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ARISTOTLE, NEWTON, EINSTEIN[1]

By Professor E. T. WHITTAKER, F.R.S.
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IT falls to us this year to commemorate the greatest of men of science, Isaac Newton, on the occasion of the three-hundredth anniversary of his birth. The centuries have not dimmed his fame, and the passage of time is unlikely ever to displace him from the supreme position. His discoveries, however—and this is part of their glory—have not persisted unchanged, but in the hands of his successors have been continually unfolding into fresh evolutions. During the eighteenth and nineteenth centuries there was an immense expansion of knowledge, springing directly from his work, and forming ultimately a vast superstructure based on the Newtonian concepts of space, mass, and force. Since 1900 the progress of science has continued, but the development of physics has changed in character: it has become subversive and radical, questioning the traditional assumptions and uprooting the old foundations. In 1915 the Newtonian doctrine of gravitation was superseded by that of Einstein: the divergence between the results of the two theories, so far as concerns the calculation of the movements of the planets, is extremely slight, and indeed, in almost all cases, too small to be detected by observation; but on the question of the essential nature of gravitation, the two conceptions differ completely and are associated with opposite philosophies of the external world. The other great discovery of the present century is the quantum theory, which in its perfected form of quantum-mechanics appeared in 1925: this also is completely irreconcilable with the postulates of Newtonian science.

We have therefore come now to the end of an age—

[1] Address of the president of the Royal Society of Edinburgh, October 26, 1942.

the age of classical physics—which we may count as having extended from the publication of Newton's "Principia" in 1687 to the acceptance of general relativity and quantum-mechanics by our own contemporaries—about 250 years. The replacement of the Newtonian fundamental assumptions by a wholly different set of concepts, which is now taking place, represents a change in the philosophical view of the world which future generations will regard probably as one of the major turning-points in the history of thought, and perhaps as the most significant event of our time.

This afternoon I propose to set the revolution of the twentieth century, by which the doctrines of classical physics have been overthrown, side by side with the revolution of the seventeenth century, by which they were originally established. It will appear that in some respects the second movement is reversing the direction of the first, and is bringing back ideas which were accepted in the great days of the Scholastic philosophy, but which, having been discarded at the Renaissance, have for the last three hundred years been unknown outside a small circle of scholars.

I have therefore taken for these remarks the title "Aristotle, Newton, Einstein." "Aristotle" stands for the interpretation of the world which was developed, on the foundation of the Aristotelian physics and metaphysics, by the Scholastic philosophers of the thirteenth century; "Newton" symbolizes classical physics, which displaced Scholasticism and is now in its turn outmoded; and "Einstein" represents the new conceptions which have arisen in connection with quantum-mechanics and general relativity and on which the physics of the future must be based.

Let us, then, first inquire what was gained and lost when the medieval philosophy was superseded in the seventeenth century by the doctrines of Descartes and Newton. To answer this question it is necessary to examine how the supersession came about. From the fourteenth century onwards, Scholasticism was decadent, and by the end of the sixteenth it had become thoroughly debased. The love of nature that had been so vital in Aristotle had almost perished; the practice of observation and experiment, on which he and St. Thomas had so strongly insisted, was neglected save by a few solitary workers; and the degenerate Schoolmen occupied themselves with futile subtleties that bore no relation to life and reality; they argued about homogeneities and heterogeneities, categorematics and syncategorematics, simpliciters and secundum quids; they resolved questions by the way of "formaliter," "materialiter," "fundamentaliter" and "eminenter"; and showed the causes of things in sympathy, antipathy and the influence of the heavens. No wonder that the virile scholars of the Renaissance broke away from it all. In Italy, under the patronage of the Medici, there was a revival of Platonism; and at Paris, in 1536, a crowded audience acclaimed the thesis of Peter Ramus, "Whatever is in Aristotle is false."

If philosophy and science were to be restored to life and health, the first necessity was, as Ramus saw, to re-establish contact with the external world. The chief pioneer in the movement back to nature, the great exemplar of the accurate quantitative observation of phenomena, was a friend of Ramus's, the Danish astronomer, Tycho Brahé, who lived from 1546 to 1601, and was thus about twenty years senior to Bacon and Galileo, and a century earlier than Newton. His observations, though made before the invention of the telescope and the micrometer, were astonishingly accurate; and some of his deductions from them were soon seen to be incompatible with the Aristotelian system of the world; thus, his memoir on a new star which appeared in the constellation Cassiopeia in 1572, by showing that this body was situated among the fixed stars, destroyed the belief in the eternal incorruptibility of the heavenly bodies; and his proof that the comet of 1577 moved around the sun in planetary space shattered the cosmology which located comets in the earth's atmosphere.

The work of Tycho firmly established the principle that natural philosophy must be based on quantitative data acquired from observation. But something more was needed in order to consummate the foundation of modern science, and this further element was contributed by his pupil Kepler. Kepler derived his conception from the revived Platonism which was then in favor; but actually it is traceable beyond Plato to his predecessors the Pythagoreans, and it may have been due to Pythagoras himself.

The original Pythagorean discovery related to the lengths of the strings of a lyre: it was found that if a string is stopped at half its length, it gives a note one octave higher; if at two thirds its length, it gives a note higher by the musical interval called a fifth, and so on. Thus simple numerical ratios were shown to exist between the lengths of strings which produce sounds harmonious to each other, and so a connection was set up between mathematics and esthetics. This was generalized into the principle that numerical laws, analogous to the numerical laws of harmony in music, were the proper means of interpreting the fundamental unity of the cosmos; that there must be a mathematical harmony of the external world underlying all phenomena; that this was the reality which philosophers sought, and that the task of men of science was to find it.

Moreover, it was asserted that the dispositions of nature were of the simplest character that could be imagined in any particular case. This consideration, which has in fact played a part of the first importance in the history of physics—in our own day it guided Einstein to the law of gravitation in curved space—was applied by Kepler in order to simplify the elaborate picture of the world which he had inherited from his predecessors. It is to be remembered that Copernicus, although he took the all-important step of placing the sun in the center of the universe, still retained the intricate machinery of epicycles which had been devised by Hipparchus to represent the motions of the planets, and which, by the successive adjunction of fresh curves to represent new discoveries, had by now become intolerably complicated: so much so that a royal patron of science, to whom it was described, remarked that "if the Deity had consulted him at the creation, he would have given Him good advice."

It seemed to Kepler that the truth must be much simpler than any one had yet realized; and that by use of the right kind of mathematics it should be possible to exhibit or suggest in some way a physical connection between the planets and the sun as the center of their motions. Eventually he succeeded in showing that the planes of the orbits of all the planets pass through the sun; that all the orbits are ellipses, having the sun as a focus; and that a line joining a planet to the sun sweeps out equal areas in equal times.

By the labors of Tycho and Kepler the modern procedure of science was instituted, and the true structure of the universe was revealed. At this point it may be observed that, while the Scholastic cosmology[2] was thereby completely disproved and overthrown, there was nothing in the new methods and discoveries that was inherently irreconcilable with the Scholastic metaphysics: the whole of Tycho's and Kepler's work might conceivably have been absorbed into the philosophy of the Schoolmen by a peaceful and conservative revolution. If this had happened, we in the twentieth century should have been spared the necessity of readjusting our position by a movement back towards Aristotelianism; but it was not to be. What did happen was a violent upheaval which swept away ontological doctrines equally with cosmological, destroying the old order entirely; an upheaval out of which the system of classical physics was formed, and which has dominated the relations of science, philosophy and religion with each other down to the present time.

The central figure of the movement on its metaphysical side was Descartes. As a young man he had become familiar with the degenerate Scholasticism of the day; but it had left him dissatisfied. Its conclusions were based principally on the affirmations of the great doctors; but the authority of the doctors was insecure, and the only branch of knowledge that seemed to be satisfactorily established was mathematics, whose procedure was to set out from self-evident postulates and to deduce from them results of practical value and incontrovertible truth. Descartes conceived the idea of searching for principles as certain as the axioms of mathematics, and on them as foundation to rebuild philosophy.

In pursuance of this design, he proposed far-reaching changes in the philosophy of nature. The first step—evidently suggested by the success of Kepler's work on the planetary orbits—was to describe the happenings of the external world in mathematical language. Now of all things presented to our observation, the spatial dimensions of bodies are the most obviously quantitative; he therefore seized on this feature, and based his system of the world on the affirmation that the characteristic of matter is extension. Another experience which is measurable is the passage of time; and hence the movement of bodies, which may be specified by the distance passed over in intervals of time, also admits of quantitative treatment. In terms of these two concepts matter and movement, Descartes proposed to explain the physical universe: quality was to be made intelligible as varying quantity.

In this scheme, extension constitutes matter, and matter constitutes space, which is therefore a plenum —there is no void. The sensations of sound, light, heat, taste and qualities generally are to be regarded as belonging to our consciousness, and purely subjective: in nature itself there is nothing but extension and the locomotion of its parts; the external world is a purely mechanical assemblage.

In the Cartesian transformation of philosophy the very meanings of the keywords were altered. Thus motion, which to the Scholastics had meant change of any kind, was now restricted to mean change of position; matter, which in the older doctrine was correlative to form, now meant simply corporeal being. Especially noteworthy is the new importance acquired by space and time. The Schoolmen had no word for "space" as we understand it; for spatium had rather the sense that "space" has in the Authorized Version of the Bible, *e.g.*, "All with one voice about the space of two hours cried out, 'Great is Diana of the Ephesians' "[3]; while locus meant the space occupied by a particular body. "Where" and "when," which to the Scholastics had been merely two among the ten predicaments of being, now came to dominate completely the description of nature.

That description was even more strictly mechanical than the Newtonian description which later superseded it, as may be seen, for instance, in their re-

[2] The word "cosmology" is here used in the sense that is customary in modern scientific writing, not the wider sense in which it is used in Scholastic philosophy.

[3] Acts xix, 34.

spective conceptions of gravitation. Gravity had been classified by the Schoolmen as an "occult quality"—that is to say, a force or tendency produced by no visible agency. Descartes denied the existence of occult qualities, and maintained, like the Greek atomists, that impact was the only mode in which one body could affect another: consequently he was compelled to furnish a new explanation of the fall of bodies towards the earth. This he did by postulating that surrounding the earth there is a vortex of subtle matter, or ether, which, by its pressure, provides the effect of gravity. Newton, on the other hand, formulated the inverse-square law without providing any mechanism to account for it; and in the preface to the second edition of the "Principia" there is a frank reversion to the Scholastic view of gravity as an occult quality.

Thus in the picture of the world arrived at by Descartes, all the phenomena of astronomy and physics, so far as they were known at the time, were represented by aggregations or motions or pressures in the plenum of space. Nothing resisted his mechanical explanations, except the thought of man; this could not be brought into any relation with extension, and was evidently not amenable to mathematical analysis. It must, therefore, he concluded, have a principle other than matter; and thus he arrived at a dualistic philosophy, and divided reality into the two great classes of extended and thinking substances, *res extensa* and *res cogitans,* the objective and the subjective, the corporeal and the spiritual world. As matter is characterized by extension, so the mind is characterized by thought: the two are completely independent, and no explanation of any relation between them is forthcoming.

The complete disjunction of the psychical from the physical, which was characteristic of Cartesianism, has profoundly affected the subsequent history of science, and indeed of almost every department of human thought. In the first generation after Descartes there was an uneasy recognition of the possibility that —since any view of the cosmos must have a theological bearing—the new natural philosophy might prove harmful to religion; and in fact a keen controversy broke out on this very question. The dispute was centered round the doctrines of space and time, which in this period underwent a profound change.

The principal agent of the change was Pierre Gassendi (1592–1655), who, opposing Descartes' representation of space as a plenum, revived the doctrines of the ancient atomists regarding the void. This implied making a distinction between matter and extension, and asserting that while space has extension, matter has solidity as well, and occupies only a part of space. Gassendi's ideas were adopted by Newton, and thus was evolved the portrayal of space and time which became finally established in classical physics. Its fundamental postulate is that all the phenomena of the external world can be described in terms of the location and motion in space of entities, each of which has some degree of persistence and continuous identity in time. Thus whatever happens, happens in space—space, the stage on which the drama of physics is to be played, is the dominating conception of the whole system. This had not been at all the point of view of Scholasticism, and, as we shall see later, the recent progress of physical discovery has shown that it is radically unsound.

By Newton, space is regarded as having a positive, objective existence, which is not attached in any way to subjective necessities of the human mind. "Absolute space," he says, "in its own nature, without regard to anything external, remains always similar and immovable"[4] and "all things are placed in space as regards order of situation."[5] It is a real entity, subsisting prior to, and independently of, the bodies which it contains; and all events in nature can be represented by movements within it. Every point of space persists throughout an infinite succession of instants of time, and the notion of simultaneity is valid, with all the implications which it carries in classical physics. In the Gassendi-Newton scheme it is not considered necessary to account for the existence of entities which are permanent over appreciable durations of time, such as (in the earlier period) particles of matter: these are postulated, and the aim of science is to explain the changing phenomena of the universe in terms of their motions. Persistence of bodies in time and their displacement in space are the concepts to which everything in the external world is to be reduced.

The attempt to fit this doctrine into the framework of philosophy and theology was confronted by the difficulty that besets all systems based on the Cartesian bifurcation between mind and matter, namely, that no provision is made for the interaction of spiritual with corporeal being. A possible solution seemed to be indicated by an idea put forward in 1647 by the Cambridge Platonist Henry More, that in some part of the human brain there is a *sensorium* or organ of internal sensation where the understanding resides, to which the images of external things are conveyed by the organs of sense, and where they have a "tactual conjunction" with the soul, which thus perceives them. Newton now boldly suggested that space might be the Sensorium of God. "Does it not appear from phenomena," he said,[6] "that there is a Being incorporeal,

[4] "Spatium absolutum, naturâ suâ sine relatione ad externum quodvis, semper manet similare et immobile," "Principia," *Schol. ad. Defin.*

[5] "In spatio quoad ordinem situs locantur universa," *ibid.*

living, intelligent, omnipresent, who in infinite space, as it were in his sensory, sees the things themselves intimately, and thoroughly perceives them, and comprehends them wholly by their immediate presence to himself?"

The idea that God had to be fitted into a scheme of which matter, space and time were the primary concepts was attacked by Leibnitz, who rejected altogether the doctrine of an absolute space and time having reality outside our minds, and maintained that space is only a conceptual entity, an order according to which situations are disposed, and time is only an order of succession. His argument against Newton may be put in a modern form somewhat as follows: During the operation of "summer time" the clock is an hour ahead of Greenwich time. This fact is, however, not made evident by any of the ordinary happenings of life, since all clocks, departures of railway trains, office hours, mealtimes and so forth, bear to each other the same relations as before: in order to detect the change we have to observe something which does not obey the Act of Parliament establishing summer time, such as the moment of sunset. Now suppose that some way could be found of compelling the heavenly bodies to adapt themselves to summer time on the same day as our clocks: then, after this, it would be impossible by any observations whatever to tell which kind of time we were keeping: the only evidence would be that furnished by memory—the recollection of the day which had only 23 hours, when the clocks were put forward. Let us now imagine that day to recede into the past, back to the creation of the world. Would there then be any difference between the two systems? Or to put the same question in another form, is there any meaning in the statement that God might have created everything an hour sooner? Newton would say, Yes. Leibnitz would say, No. I leave the fellows of the society to form their own judgment on the matter.

Another count in Leibnitz's indictment of Newtonianism related to the concept of force, the *vis motrix* of the "Principia," which in the case of gravity was represented as acting at a distance. "Some men," wrote Leibnitz, "begin to revive, under the specious name of 'forces,' the occult qualities of Scholasticism; but they bring us back again into the Kingdom of Darkness."[7] Now "force" in its statical sense, as, for instance, when we speak of "the force exerted by the weight of one pound," was a familiar idea to the Schoolmen: their physics included what they called *scientia de ponderibus,* which dealt with such matters as the law of equilibrium of the lever and the apparent weight of a body resting on an inclined plane. But the kinetic relations of force were unknown in the Middle Ages, and were first formulated in the "Principia," in the Second Law of Motion, which equates force to the product of mass and acceleration.

Newton showed how the known connection between forces and accelerations made it possible to write down equations, by which the motion could be determined. But before long it was found that, at any rate when the system studied was only a single particle, the motion could be calculated without bringing in forces or accelerations, by making use of what would now be called the principle of conservation of energy. When a pendulum is drawn to one side, so that the bob is higher than when it is hanging vertically, it has energy in the potential form (in this case due to gravitation); when the pendulum is released, it begins to swing, the potential energy being changed into energy of motion. This way of regarding dynamics shows a certain affinity with the Scholastic philosophy; for the physics which the Schoolmen appropriated from Aristotle was dominated by the idea that there are two ways of Being, potency[8] and act,[9] and that all change is a transition between a state which is potential and a state which is actual.

For a problem in classical mechanics there is of course no contradiction between the solution which is obtained by using the concept of potential energy and the solution by the original Newtonian method which uses the concept of force: the two are mathematically equivalent. But in the present century it has been found that the mutual influence between elementary particles is governed not by the laws of classical mechanics but by those of quantum mechanics, in which the concept of force is abolished and the interaction is represented by a term corresponding to the potential energy of classical mechanics, but of a more abstract character; it is called an operator, and, like potential energy, may be attached to the Aristotelian concept of potency.

To return to classical physics, a further change in its outlook was brought about by the discovery of what are called minimum-principles. A simple example is afforded by the hanging chain. Suppose that a chain is suspended between two points of support: what will be the curve in which it will dispose itself? We all know the general appearance of the curve: it is something like an arc of a circle joining the two points of suspension. Actually it is not part of a circle, but a curve known as a catenary: this was discovered towards the end of the seventeenth century by the Newtonian method of considering the forces which act between consecutive links of the chain. The problem may, however, be solved in a quite different way, with-

[6] *Opticks,* Qu. 28.

[7] "A Collection of Papers which passed between Mr. Leibnitz and Dr. Clarke" (London, 1717), p. 265.

[8] δύναμις, *potentia.*

[9] ἐνέργεια or ἐντελέχεια, *actus.*

out introducing the idea of force, by assuming that the chain arranges itself in such a way as to make its center of gravity have the lowest possible position. This assumption, that the height of the center of gravity is a minimum, is a typical minimum-principle. At least one minimum-principle was known to the ancient Greeks, namely, that when a ray of light issuing from a source is reflected at a mirror and afterwards received by an observer, then the path followed by the incident and reflected rays is shorter than any other path from the source to the observer which meets the mirror.

By a succession of discoveries it was shown that all the happenings of nature can be predicted by means of minimum-principles: the climax was reached in 1915, when Hilbert showed that all physical events (gravitational, electrical, etc.) in the universe are determined by a "world-function" which is such that its integral taken over the whole of space-time is a minimum. Such a statement as this has a decidedly Aristotelian character; for, in studying change, Aristotle always fixed his attention on the end to be fulfilled: his science was essentially teleological. Again we see how classical physics, following its own natural development, tended to deviate from the pattern devised by Newton and to return to the Aristotelian-Scholastic mould.

A change in orientation such as this, however, did not affect the fundamental assumptions of Newtonian science. We have now to consider developments of a far more subversive nature.

The first serious trouble arose in connection with the doctrine of space. The space of Gassendi and Newton was, so far as geometry was concerned, the space of Euclid: it was infinite, homogeneous and completely featureless, one point being just like another; so far as physics was concerned, it was like the vacuum of the ancient atomists, mere emptiness into which things could be put. From the philosophical point of view this concept was open to the objection that Aristotle had urged against the doctrine of the atomists, namely, that if space were devoid of local properties, the tendency of a body to move spontaneously in a particular direction (*e.g.*, the existence of a gravitational field, as we should say) would be unintelligible. As a matter of fact, the successors of Newton felt this difficulty; and, having started with a space which was in itself simply nonentity, having no property except a capacity for being occupied, they proceeded to fill it several times over with ethers designed to provide electric, magnetic and gravitational forces, and to account for the propagation of light; and as it was impossible to draw any effective distinction between those ethers and space, Newtonian space became eventually a plenum of the most elaborate kind, possessing such qualities as density and rigidity everywhere. Its points were capable of individual identification, and could be regarded as fixed; and having thus acquired a more definite and concrete substantiality than Newton himself had ever contemplated, its absolute character became an essential and inseparable axiom of classical physics. But the discovery in 1905 of the principle of relativity led to inferences incompatible with the existence of any kind of quasi-material ether: and thus the Gassendi-Newton doctrine became involved in hopeless contradiction.

(*To be concluded*)

OBITUARY

ALEŜ HRDLIĈKA

March 29, 1869–September 5, 1943

ALEŠ HRDLIČKA was born of worthy middle-class parents at Humpolec, Bohemia. In 1882 the family moved to New York. There, in 1892, he got a degree at the Eclectic Medical College of the City of New York and in 1894 from the New York Homeopathic Medical College. Soon after he joined the staff of the State Homeopathic Hospital for the Insane at Middletown, N. Y., and also became affiliated with the Pathological Institute of the N. Y. State Hospitals. His early years with the mentally and physically abnormal convinced him of the need for knowing the normal, and this became the guiding principle of his entire scientific life.

Dr. Hrdlička was truly a prodigious worker, both in the laboratory and in the field. In 1898 he took his first field trip, with Lumholtz to Mexico, where he studied the Tarahumares, the Huichols and the Tepehuanes. These trips were continued in 1899–1902, to the southwestern United States and northern Mexico, under the auspices of the Hyde expeditions of the American Museum. He had an unusual ability to "get along" with natives, and these field trips were very fruitful. They were the first of many that took him all over the world: to Egypt and the Near East in 1909, to Siberia and Mongolia in 1912, to Peru in 1913, to the Far East in 1920, to Africa, Asia and Oceania in 1925, to Alaska and the Aleutians in 1926–38, to Russia and Siberia in 1939, besides numerous trips to Europe and expeditions within the United States.

In 1903 Dr. Hrdlička became assistant curator and in 1910 curator of the Division of Physical Anthro-