known, the velocity and acceleration are therefore clearly defined. The first law gives consequently a second order differential equation for the location as a function of time; its integration determines the path and the velocity with which it will be traversed. When no force is acting, the acceleration is zero, the motion is in a straight line with constant velocity, in conformity with the principle of inertia.

The second law states the meaning of mass and "inert mass." If two masses mutually accelerate each other, the extents of the effects are inversely proportional to the masses. This is likewise true, in case the motion is from rest, for the velocities attained in equal times and for the distances covered. Geometric measurement of the distance therefore makes it possible to refer every mass back to an arbitrarily chosen unit mass. Since the accelerations are in opposite directions, the sum of the products of the mass times the velocity remains unaltered, namely, equal to zero, provided both masses started from rest. As this product is defined as impulse, the foregoing laws can be restated in the form preferred today:

1. The force is equal to the change in impulse per unit time.[1]
2. In a system that is not influenced from without, and consisting of two, or even any desired number of masses, the total impulse is constant. (Law of the conservation of impulses.)

It is implicit in these statements that the forces exerted by two bodies on each other are not disturbed by a third body and that the mass is an unchangeable characteristic of the bodies. The latter assumption has always been an *a priori* postulate in mechanics, because no changes in the mass were ever revealed by weighings. Similarly, one of the most important facts learned in chemistry, which was developing into a science in the eighteenth century, was that the total mass of the reacting substances remains constant during chemical reactions. Antoine Laurent Lavoisier rendered particular service in this respect. A series of especially careful weighings, made in the years 1895 to 1906 by Hans Landolt (1831-1910), substantiated this belief. Nevertheless, today the constancy of mass is regarded as only an approximation that admittedly is fully adequate to the needs of mechanics, chemistry, and many branches of physics.

In the experiments, which provided the basis for this result, the forces were measured by means of weights, a long approved practice that is still in vogue. If the weights did not act perpendicularly downwards, the cords holding them were drawn

[1] Even Newton used this formulation.

over drums. Hence, the concept of force was really quite well established by experiment, and therefore it might well be thought to have been divested of every thing of a secret or metaphysical nature. But the seventeenth and eighteenth centuries were by no means so logical. The fact that the abstract meaning of the word "force" was not entirely clarified led to confusion upon confusion. Since every conscious employment of force by man is preceded by an act of will, something deeper was sought within the physical notion of force. This mysterious something in the case of gravity, for example, was thought to be an innate tendency of bodies to unite with others of their own kind. It is difficult for us moderns to comprehend this standpoint. How generally it was accepted even by leading minds of the time is shown by the famous dispute over the "natural measure of force" between the Cartesians and Leibniz and his followers. One party took this to be the impulse produced in a given time by the force, the other side believed it to be what is now known as kinetic energy, which formerly was often called "vital force." Newton was not able to take a definite stand on this matter. Although even d'Alembert (1717-1783) labeled the endless discussion simply a battle of words, the concept of force in many minds, nevertheless, retained something of its mystical nature up to 1874, when Gustav Robert Kirchhoff (1824-1887) uttered the redeeming word in the first sentence of his Lectures on Mechanics. "Mechanics is the science of motion; its task is to describe completely and in the simplest manner the motions occurring in nature." Accordingly, it is merely a matter of treating the vector denoting force as a function of the location of the mass point or the time, or even of both. The velocity can also be a determinant, in frictional forces, for instance. The integration of the Newtonian equation of motion then becomes a purely mathematical problem, whose solution provides the answer to every justifiable question concerning motion. Physics cannot and need not do more than this. If the reader finds something of causal explanation lacking in the word "describe," he should note that the explanation of a natural event can consist only of bringing it into relationship with other occurrences by means of known natural laws, i.e., by describing a complex of related events as a whole. This fact has now been generally accepted and prevails in other fields as well as in mechanics.

A second series of important developments came in the same period. In 1643 Evangelista Torricelli (1608-1647), prompted by an experiment performed with a suction pump by Galilei, invented the mercury barometer. Blaise Pascal (1623-1662) in 1648 instructed his brother-in-law Perier to compare the height of the mercury column on the Puy de Dôme and at Clermont (a difference in elevation of about 1000 meters). Otto von Guericke (1602-1686) invented the air pump and with its aid cleared up the nature of atmospheric pressure by means of many impressive experiments.[2] It has already been pointed out in the Introduction that the Boyle-Mariotte law stating the relation between pressure and volume of the air was known by 1662. At that time, other gases[3] were not available since hydrogen was not discovered by Henry Cavendish until 1766; oxygen, by Karl W. Scheele (1742-1786), in 1769; and nitrogen in 1772, by Daniel Rutherford (1749-1819). In 1676, Robert Hooke (1635-1703), a contemporary of Pascal, discovered the proportionality in simple cases between deformation and stress in solids.

Thus, around 1700, were laid the physical foundations on which the next century and a half could build the magnificent structure of mechanics. Its completeness is characterized by the fact that this development lay predominantly in the hands of the mathematicians. The French took the leading part in this movement during the eighteenth century. In fact, Newton's ideas were propagated first in France, not only among the men

[2] The "Magdeburg hemispheres" were demonstrated in 1656. However, Guericke did not write a comprehensive account of his experiments until 1663; it was published in 1672 as "Experimenta Nova (ut vocantur) Magdeburgica de Vacuo Spatio."

[3] The word "gas" is found about 1640 in the writings of the Dutch chemist-physician J. B. van Helmont (1577-1644); presumably, it came from the word "chaos," employed by Paracelsus for "mixtures of airs."

of science, but the "Enlightenment" carried them into far wider circles. This is a model example of the influence of physics on the general mental growth, and therefore also on political development. Special mention of the following is merited: Daniel Bernoulli (1700-1782), Leonhard Euler (1707-1783), who studied systems of several mass points, solid bodies, and hydrodynamics; Jean Lerond d'Alembert, the author of the principle that bears his name and which replaces the equations of motion; Joseph Louis Lagrange (1736-1813), who gave these differential equations a form especially suited to more complicated cases; Pierre Simon Marquis de Laplace (1749-1827), whose five-volume "Mécanique celeste," which appeared in 1800, contains much more than its title implies, namely, among others, a theory of liquid waves and capillarity. Thus the highest flowering of analytical mechanics was reached. Mention should be made also of: Louis Poinsot (1777-1859) to whom is due the completion of the theory of the rigid body; Gaspard Gustave Coriolis (1792-1843), who analyzed the effect, for instance, of the earth's rotation on the events that took place on this planet; Augustin Louis Cauchy (1789-1857), who, in 1822, contributed the most general mathematical formulation of the exceedingly important concepts of elastic strain and deformation, and by using Hooke's law, gave the mechanics of deformable bodies its final form; William Rowan Hamilton (1805-1865), who set up the principle of least action, which will be discussed presently; Karl Gustav Jacob Jacobi (1804-1851), who invented the method of the Hamilton-Jacobi differential equation for systems of several bodies. The studies of Jean Leon Poiseuille (1799-1869) on the internal friction of liquids and gases (1846-47), and the Helmholtz vortex laws (1858) can be considered as essentially closing this epoch, even though subsequent eminent investigators, especially Lord Rayleigh (1842-1919), Osborne Reynolds (1842-1912), and L. Prandtl still further advanced the dynamics of frictional liquids and gases. Such studies are still being carried on, particularly for purposes relating to the construction of water and air craft. The difference between orderly "laminar" and disorderly "turbulent" flow plays a part in this. If, however, experimental studies are also added, sometimes with enormous technical expenditure, this is done solely because the corresponding problems cannot be solved by present-day mathematics, or only with the expenditure of an inordinate amount of time. Nobody expects these studies to yield results that would go beyond the Newtonian foundations.

Only two results from the wealth of post-Newtonian development will be emphasized here. From Euler's time on, the mathematicians had set up variation principles, which were equivalent to the equations of motion, in fact, they contained the latter within themselves. A form of a principle of this type, which bears his name, was enthusiastically promulgated by Pierre Louis Maupertuis (1698-1759), but Lagrange was the first to state it correctly. The best known of these is Hamilton's *principle of least action,* which in 1886 was applied to a whole series of nonmechanical processes by Hermann von Helmholtz (1821-1894). Max Planck (1858-1947) regarded this as the most comprehensive of all natural laws. It deals with a time integral, to be formed between two fixed points of time with respect to the difference of the potential and kinetic energy, and states that for the actual motion this integral is smaller than for any other conceivable one that leads from the same initial to the same final condition. When such principles were brought out in the eighteenth century, they caused a tremendous sensation. The differential equations of motion determine what happens at a given instant from the immediately preceding motion, in conformity with the causal concept of nature. In these principles, on the contrary, the entire motion over a finite period of time is taken into account all at once, as though the future plays a part in determining the present. Accordingly, a teleological factor seemed to have been introduced into physics, and certain enthusiasts even went so far as to imagine that they were being given here a glimpse into the world plan set up by the Creator, Who had ordained that the values appearing in these principles should be kept as small as possible. The

Leibniz idea of "the best of all possible worlds" smacks of this notion.

Of course, a mathematical error was at the bottom of this doctrine. Later critical studies revealed that although these quantities always have an extreme value for the real motion, the value is by no means invariably a minimum. Furthermore, it soon became evident that variation principles can be set up for differential equations other than those pertaining to mechanics. Consequently, the principle of least action and all similar ideas were put back into their proper position as highly valuable mathematical aids.

This could be an appropriate place to mention a second, and far more important point, namely, the law of the conservation of energy, which had had a history within mechanics even before it emerged from this province to become a universal law. However, it will be discussed in Chapter VIII.

R. W. Hamilton, who also contributed to the development of geometric optics, pointed out the mathematical similarity between this discipline and mechanics. A light ray and the path of a mass point correspond so that it must be possible to recombine the paths of all of the mass points which issue from a point with the same velocity into a "focus" and thus mechanically produce "optical" representation. Of course, this could not be accomplished until the discovery of electrons, i.e., of particles in which the action of gravity can be completely overshadowed by electrical forces. However, the electron microscope, at least in its electrostatic form,[4] is the direct application of the Hamiltonian concept.

The relativity theory, formulated in 1905 by Albert Einstein, does not greatly alter the dynamics of the mass point, as was shown by Planck in 1906. (Einstein's fundamental work is incorrect in this regard.) A distinctive feature is the inclusion of a universal constant, whose mechanical significance had

[4] There is also a magnetic model.

hitherto been unrecognized, namely, the velocity of light in empty space. The proposition that force equals change of impulse per unit time is preserved, likewise the conservation of impulse in a closed system. Just as before, this gives rise to the energy law; but now the relations between impulse and energy change as the velocity changes. Although this change is noticeable only for velocities approaching that of light, nevertheless, in this region, impulse and energy increase without limit, with the result that no object can ever reach the velocity of light. The latter is the unattainable upper limit of all corpuscular velocities. Electron velocities up to 99 per cent that of light and higher have been found in radioactive atomic disintegrations, velocities exceeding that of light have never been established experimentally. The validity of the relativity formula for impulse was established by numerous measurements (1906-1910) of the deflection of fast electrons carried out by Walter Kaufmann (1871-1947), Alfred Heinrich Bucherer (1863-1927), Charles Eugène Guye (1866-1942), and Simon Ratnowsky (1884-1945).

The change in the mass concept, which this theory forces on the physicist, is fundamentally of still greater importance. As Einstein demonstrated from it in 1905, every addition of internal energy must increase the mass, and by an amount that is obtained by dividing the energy, measured in mechanical units, by the square of the velocity of light. However, because of the magnitude of this velocity (3×10^{10} cm/sec), the changes are insignificant in all processes which are designated as mechanical, electrical, or thermal. No change in the total mass of the reacting substances can be observed even in the most vigorous chemical changes that have the greatest heats of reaction. In nuclear physics, however, this law of the inertia of energy acquires an enormous significance (see Chapter X).

What does mechanics accomplish? Exceptionally much. It provides the basis for every technical construction, in so far as the latter is mechanical, and it thus enters intimately into daily life. It finds application in the biological sciences; for instance, as mechanics of the bodily movements or of hearing. It contains the theory of the deformation of solids that are subjected to elastic stress, of flow in liquids and gases, and furthermore of the elastic vibrations and waves that are possible in all such bodies, i.e., of the whole field of acoustics, to the extent that the latter is physical in nature. It has, to emphasize a particular case, led to a theory of covibration, whose significance goes far beyond the province of mechanics and which, for instance, is basic to the understanding of electrical oscillations. It describes, in agreement with all observations, the motions of masses whose weights range from that of the fixed stars (10^{32}–10^{33} grams) to that of ultramicroscopic particles (10^{-18} gram). In fact, it has confirmed, in part, the experimental data on the motion of molecules, atoms, and the still smaller elementary particles (electrons, etc.). Consequently it became the basis of the kinetic theory of gases and of the Boltzmann-Gibbs formulation of physical statistics. It combines all these elements into a structure of majestic architecture and imposing beauty. Hence, it is not surprising that for many years mechanics was regarded as equivalent to the whole of physics and accordingly the purpose of the latter was viewed frankly as an effort to relate all processes back to mechanics. Even after it was realized, around 1900, that this could not be done for electrodynamics, many erroneously still considered mechanics as ranking above experience, like mathematics, for instance. The shock was therefore all the greater, when, from 1900 on, the validity of the quantum theory became increasingly evident in ever-widening areas. But even where it displaces mechanics, this theory retains unchanged two of the latter's laws: the conservation of energy and the conservation of impulse.

Acoustics, however, is one branch of mechanics that developed rather independently, particularly in its earlier stages. Even the ancients knew that pure tones, in contrast to noises, are due to periodic vibrations of the source of the sound. Pythagoras (582?-500? B.C.) knew, in addition, perhaps from Egyptian sources, that strings, which are tuned in harmonic intervals of octaves, fifths, etc., have lengths, which, other conditions being constant, are in the ratio of 1:2:3 and so on. The deep impression that this discovery made came from the great stress which the Pythagoreans placed on number in their general view of the world. Organs were widely distributed as early as the ninth century of the Christian era, and the builders must have known the corresponding facts about organ pipes. However, other than this, the knowledge of acoustics apparently took no part in the great advances experienced by the musical art in the two millennia after Pythagoras. Again, it was Galilei who provided the decisive impulse that promoted further development. In his *Discorsi* of 1638 (see p. 15), he declared that the vibration frequency is the physical correlate of the sensation of pitch; he regarded the relation of the vibration frequencies as determinants of the relative heights of two tones, and he also showed how the vibration frequency of a string depends on its length, the tension to which it is subjected, and its mass. He observed and explained the excitation of vibration through resonance, and he also particularly recognized the existence of stationary waves, the latter on the surface of water in vessels, which he had caused to emit notes by rubbing. At about the same time, namely in 1636, his former pupil Marin Mersenne (1588-1648) advanced somewhat farther. He made the first absolute measurement of vibration frequencies and of the speed of sound in air. In addition, he contributed the observation that a string usually emits its harmonic overtones along with the fundamental. Joseph Sauveur (1653-1716) did the same for organ pipes; he was acquainted with the properties of vibrations and determined the position of nodes and loops on vibrating strings by means of paper riders, a method still in use.

The fact that sound, in contrast to light, is not transmitted through an evacuated space was experimentally demonstrated by Otto von Guericke. The relation of the speed of sound to the compressibility and density of the atmosphere was calculated for the first time by Newton in his *Principia,* although his formula did not agree with experiment until Laplace, in 1826, replaced the isothermal by the adiabatic compressibility. The mathematical treatment of mechanics in the eighteenth century also benefited acoustics. However, the latter produced no other eminent experimenter until the advent of Ernst Friedrich Chladni (1756-1824), the "Father of Modern Acoustics." In 1802, he, among others, compared the longer known transverse vibrations of strings and rods with longitudinal and torsional vibrations; he made visible, by means of sand figures which now bear his name, the nodal lines of vibrating plates; he also measured the velocity of sound in gases other than air. Despite the direct observation (1762) by Benjamin Franklin (1706-1790), doubt persisted for many years regarding the transmission of sound through liquids, because they were supposed to be incompressible. However, incontrovertible proof of this fact was furnished in 1827 by Jean Daniel Colladon (1802-1893) and Jacob Franz Sturm (1803-1855) who found the speed of sound in Lake Geneva to be 1.435×10^5 cm/sec.

During the further course of the nineteenth century, physical acoustics became increasingly a part of the field of elastic waves. The ideas of interference, diffraction, and dispersion at obstacles, were carried over into sound from optics. Doppler's principle, which originated in 1842 as an optical idea (Chapter VI), received its first confirmation in the changes in pitch that are heard when whistling locomotives go by. Fourier analysis, which was originally invented to deal with problems in the conduction of heat (Chapter VII), experienced a triumph when it was applied to sound waves, especially since the resolution of any periodic vibration into sinusoidal vibrations corresponds to a direct psychological reality; the ear is capable of hearing the sinusoidal vibrations separately, a fact established in 1843 by Georg Simon Ohm (1787-1854). In cases where this analysis is not possible, because of inadequate intensity or lack of practice, these vibrations nevertheless determine the timbre or quality of the mixture of tones, a fact emphasized especially by Helmholtz in his *Theory of Tone Sensations* (1862).

Great technical problems were presented to acoustics after Philipp Reis (1834-1874) and Alexander Graham Bell (1847-1922) invented the telephone in 1861 and 1875, respectively, and again after 1878 when David Elwood Hughes (1831-1900) materially improved the Reis microphone. The best possible reproduction of the human voice and musical sounds had become necessary. The importance of the new field of application, "electro-acoustics," was further heightened by the transmission of sound by means of electrical waves, a fruit of World War I (1914-1918). The phonograph, invented in 1877 by Thomas Alva Edison (1847-1931), also falls into this category.

During this same war, Paul Langevin (1872-1946) found that quartz plates, if excited by piezoelectricity, could be used to produce sound waves in water, with vibrations of the order of 100,000 per second, i.e., far above the audible limit. This "ultrasound" was to be used in the detection of submerged submarines. These ultrasonic waves were subsequently used by physicists in studies of the properties of solid bodies, for measuring the velocity of sound in gases and liquids with respect to vibration frequency, and for various other purposes. Such waves also play a certain role in biological research.

In conclusion, mention should be made of another advance, which, though it was of a more public nature, nevertheless, had a marked effect on the whole of physics. On June 2, 1799, the Legislative Assembly in Paris adopted the kilogram as the standard unit of mass and the meter as the unit of length. These units, together with the much older unit of time, the second, form the basis of the cgs (centimeter/gram/second) system, to which modern physics relates all mechanical electrical, and magnetic units.